Xyce™ Parallel Electronic Simulator
Users’ Guide, Version 6.9

Eric R. Keiter, Karthik V. Aadithya, Ting Mei, Thomas V. Russo, Richard L. Schiek,
Peter E. Sholander, Heidi K. Thornquist, Jason C. Verley

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Xyce™ Parallel Electronic Simulator
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Electrical Models and Simulation

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Abstract

This manual describes the use of the Xyce Parallel Electronic Simulator. Xyce has been designed as a SPICE-compatible, high-performance analog circuit simulator, and has been written to support the simulation needs of the Sandia National Laboratories electrical designers. This development has focused on improving capability over the current state-of-the-art in the following areas:

■ Capability to solve extremely large circuit problems by supporting large-scale parallel computing platforms (up to thousands of processors). This includes support for most popular parallel and serial computers.

■ A differential-algebraic-equation (DAE) formulation, which better isolates the device model package from solver algorithms. This allows one to develop new types of analysis without requiring the implementation of analysis-specific device models.

■ Device models that are specifically tailored to meet Sandia’s needs, including some radiation-aware devices (for Sandia users only).

■ Object-oriented code design and implementation using modern coding practices.

Xyce is a parallel code in the most general sense of the phrase — a message passing parallel implementation — which allows it to run efficiently a wide range of computing platforms. These include serial, shared-memory and distributed-memory parallel platforms. Attention has been paid to the specific nature of circuit-simulation problems to ensure that optimal parallel efficiency is achieved as the number of processors grows.
Acknowledgements

We would like to acknowledge all the code and test suite developers who have contributed to the Xyce project over the years: Alan Lundin, Arlon Waters, Ashley Meek, Bart van Bloemen Waanders, Brad Bond, Brian Fett, Christina Warrender, David Baur, David Day, David Shirley, Deborah Fixel, Derek Barnes, Eric Rankin, Erik Zeek, Gary Hennigan, Herman "Buddy" Watts, Jim Emery, Keith Santarelli, Laura Boucheron, Lawrence Musson, Mary Meinelt, Mingyu "Genie" Hsieh, Nicholas Johnson, Philip Campbell, Rebecca Arnold, Regina Schells, Richard Drake, Robert Hoekstra, Roger Pawlowski, Russell Hooper, Samuel Browne, Scott Hutchinson, Smitha Sam, Steven Verzi, Tamara Kolda, Timur Takhtaganov, and Todd Coffey.

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1. Introduction

Welcome to Xyce

The Xyce Parallel Electronic Simulator is a SPICE-compatible [1] [2] circuit simulator that has been written to support the unique simulation needs of electrical designers at Sandia National Laboratories. It is specifically targeted to run on large-scale parallel computing platforms, but is also available on a variety of architectures including single processor workstations. It aims to support a variety of devices and models specific to Sandia needs, as well as standard capabilities available from current commercial simulators.
1.1 Xyce Overview

The Xyce Parallel Electronic Simulator project was started in 1999 to support the simulation needs of electrical designers at Sandia National Laboratories and has evolved into a mature platform for large-scale circuit simulation.

Xyce includes several unique features. An important driver has been the need to simulate very large-scale circuits (100,000 devices or more) on the transistor level. To this end, scalable algorithms for simulating large circuits in parallel have been developed. In addition Xyce includes novel approaches to numerical kernels including model-order reduction, continuation algorithms, time-integration, nonlinear and linear solvers. Also, unlike most SPICE-based codes, Xyce uses a differential-algebraic-equation (DAE) formulation, which better isolates the device model package from solver algorithms.

1.2 Xyce Capabilities

1.2.1 Support for Large-Scale Parallel Computing

Xyce is a truly parallel simulation code, designed and written from the ground up to support large-scale parallel computing architectures with up to thousands of processors. This provides Xyce the capability to solve large circuit problems with quick enough runtimes to make these simulations practical. Xyce uses a message passing parallel implementation, allowing it to run efficiently on a variety of parallel computing platforms. These include serial, shared-memory and distributed-memory parallel. Careful attention has been paid to the specific nature of circuit-simulation problems to ensure optimal parallel efficiency, even as the number of processors increases.

1.2.2 Differential-Algebraic Equation (DAE) formulation

Xyce has been designed to use a DAE formulation. Among other advantages, this has the benefit of allowing the device models to be nearly independent of the type analysis to be performed, and allows a lot of encapsulation between the models and the solver layers of the source code. In a SPICE-based code, new device functions are created for each type of analysis, such as transient and AC analysis. With Xyce’s DAE implementation, this is not necessary. The same device load functions can be used for all analysis types, resulting in faster development time for new types of analysis.

1.2.3 Device Model Support

The Xyce development team continually adds new device models to Xyce to meet the needs of Sandia users. This includes the full set of models that can be found in most SPICE-based codes. For current device availability, consult The Xyce Reference Guide [3].
1.3 Reference Guide

The Xyce User’s Guide companion document, the Xyce Reference Guide [3], contains detailed information including a netlist reference for Xyce-supported input-file commands and elements; a command line reference, which describes the available command line arguments; and quick-references for users of other circuit codes, such as Orcad’s PSpice [4].

1.4 How to Use this Guide

This guide is designed to enable one to quickly find the information needed to use Xyce. It assumes familiarity with basic Unix-type commands, and how Unix manages applications and files to perform routine tasks (e.g., starting applications, opening files, and saving work).

Typographical conventions

Table 1.1 defines the typographical conventions used in this guide.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Example</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typewriter text</td>
<td>mpirun -np 4</td>
<td>Commands entered from the keyboard on the command line or text entered in a netlist.</td>
</tr>
<tr>
<td>Bold Roman Font</td>
<td>Set nominal temperature using the TNOM option.</td>
<td>SPICE-type parameters used in models, etc.</td>
</tr>
<tr>
<td>Gray Shaded Text</td>
<td>DEBUGLEVEL</td>
<td>Feature that is designed primarily for use by Xyce developers.</td>
</tr>
<tr>
<td>[text in brackets]</td>
<td>Xyce [options] &lt;netlist&gt;</td>
<td>Optional parameters.</td>
</tr>
<tr>
<td>&lt;text in angle brackets&gt;</td>
<td>Xyce [options] &lt;netlist&gt;</td>
<td>Parameters to be inserted by the user.</td>
</tr>
<tr>
<td>&lt;object with asterisk&gt;*</td>
<td>K1 &lt;ind. 1&gt; [&lt;ind. n&gt;*]</td>
<td>Parameter that may be multiply specified.</td>
</tr>
<tr>
<td>&lt;TEXT1</td>
<td>TEXT2&gt;</td>
<td>.PRINT TRAN + DELIMITER=&lt;TAB</td>
</tr>
</tbody>
</table>
Chapter Overview

This chapter describes the basic mechanics of installing and running Xyce. It includes the following sections:

- Section 2.1 Xyce Installation
- Section 2.2 Running Xyce
2.1 **Xyce** Installation

*Xyce* is distributed in two ways: source code and binary installers. Instructions for both methods of installation are available on the [Xyce](http://xyce.sandia.gov) web site.

2.1.1 Postinstallation steps: PATH setting

In order to run *Xyce*, either type the path to its binary every time, or add the installed location of *Xyce* to the PATH variable. Do so by editing the shell start-up file (.bashrc if your shell is bash, .profile if the shell is sh, or .cshrc if the shell is the c-shell). Exact syntax depends on the shell used, but for bash and sh the syntax is:

```
export PATH=$PATH:/usr/local/Xyce-Release-6.9.0/bin
```

The exact path will depend on the installed version of *Xyce*. Look in `/usr/local` with the following command:

```
ls -l /usr/local
```

to identify the actual install directory used by the installed version of *Xyce*. Once entered into the start-up file, the path will be set this way at the next log in. The same command can be issued directly in the command line and it will take effect immediately.

Binary installations on Windows create a “Command Prompt” shortcut for Xyce that sets this path for you. When the command prompt is opened with this shortcut, Xyce may simply be invoked by typing its name.

2.2 Running **Xyce**

While it is possible to connect *Xyce* to graphical interfaces, such as gEDA [5] or Qucs-s [6], *Xyce* is not provided with any graphical user interface. It is primarily used as a command-line-only program across all supported platforms, including traditionally “GUI-centered” platforms such as Mac OS X and Microsoft Windows.

This section describes how *Xyce* is run from the command line, for serial and MPI parallel simulations.

2.2.1 Command Line Simulation

The syntax for running *Xyce* from the command line differs depending it is the serial or parallel version.
Running Xyce

Assuming the Xyce executable in in the user's path, then the commands for running Xyce are:

- Running serial Xyce:
  
  Xyce [options] <netlist filename>

- Running Xyce in parallel:
  
  mpirun -np <# procs> Xyce [options] <netlist filename>

Note that mpiexec is sometimes provided as an alternative to mpirun. With Open MPI, the two commands are identical, but that is not the case for all MPI implementations.

General comments

The [options] are the command line arguments for Xyce. For example, to log output to a file named sample.log type:

  Xyce -l sample.log <netlist filename>

The next example runs parallel Xyce on four processors and places the results into a comma separated value file named results.csv (assuming a source code install):

  mpirun -np 4 Xyce -delim COMMA -o results.csv <netlist filename>

While Xyce is running, simulation progress is output to the command line window along with any error messages.

Xyce assumes that <netlist filename> is either in the current working directory, or includes the path (full or relative) to the netlist file. Enclose the filename in quotation marks (") if the path contains spaces. Help is accessible with the -h option.

Consult the documentation installed with MPI on the user's platform for more details concerning MPI options. The -np <# procs> denotes the number of processors to use for the simulation. **NOTE: It is critical that the number of processors used must be smaller than the number of devices and voltage nodes in the netlist.**

Guidance for Running Xyce in Parallel

The basic mechanics of running Xyce in parallel have been discussed above. For general guidance regarding solver options, partitioning options, and other parallel issues, refer to chapter 10. Distributed memory circuit simulation still contains a number of research issues, so obtaining an optimal simulation in parallel is a bit of an art.

**NOTE: If you are running on Linux, please see chapter 10 especially section 10.2 for critical guidance on OpenMPI options that can seriously impact the performance of parallel jobs on a multiuser system.**
2.2.2 Command Line Options

**Xyce** supports a handful of command line options that must be given before the netlist filename. Table 2.1 lists **Xyce** core options.

Table 2.1: List of **Xyce** command line arguments.

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
<th>Usage</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>-h</td>
<td>Help option. Prints usage and exits.</td>
<td>-h</td>
<td>-</td>
</tr>
<tr>
<td>-v</td>
<td>Prints the version banner and exits.</td>
<td>-v</td>
<td>-</td>
</tr>
<tr>
<td>-delim</td>
<td>Set the output file field delimiter.</td>
<td>-delim &lt;TAB</td>
<td>COMMA</td>
</tr>
<tr>
<td>-o</td>
<td>Place the results into specified file.</td>
<td>-o &lt;file&gt;</td>
<td>-</td>
</tr>
<tr>
<td>-l</td>
<td>Place the log output into specified file.</td>
<td>-l &lt;file&gt;</td>
<td>-</td>
</tr>
<tr>
<td>-r</td>
<td>Output a binary rawfile.</td>
<td>-r &lt;file&gt;</td>
<td>-</td>
</tr>
<tr>
<td>-a</td>
<td>Use with -r to output a readable (ascii) rawfile.</td>
<td>-r &lt;file&gt; -a</td>
<td>-</td>
</tr>
<tr>
<td>-nox</td>
<td>Use the NOX nonlinear solver.</td>
<td>-nox &lt;ON</td>
<td>OFF&gt;</td>
</tr>
<tr>
<td>-info</td>
<td>Output information on parameters.</td>
<td>-info [device prefix] [level] [ON</td>
<td>OFF]</td>
</tr>
<tr>
<td>-linsolv</td>
<td>Set the linear solver.</td>
<td>-linsolv &lt;KLU</td>
<td>KSPARSE</td>
</tr>
<tr>
<td>-param</td>
<td>Print a terse summary of model parameters, device parameters and default values.</td>
<td>-param</td>
<td>-</td>
</tr>
<tr>
<td>-syntax</td>
<td>Check netlist syntax and exit.</td>
<td>-syntax</td>
<td>-</td>
</tr>
<tr>
<td>-norun</td>
<td>Netlist syntax and topology and exit.</td>
<td>-norun</td>
<td>-</td>
</tr>
<tr>
<td>-randseed</td>
<td>Set random number seed for expression library’s random number functions.</td>
<td>-randseed &lt;number&gt;</td>
<td>-</td>
</tr>
<tr>
<td>-maxord</td>
<td>Maximum time integration order.</td>
<td>-maxord &lt;1..5&gt;</td>
<td>-</td>
</tr>
<tr>
<td>-gui</td>
<td>GUI file output.</td>
<td>-gui</td>
<td>-</td>
</tr>
<tr>
<td>-jacobian_test</td>
<td>Jacobian matrix diagnostic.</td>
<td>-jacobian_test</td>
<td>-</td>
</tr>
</tbody>
</table>
abled by default, and older, deprecated features. The Xyce Reference Guide [3] provides a comprehensive list, including trial and deprecated options.
3. Simulation Examples with Xyce

Chapter Overview

This chapter provides several simple examples of Xyce usage. An example circuit is provided for each available analysis type.

- Section 3.1 Example Circuit Construction
- Section 3.2 DC Sweep Analysis
- Section 3.3 Transient Analysis
3.1 Example Circuit Construction

This section describes how to use Xyce to create the simple diode clipper circuit shown in figure 3.1.

Xyce only supports circuit creation via netlist editing. Xyce supports most of the standard netlist entries common to Berkeley SPICE 3F5 and Orcad PSpice. For users familiar with PSpice netlists, the Xyce Reference Guide [3] lists the differences between PSpice and Xyce netlists.

Example: diode clipper circuit

![Diode Clipper Circuit Schematic](image)

**Figure 3.1.** Schematic of diode clipper circuit with DC and transient voltage sources.

Using a plain text editor (e.g., vi, Emacs, Notepad), but not a word processor (e.g., OpenOffice or Microsoft Word), create a file containing the netlist of figure 3.2. For this example, the file is named `clipper.cir`

The netlist in figure 3.2 illustrates some of the syntax of a netlist input file. Netlists always begin with a title line (*e.g.* "Diode Clipper Circuit"), and may contain comments (lines beginning with the "*" character), devices, and model definitions. Netlists must always end with the ".*END" statement.

The diode clipper circuit contains two-terminal devices (diodes, resistors, and capacitors), each of which specifies two connecting nodes and either a model (for the diode) or a value (resistance or...
capacitance). The netlist of figure 3.2 describes the circuit shown in the schematic of figure 3.1. This netlist file is not yet complete and will not run properly using Xyce (see section 2.2 for instructions on running Xyce) as it lacks an analysis statement. This chapter later describes how to add the appropriate analysis statement and run the diode clipper circuit.

```
Diode Clipper Circuit
*
* Voltage Sources
VCC 1 0 5V
VIN 3 0 0V
* Diodes
D1 2 1 D1N3940
D2 0 2 D1N3940
* Resistors
R1 2 3 1K
R2 1 2 3.3K
R3 2 0 3.3K
R4 4 0 5.6K
* Capacitor
C1 2 4 0.47u
*
* GENERIC FUNCTIONAL EQUIVALENT = 1N3940
* TYPE: DIODE
* SUBTYPE: RECTIFIER
.MODEL D1N3940 D(
+     IS = 4E-10
+     RS = .105
+     N = 1.48
+     TT = 8E-7
+     CJ0 = 1.95E-11
+     VJ = .4
+     M = .38
+     EG = 1.36
+     XTI = -8
+     KF = 0
+     AF = 1
+     FC = .9
+     BV = 600
+     IBV = 1E-4)
*
.END
```

Figure 3.2. Diode clipper circuit netlist
3.2 DC Sweep Analysis

This section includes an example of DC sweep analysis using Xyce. The DC response of the clipper circuit is obtained by sweeping the DC voltage source (Vin) from -10 to 15 volts in one-volt steps. Chapter 7.2 provides more details about DC analysis, as does the Xyce Reference Guide [3].

Example: DC sweep analysis

To set up and run a DC sweep analysis using the diode clipper circuit:

1. Open the diode clipper circuit netlist file (clipper.cir) using a standard text editor (e.g., vi, Emacs, Notepad, etc.).

2. Enter the analysis control statement (as shown in the netlist in figure 3.4):

   .DC VIN -10 15 1

3. Enter the output control statement:

   .PRINT DC V(3) V(2) V(4)

4. Save the netlist file and run Xyce on the circuit. For example, to run serial Xyce:

   Xyce clipper.cir

5. Open the results file (clipper.cir.prn) and examine (or plot) the output voltages that were calculated for nodes 3 (Vin), 2 and 4 (Out). Figure 3.3 shows the output plotted as a function of the swept variable Vin.

![Figure 3.3. DC sweep voltages at Vin, node 2, and Vout](image-url)
Diode Clipper Circuit with DC sweep analysis statement

* Voltage Sources
VCC 1 0 5V
VIN 3 0 0V
* Analysis Command
.DC VIN -10 15 1
* Output
.PRINT DC V(3) V(2) V(4)
* Diodes
D1 2 1 D1N3940
D2 0 2 D1N3940
* Resistors
R1 2 3 1K
R2 1 2 3.3K
R3 2 0 3.3K
R4 4 0 5.6K
* Capacitor
C1 2 4 0.47u

* GENERIC FUNCTIONAL EQUIVALENT = 1N3940
* TYPE: DIODE
* SUBTYPE: RECTIFIER
.MODEL D1N3940 D(
+ IS = 4E-10
+ RS = .105
+ N = 1.48
+ TT = 8E-7
+ CJ0 = 1.95E-11
+ VJ = .4
+ M = .38
+ EG = 1.36
+ XTI = -8
+ KF = 0
+ AF = 1
+ FC = .9
+ BV = 600
+ IBV = 1E-4)
*
.END

Figure 3.4. Diode clipper circuit netlist for DC sweep analysis
3.3 Transient Analysis

This section contains an example of transient analysis in Xyce. In this example, the DC analysis of the diode clipper circuit of the previous section has been modified so that the input voltage source \( (\text{Vin}) \) is a time-dependent sinusoidal input source. The frequency of \( \text{Vin} \) is 1 kHz, and has an amplitude of 10 volts. For more details about transient analysis see chapter 7.3, or the Xyce Reference Guide [3].

Example: transient analysis

To set up and run a transient analysis using the diode clipper circuit:

1. Open the diode clipper circuit netlist file (clipper.cir) using a standard text editor (e.g., VI, Emacs, Notepad, etc.).

2. Remove DC analysis and output statements if added in the previous example (figure 3.4).

3. Enter the analysis control (as shown in the netlist in figure 3.5):

   \[ .TRAN 2\text{ns} 2\text{ms} \]

4. Enter the output control statement:

   \[ .PRINT \text{TRAN} \; V(3) \; V(2) \; V(4) \]

5. Modify the input voltage source (\( \text{Vin} \)) to generate the sinusoidal input signal:

   \[ \text{VIN} \; 3 \; 0 \; \text{SIN}(0V \; 10V \; 1kHz) \]

6. At this point, the netlist should look similar to the netlist in figure 3.5. Save the netlist file and run Xyce on the circuit. For example, to run serial Xyce:

   \[ \text{Xyce clipper.cir} \]

7. Open the results file and examine (or plot) the output voltages for nodes 3 (\( \text{Vin} \)), 2, and 4 (\( \text{Out} \)). The plot in figure 3.6 shows the output plotted as a function of time.

Figure 3.5 shows the modified netlist and figure 3.6 shows the corresponding results.
Diode clipper circuit with transient analysis statement
*
* Voltage Sources
VCC 1 0 5V
VIN 3 0 SIN(0V 10V 1kHz)
* Analysis Command
.TRAN 2ns 2ms
* Output
.PRINT TRAN V(3) V(2) V(4)
* Diodes
D1 2 1 D1N3940
D2 0 2 D1N3940
* Resistors
R1 2 3 1K
R2 1 2 3.3K
R3 2 0 3.3K
R4 4 0 5.6K
* Capacitor
C1 2 4 0.47u
*
* GENERIC FUNCTIONAL EQUIVALENT = 1N3940
* TYPE: DIODE
* SUBTYPE: RECTIFIER
.MODEL D1N3940 D(
  +    IS = 4E-10
  +    RS = .105
  +    N = 1.48
  +    TT = 8E-7
  +    CJO = 1.95E-11
  +    VJ = .4
  +    M = .38
  +    EG = 1.36
  +    XTI = -8
  +    KF = 0
  +    AF = 1
  +    FC = .9
  +    BV = 600
  +    IBV = 1E-4)
*
.END

**Figure 3.5.** Diode clipper circuit netlist for transient analysis
Figure 3.6. Sinusoidal input signal and clipped outputs
Chapter Overview

This chapter contains introductory material on netlist syntax and usage. Sections include:

- Section 4.1 General Overview
- Section 4.2 Devices Available for Simulation
- Section 4.3 Parameters and Expressions
4.1 General Overview

4.1.1 Introduction

Using a netlist to describe a circuit for Xyce is the primary method for running a circuit simulation. Netlist support within Xyce largely conforms to that used by Berkeley SPICE 3F5 with several new options for controlling functionality unique to Xyce.

In a netlist, the circuit is described by a set of *element lines* defining circuit elements and their associated parameters, the circuit topology (i.e., the connection of the circuit elements), and a variety of control options for the simulation. The first line in the netlist file must be a title and the last line must be “.END”. Between these two constraints, the order of the statements is irrelevant.

4.1.2 Nodes

Nodes and elements form the foundation for the circuit topology. Each node represents a point in the circuit that is connected to the leads of multiple elements (devices). Each lead of every element is connected to a node, and each node is connected to multiple element leads.

A node is simply a named point in the circuit. The naming of normal nodes is only known within the level of circuit hierarchy where they appear; normal nodes defined in the main circuit are not visible to subcircuits, nor are nodes defined in a subcircuit visible to the top-level circuit. Nodes can be passed into subcircuits through an argument list, and in this case subcircuits are given limited access to nodes from the upper-level circuit.

**Global Nodes**

For cases where a particular node is used widely throughout various subcircuits it can be more convenient to use a global node, which is referenced by the same name throughout the circuit. This is often the case for power rails such as VDD or VSS.

Global nodes start with the prefix $G$. Examples of global node names would be: $G_VDD$ or $G1$. Nodes or global nodes require no declaration, as they are declared implicitly by appearing in *element lines*.

4.1.3 Elements

An *element line* defines each circuit element instance. While each element type determines the specific format, the general format is given by:

```
<type><name> <node information> <element information...>
```

The `<type>` must be a letter (A through Z) with the `<name>` immediately following. For example, RARESISTOR specifies a device of type “R” (for “Resistor”) with a name ARESISTOR. Nodes are
separated by spaces, and additional element information required by the device is given after the
node list as described in the Netlist Reference section of the Xyce Reference Guide [3]. Xyce
ignores character case when reading a netlist such that RARESISTOR is equivalent to raresistor.
The only exception to this case insensitivity occurs when including external files in a netlist where
the filename specified in the netlist must have the same case as the actual filename.

A number field may be an integer or a floating-point value. Either one may be followed by one of
the following scaling factors shown in Table 4.1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Equivalent Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>G</td>
<td>$10^{9}$</td>
</tr>
<tr>
<td>Meg</td>
<td>$10^{6}$</td>
</tr>
<tr>
<td>K</td>
<td>$10^{3}$</td>
</tr>
<tr>
<td>mil</td>
<td>$25.4^{-6}$</td>
</tr>
<tr>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>u ($\mu$)</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>n</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>p</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>f</td>
<td>$10^{-15}$</td>
</tr>
</tbody>
</table>

Node information is given in terms of node names, which are character strings. One key require-
ment is that the ground node is named ‘0’. (Note: Consult the Xyce Reference Guide [3] for more
details on allowed characters in both node names and device names.) There is one restriction on
the circuit topology: there can be no loop of voltage sources and/or inductors. In addition to this
requirement, the following additional topology constraints are highly recommended:

■ Every node has a DC path to ground.
■ Every node has at least two connections (with the exception of unterminated transmission
  lines and MOSFET substrate nodes).

While Xyce can theoretically handle netlists that violate the above two constraints, such topologies
are typically the result of human error in creating a netlist file, and will often lead to convergence
failures. Chapter 13 provides more information on this topic.

The following line provides an example of an element line that defines a resistor between nodes 1
and 3 with a resistance value of 10kΩ.
Title, Comments and End

The first line of the netlist is the title line of the netlist. This line is treated as a comment even if it does not begin with an asterisk. It is a common mistake to forget the meaning of this first line and begin the circuit elements on the first line; doing so will probably result in a parsing error.

Example: Test RLC Circuit

The "END" line must be the last line in the netlist.

Example: .END

Comments are supported in netlists and are indicated by placing an asterisk at the beginning of the comment line. They may occur anywhere in the netlist but they must be at the beginning of a line. Xyce also supports in-line comments. An in-line comment is designated by a semicolon and may occur on any line. Xyce ignores everything after a semicolon. Xyce considers lines beginning with leading whitespace as comments unless the first character after the whitespace is a + symbol, in which case it treats the line as a continuation.

Example: * This is a netlist comment.

Example: WRONG:.DC .... * This type of in-line comment is not supported.

Example: .DC .... ; This type of in-line comment is supported.

Continuation Lines

Continuation lines begin with a + symbol, and their contents are appended to those of the previous line. If the previous line or lines were comments, the continuation line is appended to the first noncomment line preceding it. Continuation lines can have leading whitespace before the + symbol.

Netlist Commands

Command elements are used to describe the analysis being defined by the netlist. Examples include analysis types, initial conditions, device models, and output control. The Xyce Reference Guide [3] contains a reference for these commands.

Example: .PRINT TRAN V(Vout)
Analog Devices

Xyce-supported analog devices include most of the standard circuit components normally found in circuit simulators, such as SPICE 3F5, PSpice, etc., plus several Sandia-specific devices.

Example: \[ D_{CR303} \text{ N}_0065 \text{ 0} D_{159700} \]


4.2 Devices Available for Simulation

The analog devices available in Xyce include all of the standard circuit components needed for most analog circuits. User-defined models may be implemented using the .MODEL (model definition) statement, and macromodels can be created as subcircuits using the .SUBCKT (subcircuit) statement.

In addition to the traditional analog devices, which are modeled in Xyce by sets of coupled differential algebraic equations, Xyce also supports digital behavioral models. The digital devices are behavioral devices in the sense that they rely on truth tables to determine their outputs. Once one or more of a digital device's inputs go past user-specified thresholds, its outputs will change according to its truth table after a user-specified delay time. The impedance characteristics of the inputs and outputs of the digital devices are modeled with RC time constants.

Xyce also include TCAD devices, which solve a coupled set of partial differential equations (PDEs), discretized on a mesh. The use of these devices are described in detail in Chapter [14].

The device element statements in the netlist always start with the name of the individual device instance. The first letter of the name determines the device type. The format of the subsequent information depends on the device type and its parameters. Table 4.2 provides a quick reference to the analog devices and their netlist formats as supported by Xyce. Except where noted, the devices are based upon those found in [7]. The Xyce Reference Guide [3] provides a complete description of the syntax for all the supported devices.

Table 4.2: Analog Device Quick Reference.

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Letter</th>
<th>Typical Netlist Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear Dependent Source (B Source)</td>
<td>B</td>
<td>[ B&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; + &lt;I or V&gt;=&lt;expression&gt; ]</td>
</tr>
<tr>
<td>Capacitor</td>
<td>C</td>
<td>[ C&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; [model name] &lt;value&gt; + [IC=&lt;initial value&gt;] ]</td>
</tr>
<tr>
<td>Diode</td>
<td>D</td>
<td>[ D&lt;name&gt; &lt;anode node&gt; &lt;cathode node&gt; + &lt;model name&gt; [area value] ]</td>
</tr>
<tr>
<td>Voltage Controlled Voltage Source</td>
<td>E</td>
<td>[ E&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;+ controlling node&gt; + &lt;- controlling node&gt; &lt;gain&gt; ]</td>
</tr>
<tr>
<td>Device Type</td>
<td>Letter</td>
<td>Typical Netlist Format</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>--------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Current Controlled Current Source</td>
<td>F</td>
<td>F&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;gain&gt;</td>
</tr>
<tr>
<td>Voltage Controlled Current Source</td>
<td>G</td>
<td>G&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;+ controlling node&gt; &lt;transconductance&gt;</td>
</tr>
<tr>
<td>Current Controlled Voltage Source</td>
<td>H</td>
<td>H&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;gain&gt;</td>
</tr>
<tr>
<td>Independent Current Source</td>
<td>I</td>
<td>I&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; [DC] &lt;value&gt; [AC] [magnitude value [phase value]] [transient specification]</td>
</tr>
<tr>
<td>Mutual Inductor</td>
<td>K</td>
<td>K&lt;name&gt; &lt;+ inductor name&gt; [ind. n]* &lt;linear coupling or model&gt;</td>
</tr>
<tr>
<td>Inductor</td>
<td>L</td>
<td>L&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;model name&gt; &lt;value&gt; [IC=&lt;initial value&gt;]</td>
</tr>
<tr>
<td>JFET</td>
<td>J</td>
<td>J&lt;name&gt; &lt;+ drain node&gt; &lt;gate node&gt; &lt;source node&gt; &lt;model name&gt; [area value]</td>
</tr>
<tr>
<td>MOSFET</td>
<td>M</td>
<td>M&lt;name&gt; &lt;+ drain node&gt; &lt;gate node&gt; &lt;source node&gt; &lt;bulk/substrate node&gt; [SOI nodes] &lt;model name&gt; [common model parameter]</td>
</tr>
<tr>
<td>Lossy Transmission Line (LTRA)</td>
<td>O</td>
<td>O&lt;name&gt; &lt;+ A port (+) node&gt; &lt;A port (-) node&gt; &lt;B port (+) node&gt; &lt;B port (-) node&gt; &lt;model name&gt;</td>
</tr>
<tr>
<td>Bipolar Junction Transistor (BJT)</td>
<td>Q</td>
<td>Q&lt;name&gt; &lt;+ collector node&gt; &lt;base node&gt; &lt;emitter node&gt; &lt;substrate node&gt; &lt;model name&gt; [area value]</td>
</tr>
<tr>
<td>Resistor</td>
<td>R</td>
<td>R&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; [model name] &lt;value&gt; [L=&lt;length&gt; [W=&lt;width&gt;]]</td>
</tr>
<tr>
<td>Voltage Controlled Switch</td>
<td>S</td>
<td>S&lt;name&gt; &lt;+ switch node&gt; &lt;- switch node&gt; &lt;controlling node&gt; &lt;model name&gt;</td>
</tr>
<tr>
<td>Transmission Line</td>
<td>T</td>
<td>T&lt;name&gt; &lt;+ A port + node&gt; &lt;A port - node&gt; &lt;B port + node&gt; &lt;B port - node&gt; &lt;ideal specification&gt;</td>
</tr>
<tr>
<td>Digital Devices</td>
<td>U</td>
<td>U&lt;name&gt; &lt;+ type&gt; &lt;digital power node&gt; &lt;digital ground node&gt; [node]* &lt;model name&gt;</td>
</tr>
<tr>
<td>Independent Voltage Source</td>
<td>V</td>
<td>V&lt;name&gt; &lt;+ node&gt; &lt;- node&gt; [DC] &lt;value&gt; [AC] [magnitude value [phase value]] [transient specification]</td>
</tr>
<tr>
<td>Subcircuit</td>
<td>X</td>
<td>X&lt;name&gt; [node]* &lt;subcircuit name&gt; [PARAMS:&lt;name&gt;=&lt;value&gt;]*</td>
</tr>
<tr>
<td>Current Controlled Switch</td>
<td>W</td>
<td>W&lt;name&gt; &lt;+ switch node&gt; &lt;- switch node&gt; &lt;controlling V device name&gt; &lt;model name&gt;</td>
</tr>
<tr>
<td>Digital Devices, Y Type (deprecated)</td>
<td>Y</td>
<td>Y&lt;name&gt; &lt;+ type&gt; [node]* &lt;model name&gt;</td>
</tr>
</tbody>
</table>
Table 4.2: Analog Device Quick Reference.

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Letter</th>
<th>Typical Netlist Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDE Devices</td>
<td>YPDE</td>
<td>YPDE &lt;name&gt; [node]* &lt;model name&gt;</td>
</tr>
<tr>
<td>Accelerated masses</td>
<td>YACC</td>
<td>YACC &lt;name&gt; &lt;acceleration&gt; &lt;velocity&gt; &lt;position&gt; + [x0=&lt;initial position&gt;] [v0=&lt;initial velocity&gt;]</td>
</tr>
<tr>
<td>Memristor Device</td>
<td>YMEMRISTOR</td>
<td>YMEMRISTOR &lt;name&gt; &lt;+ node&gt; &lt;- node&gt; &lt;model name&gt;</td>
</tr>
<tr>
<td>MESFET</td>
<td>Z</td>
<td>Z&lt;name&gt; &lt;drain node&gt; &lt;gate node&gt; &lt;source node&gt; + &lt;model name&gt; [area value]</td>
</tr>
</tbody>
</table>

4.3 Parameters and Expressions

In addition to explicit values, the user may use parameters and expressions to symbolize numeric values in the circuit design.

4.3.1 Parameters

A parameter is a symbolic name representing a numeric value. Parameters must start with a letter or underscore. The characters after the first can be letter, underscore, or digits. Once a parameter is defined (by having its name declared and having a value assigned to it) at a particular level in the circuit hierarchy, it can be used to represent circuit values at that level or any level directly beneath it in the circuit hierarchy. One way to use parameters is to apply the same value to multiple part instances.

4.3.2 How to Declare and Use Parameters

For using a parameter in a circuit, one must:

- Define the parameter using a .PARAM statement within a netlist
- Replace an explicit value with the parameter in the circuit

Xyce reserves the following keywords that may not be used as parameter names:

- Time
- Vt
- Temp
- GMIN

Time, TEMP, Vt and GMIN are reserved and defined and may be used in B source expressions. At this time they do not work in global_param expressions.
Example: Declaring a parameter

1. Locate the level in the circuit hierarchy at which the .PARAM statement declaring a parameter will be placed. To declare a parameter capable of being used anywhere in the netlist, place the .PARAM statement at the top-most level of the circuit.

2. Name the parameter and give it a value. The value can be numeric or given by an expression:

```
.SUBCKT subckt1 n1 n2 n3
.PARAM res = 100
*
* other netlist statements here
*
.ENDS
```

3. NOTE: The parameter res can be used anywhere within the subcircuit subckt1, including subcircuits defined within it, but cannot be used outside of subckt1.

Example: Using a parameter in the circuit

1. Locate the numeric value (a device instance parameter value, model parameter value, etc.) that is to be replaced by a parameter.

2. Replace the numeric value with the parameter name contained within braces ({{}}) as in:

```
R1 1 2 {res}
```

NOTE: Ensure the value being replaced remains accessible within the current hierarchy level.

Limitations on parameter definitions

As chapter 6 describes, there is considerable flexibility in the use of parameters. They can be set to expressions containing other parameters, and can be passed down the hierarchy into subcircuits. Fundamentally, however, parameters are constants evaluated at the beginning of a run; therefore, all terms in the expression defining the parameter must be constants known at the beginning of the run. It is not legal to use time-dependent expressions in parameter declarations (either by including voltage nodes or currents, or by including reference to the variable TIME).

Parameters defined within a given scope can be used in any expression within that scope. The only limitation on ordering is for the use of a parameter in an expression that defines the value of another parameter. In that case, all parameters used in the expression must be defined before being used to define another parameter. So, in the following example:

```
R1 1 0 {B+C} ; OK because the expression is not used to define a param
.PARAM A=3
.PARAM B={A+1} ; OK because A is defined above
.PARAM D={C+2} ; Illegal because C is not yet known
.PARAM C=2
```

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4.3.3 Global Parameters

A normal parameter defined at the main circuit level will have global scope. Such parameters suffer from limitations, such as: (1) they are constant during the simulation, and (2) the parameter may redefined within a subcircuit, which would change the value in the subcircuit and below. Global parameters address these limitations.

A global parameter differs from a normal parameter in that it can only be defined at the main circuit level, and it is allowed to change during a simulation. Global parameters act as variables rather than constants during the simulation. Examples of some global parameter usages are:

```
.param dTdt=100
.global_param T={27+dTdt*time}
R1 1 2 RMOD TEMP={T}
```

or

```
.global_param T=27
R1 1 2 RMOD TEMP={T}
C1 1 2 CMOD TEMP={T}
.step T 20 50 10
```

In these examples, T is used to represent an environmental variable that changes.

NOTE: Normal parameters may be used in expressions defining global parameters, but the opposite is not allowed.

4.3.4 Expressions

In Xyce, an expression is a mathematical relationship that may be used any place one would use a number (numeric or boolean). Except in the case of expressions used in analog behavioral modeling sources (see chapter 6), Xyce evaluates the expression to a value when it reads in the circuit netlist, not each time its value is needed. Therefore, all terms in an expression must be known at the beginning of a run.

To use an expression in a circuit netlist:

1. Locate the value to be replaced (component, model parameter, etc.).
2. Substitute the value with an expression using the {} syntax:

```
{expression}
```

where expression can contain any of the following:

- Arithmetic and logical operators.
- Arithmetic, trigonometric, or SPICE-type functions.
User-defined functions.
User-defined parameters within scope.
Literal operands.

The braces (\{}\}) instruct \textbf{Xyce} to evaluate the expression and use the resulting value. Additional time-dependent constructs are available in expressions used in analog behavioral modeling sources (see chapter \textit{5}). Complete documentation of supported functions and operators may be found in the \textbf{Xyce} Reference Guide \cite{3}.

Example: Using an expression

Scaling the DC voltage of a $12\,\text{V}$ independent voltage source, designated $\text{VF}$, by some factor can be accomplished by the following netlist statements (in this example the factor is 1.5):

\begin{verbatim}
.PARAM FACTORV=1.5
VF 3 4 \{(FACTORV*12)\}
\end{verbatim}

\textbf{Xyce} will evaluate the expression to $12 \times 1.5$ or 18 volts.
5. Working with Subcircuits and Models

Chapter Overview

This chapter provides model examples and summarizes ways to create and modify models. Sections include:

- Section 5.1 Model Definition
- Section 5.2 Subcircuit Creation
- Section 5.3 Model Organization
- Section 5.4 Model Interpolation
5.1 Model Definitions

A model describes the electrical performance of a part, such as a specific vendor’s version of a 2N2222 transistor. To simulate a part requires specification of simulation properties. These properties define the model of the part.

Depending on the given device type and the requirements of the circuit design, a model is specified using a model parameter set, a subcircuit netlist, or both.

In general, model parameter sets define the parameters used in ideal models of specific device types, while subcircuit netlists allow the user to combine ideal device models to simulate more complex effects. For example, one could simulate a bipolar transistor using the Xyce BJT device by specifying model parameters extracted to fit the simulation behavior to the behavior of the part used. One could also develop a subcircuit macro-model of a capacitor that adds effects such as lead inductance and resistance to the basic capacitor device.

Both methods of defining a model use a netlist format, with precise syntax rules. In this section we give an overview of how to define model parameter sets in Xyce. A subsequent subsection will provide a similar overview of how to define subcircuit models. For full details, consult the Xyce Reference Guide [3].

Defining models using model parameters

Although Xyce has no built-in part models, models can be defined for a device by changing some or all of the model parameters from their defaults via the .MODEL statement. For example:

\[
\text{M5 3 2 1 0 MLOAD1} \\
.\text{MODEL MLOAD1 NMOS (LEVEL=3 VTO=0.5 CJ=0.025pF)}
\]

This example defines a MOSFET device M5 that is an instance of a part described by the model parameter set MLOAD1. The MLOAD1 parameter set is defined in the .MODEL statement.

Most device types in Xyce support some form of model parameters. Consult the Xyce Reference Guide [3] for the model parameters supported by each device type.

Defining models using subcircuit netlists

In Xyce, models may also be defined using the .SUBCKT/.ENDS subcircuit syntax. This syntax allows the creation of Netlists, which define the configuration and function of the part, and the use of Variable input parameters, which can be used to create device-specific implementations of the model. The .SUBCKT syntax, and an example of how to use .SUBCKT to implement a model, is given in Section 5.2.
5.2 Subcircuit Creation

A subcircuit can be created within Xyce using the .SUBCKT keyword. The .ENDS keyword is used to mark the end of the subcircuit. All the lines between the two keywords are considered to be part of the subcircuit. Figure 5.1 provides an example of how a subcircuit is defined and used.

**Figure 5.1.** Example subcircuit model.

In this example, a subcircuit model named 13dsc1, which implements one part of a microstrip transmission line, is defined between the .SUBCKT/.ENDS lines; and two different instances of the subcircuit are used in the X lines. This somewhat artificial example shows how input parameters are used, where the last capacitor in the subcircuit is scaled by the input parameter ScaleFac. If input parameters are not specified on the X line (as in the case of device X6), then the default values specified on the .SUBCKT line are used. Non-default values are specified on the X line using the PARAMS: keyword. Consult the Xyce Reference Guide [3] for precise syntax.

In addition to devices, a subcircuit may contain definitions, such as models via the .MODEL statement, parameters via the .PARAM statement, and functions via the .FUNC statement. Xyce also
supports the definition of one or more subcircuits within another subcircuit. Subcircuits can be
nested to an arbitrary extent, where one subcircuit can contain another subcircuit, which can con-
tain yet another subcircuit, and so on.

The creation of nested subcircuits requires an understanding of “scope,” such that each subcircuit
defines the scope for the definitions it contains. That is, the definitions contained within a subcircuit
can be used within that subcircuit and within any subcircuit it contains, but not at any higher level.
Definitions occurring in the main circuit have global scope and can be used anywhere in the circuit.
A name, such as a model, parameter, function, or subcircuit name, occurring in a definition at one
level of a circuit hierarchy can be redefined at any lower level contained directly by that subcircuit.
In this case, the new definition applies at the given level and those below.

5.2.1 Examples of Scoping for Parameters, Models and Functions

The idea of “scope” may be best illustrated by examples. This section gives example for pa-
rameters and models. However, this discussion also applies to functions (defined with .FUNC
statements).

In the netlist provided in Figure 5.2, the model named MOD1 can be used in subcircuits SUB1 and
SUB2, but not in the subcircuit SUB3. The parameter P1 has a value of 10 in subcircuit SUB1 and
a value of 20 in subcircuit SUB2. In subcircuit SUB3, P1 has no meaning. In addition, MOD1 and P1
would have no meaning at the main circuit level.

```
.SUBCKT SUB1 1 2 3 4
.MODEL MOD1 NMOS(LEVEL=2)
.PARAM P1=10

.SUBCKT SUB2 1 3 2 4
.PARAM P1=20

.ENDS
.ENDS

.SUBCKT SUB3 1 2 3 4

.ENDS
```

Figure 5.2. Example subcircuit hierarchy, with scoping.
In the netlist provided in Figure 5.3, the parameters $P_2$ and $P_3$ are defined in the main circuit. So, $P_2$ is accessible in subcircuit SUB4, and has a value of 5 there. The parameter $P_3$ was redefined in the context of subcircuit SUB4. So, $P_3$ has a value of 10 in the main circuit, and a value of 15 in the context of subcircuit SUB4 and any subcircuit subsequently defined within subcircuit SUB4.

```
* parameters defined in main circuit
.PARAM P2=5
.PARAM P3=10

.SUBCKT SUB4 1 2 3 4
.PARAM P3=15
 *
 * subcircuit devices omitted for brevity
 *
.ENDS
```

**Figure 5.3.** Example subcircuit, with parameter definition override.

In the netlist provided in Figure 5.4, the definition of subcircuit SUB5 defines the argument $A_1$. The subcircuit instance $X_1$ would use the default value of 5 for $A_1$. So the resistance value of device $X_1:R_1$ would be 5. The subcircuit instance $X_2$ uses the specified $A_1$ value of 10. So the resistance value of device $X_2:R_1$ would be 10. Another key point about “scope” is that node, device, and model names are scoped to the subcircuit in which they are defined. So, it is allowable to use names in a subcircuit that has been previously used in either the main circuit netlist or in other subcircuit definitions. When the subcircuits are flattened (expanded to become part of the main netlist), all of their names are given prefixes via their subcircuit instance names. For example, device $R_1$ in subcircuit $X_1$ becomes the unique device name $X_1:R_1$ after expansion.

```
* subcircuit instance lines
X1 a b SUB5
X2 e f SUB5 PARAMS: A1=10
R1 1 2 2
 *
 * Note use of {} around A1 and FSIN parameters in
 * the body of the subcircuit definition.
 .SUBCKT SUB5 1 2 PARAMS: A1=5 FSIN=1
 VSIN 1 g SIN(0 1V {FSIN} 0)
 R1 g 2 {A1}
 .ENDS
```

**Figure 5.4.** Example subcircuit, with PARAMS arguments.
5.3 Model Organization

While it is always possible to make a self-contained netlist in which all models for all parts are included along with the circuit definition, Xyce provides a simple mechanism to conveniently organize frequently used models into separate model libraries. Models are simply collected into model library files, and then accessed by netlists as needed by inserting an .INCLUDE directive. This section describes that process in detail.

5.3.1 Model Libraries

Device model and subcircuit definitions may be organized into model libraries as text files (similar to netlist files) with one or more model definitions. Many users choose to name model library files ending with .lib, but they may be named using any convention.

In general, most users create model libraries files that include similar model types. In these files, the header comments describe the models therein.

5.3.2 Model Library Configuration using .INCLUDE

Xyce uses model libraries by inserting an .INCLUDE statement into a netlist. Once a file is included, its contents become available to the netlist just as if the entire contents had been inserted directly into the netlist.

As an example, one might create the following model library file called bjtmodels.lib, containing .MODEL statements for common types of bipolar junction transistors:

```plaintext
*bjtmodels.lib
*Bipolar transistor models
.MODEL Q2N2222 NPN (Is=14.34f Xti=3 Eg=1.11 Vaf=74.03 Bf=5 Ne=1.307
+  Ise=14.34f Ikf=.2847 Xtb=1.5 Br=6.092 Nc=2 Isc=0 Ikr=0 Rc=1
+  Cjc=7.306p Mjc=.3416 Vjc=.75 Fc=.5 Cje=22.01p Mje=.377 Vje=.75
+  Tr=46.91n Tf=411.1p Itf=.6 Vtf=1.7 Xtf=3 Rb=10)

.MODEL 2N3700 NPN (IS=17.2E-15 BF=100)

.MODEL 2N2907A PNP (IS=1.E-12 BF=100)
```

The models Q2N2222, 2N3700 and 2N2907A could then be used in a netlist by including the bjtmodels.lib file.

```plaintext
.INCLUDE "bjtmodels.lib"
Q1 1 2 3 Q2N2222
Q2 5 6 7 2N3700
```
Because the contents of an included file are simply inserted into the netlist at the point where the
INCLUDE statement appears, the scoping rules for INCLUDE statements are the same as for other
types of definitions as outlined in the preceding subsections.

NOTE: The path to the library file is assumed to be relative to the execution directory, but absolute
pathnames are permissible. The entire file name, including its “extension” must be specified.
There is no assumed default extension.

5.3.3 Model Library Configuration using .LIB

An alternative technique for organizing model libraries employs the .LIB command. With .LIB, a
library file can contain multiple versions of a model and specific versions may be selected at the
top level using a keyword on the .LIB line.

There are two different uses for the .LIB command. In the main netlist, .LIB functions in a similar
manner to INCLUDE: it reads in a file. Inside that file, .LIB and .ENDL are used to specify blocks
of model code that may be included independently of other parts of the same file.

As an example, if you had two different 2N2222 transistor models extracted at different TNOM
values, you could define them in a model library inside .LIB/.ENDL pairs:

* transistors.lib file
  .lib roomtemp
  .MODEL Q2N2222 NPN (TNOM=27 Is=14.34f Xti=3 Eg=1.11 Vaf=74.03 Bf=5 Ne=1.307
  + Ise=14.34f Ikf=.2847 Xtb=1.5 Br=6.092 Nc=2 Isc=0 Ikr=0 Rc=1
  + Cjc=7.306p Mjc=.3416 Vjc=.75 Fc=.5 Cje=22.01p Mje=.377 Vje=.75
  + Tr=46.91n Tf=411.1p Itf=.6 Vtf=1.7 Xtf=3 Rb=10)
  .endl

  .lib hightemp
  .MODEL Q2N2222 NPN (TNOM=55 [...parameters omitted for brevity...])
  .endl

Note that both models are given identical names, but are enclosed within .LIB/.ENDL pairs with
different names. When this file is used in a netlist, a specific model can be used by specifying it
on the .LIB line in the main netlist.

*This netlist uses only the high temperature model from the library
  .lib transistors.lib hightemp
  Q1 collector base emitter Q2N2222
  [...]

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The exact format and usage of the `.LIB` command is documented in the *Xyce* Reference Guide [3].

### 5.4 Model Interpolation

Traditionally, SPICE simulators handle thermal effects by coding the temperature dependence of model parameters into each device. These expressions modify the nominal device parameters given in the `.MODEL` card when the ambient temperature is not equal to \( T_{\text{NOM}} \), the temperature at which the nominal device parameters were extracted.

These temperature correction equations may be reasonable at temperatures close to \( T_{\text{NOM}} \), but Sandia users of *Xyce* have found them inadequate when simulations must be performed over a wide range of temperatures. To address this inadequacy, *Xyce* implements a model interpolation option that allows the user to specify multiple `.MODEL` cards, each extracted from real device measurements at a different \( T_{\text{NOM}} \). From these model cards, *Xyce* will interpolate parameters based on the ambient temperature using either piecewise linear or quadratic interpolation.

Interpolation of models is accessed through the model parameter `TEMPMODEL` in the models that support this capability. In the netlist, a base model is specified, and is followed by multiple models at other temperatures.

Interpolation of model cards in this fashion is implemented in the BJT level 1, JFET, MESFET, and MOSFETS levels 1-6, 10, and 18.

The use of model interpolation is best shown by example:

```plaintext
Jtest 1a 2a 3 SA2108 TEMP= 40
*
  .MODEL SA2108 PJF ( TEMPMODEL=QUADRATIC TNOM = 27
  + LEVEL=2 BETA= 0.003130 VTO = -1.9966 PB = 1.046
  + LAMBDA = 0.00401 DELTA = 0.578; THETA = 0;
  + IS = 1.393E-10 RS = 1e-3)
*
  .MODEL SA2108 PJF ( TEMPMODEL=QUADRATIC TNOM = -55
  + LEVEL=2 BETA = 0.00365 VTO = -1.9360 PB = 0.304
  + LAMBDA = 0.00286 DELTA = 0.2540 THETA = 0.0
  + IS = 1.393E-10 RD = 0.0 RS = 1e-3)
*
  .MODEL SA2108 PJF ( TEMPMODEL=QUADRATIC TNOM = 90
  + LEVEL=2 BETA = 0.002770 VTO = -2.0350 PB = 1.507
  + LAMBDA = 0.00528 DELTA = 0.630 THETA = 0.0
  + IS = 1.393E-10 RS = 5.66)
```

Note that the model names are all identical for the three `.MODEL` lines, and that they all specify `TEPMODEL=QUADRATIC`, but with different \( T_{\text{NOM}} \). For parameters that appear in all three `.MODEL` lines, the value of the parameter will be interpolated using the `TEMP=` value in the device line in the
first line, which is 40°C in this example. For parameters that are not interpolated, such as \( \text{RD} \), it is not necessary to include these in the second and third .MODEL lines.

The only valid arguments for \textbf{TEMPP\textsc{\textsc{m}}\textsc{od}e}l are \textbf{QUADRATIC} and \textbf{PWL} (piecewise linear). The quadratic method includes a limiting feature that prevents the parameter value from exceeding the range of values specified in the .MODEL lines. For example, the \( \text{RS} \) value in the example would take on negative values for most of the interval between -55 and 27, as the value at 90 is very high. This truncation is necessary as parameters can easily take on values (such as the negative resistance of \( \text{RS} \) in this example) that will cause a \textsc{xyce} failure.

With the BJT parameters \( \text{IS} \) and \( \text{ISE} \), interpolation is done not on the parameter itself, but on the log of the parameter. This provides excellent interpolation of these two parameters, that vary over many orders of magnitude, for quadratic and piecewise linear temperature dependence.

The interpolation scheme used for model interpolation bases the interpolation on the difference between the ambient temperature and the \( \text{T\textsc{n}\text{o}\text{m}} \) value of the first model card in the netlist, which can sometimes lead to poorly conditioned interpolation. Thus it is often best that the first model card in the netlist be the one that has the “middle” \( \text{T\text{\textsc{no}}\text{m}} \), as in the example above. This assures that no matter where in the range of temperature values the ambient temperature lies, it is a minimal distance from the base point of the interpolation.
6. Analog Behavioral Modeling

Chapter Overview

This chapter describes analog behavioral modeling in Xyce. Sections include:

- Section 6.1 Overview of Analog Behavioral Modeling
- Section 6.2 Specifying ABM Devices
- Section 6.3 Guidance for ABM Use
6.1 Overview of Analog Behavioral Modeling (ABM)

The analog behavioral modeling capability of Xyce provides for flexible descriptions of electronic components or subsystems in terms of a transfer function or lookup table. In other words, a mathematical relationship is used to model a circuit segment thereby removing the need for component-by-component design information for those components or subsystems.

The B device, or nonlinear dependent source, is the primary device used for analog behavioral modeling in Xyce. A B device can serve as either a voltage or current source, and by using expressions dependent on voltages and currents elsewhere in the circuit the user can produce a wide range of behaviors.

6.2 Specifying ABM Devices

ABM devices (B devices) are specified in a netlist the same way as other devices. Customizing the operational behavior of the device is achieved by defining an ABM expression describing how inputs are transformed into outputs.

For example, the following pair of lines would provide exactly the same behavior as a 10K resistor between nodes 1 and 2, and is written to be a current source with current specified using Ohm's law and the constant resistance value of 10K Ω.

```
.PARAM Res1=10K
Blinearres 1 2 I={(V(2)-V(1))/Res1}
```

A nonlinear resistor could be specified similarly:

```
.PARAM R1=0.15
.PARAM R2=6
.PARAM E2 = {2*E1}
.PARAM delr = {R1-R0}
.PARAM k1 = {1/E1**2}
.PARAM r2 = {R0+sqrt(2)*delr}

.FUNC Rreg1(a,b,c,d) {a +(b-a)*c/d}
.FUNC Rreg2(a,b,c,d,f) {a+sqrt(2-b*(2*c-d)**2)*f}

Bnlr 4 2 V = {I(Vmon) * IF( + V(101) < E1, Rreg1(R0,R1,V(101),E1), + IF( + V(101) < E2, Rreg2(R0,k1,E1,V(101),delr), R2 + )
```

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In this example, \textit{Bnlr} provides a voltage between nodes 4 and 2, determined using Ohm's law with a resistance that is a function of the voltage on node 101 and a number of parameters. These two examples demonstrate how the B source can be used either as a voltage source (by specifying \(V=\{\text{expression}\}\)) or as a current source (with \(I=\{\text{expression}\}\)).

\textbf{NOTE:} Unlike expressions used in parameters or function declarations, expressions in the nonlinear dependent source may contain voltages and currents from other parts of the circuit, or even explicit time-dependent functions. \textit{Xyce} evaluates these expressions when the current or voltage through the ABM source is needed. In contrast, expressions used in parameters or function declarations are evaluated only once, prior to the start of the circuit simulation.

### 6.2.1 Additional constructs for use in ABM expressions

ABM expressions follow the same rules as other expressions in a netlist, with the additional ability to specify signals (node voltages and voltage source currents) and explicitly time-dependent functions in the expression. In ABM expressions, refer to signals by name. \textit{Xyce} recognizes the following constructs in ABM expressions:

- \(V(<\text{node name}>)\)
- \(V(<\text{node name}>,<\text{node name}>)\) (the voltage difference between the first and second nodes)
- \(I(<\text{voltage source name}>)\)
- The variable, \(\text{TIME}\)
- The constants, \(\pi\) and \(e\), respectively.
- Lookup tables

In a hierarchical circuit (a circuit with possibly nested levels of subcircuits), voltage source names in an ABM expression must be the name of a voltage source in the same subcircuit as the ABM device, or in a subcircuit instantiated by that subcircuit. Similarly, node names in an ABM expression must be the node names of one or more devices in the same subcircuit as the ABM device, or in a subcircuit instantiated by that subcircuit.

### 6.2.2 Examples of Analog Behavioral Modeling

A variety of examples of legal usage of analog behavioral modeling is probably the most effective means of demonstrating what is allowed. The following netlist fragment shows the range of simple items allowed in ABM expressions:

* Current through B1 given as expression of voltage drop between
* nodes 2 and 3 plus current through voltage source Vr4mon
B1 1 0 I={}V(2,3) + I(Vr4mon)\}
R4 2 0 10K
Vr4mon 2a 2 0V

* Voltage across device Em given as time-dependent expression
Em 3 2a VALUE={}PAR3+1000*time\}

* Voltage across device B2 set to current through device Em
B2 2a 0 V={}I(Em)\}

* Voltage across device B3 is function of voltage on node two and current through device VdrainM3
B3 6 4 V={}I(VdrainM3)+V(2)\}

* Voltage across device B4 is function of an internal node named "5" of subcircuit instance X1
B4 4 5 V={}V(X1:5)\}

X1 1 3 mysubcircuit

* Current through device B5 taken from current through internal device V4 of subcircuit instance X1
B5 4 5 I={}I(X1:V4)\}

The range of items that can be used in the current and voltage parameters of a B (or E, F, G, or H) source is far greater than what is allowed for expressions in other contexts. In particular, the use of solution values (V(*), V(*,*), I(V*)) are prohibited in all other expressions because they lead to unstable behavior if used elsewhere beside ABM. Time-dependent expressions are allowed for some device parameters, but this feature should be used with caution, as the behavior of a non-ABM device cannot be guaranteed to be correct when its device parameters are not constant throughout a simulation run.

In addition to these simple items, lookup tables provide a means of specifying a piecewise linear function in an expression. A table expression is specified with the keyword TABLE followed by an expression that is evaluated as the independent variable of the function, followed by a list of pairs of independent variable/dependent variable values. For example:

**Example:**

B1 1 0 V={}TABLE \{time\} = (0, 0) (1, 2) (2, 4) (3, 6)\}

An equivalent example uses the table function, which has a simpler syntax, but may be hard to read for long tables:

**Example:**

B1 1 0 V={}TABLE(time, 0, 0, 1, 2, 4, 3, 6)\}

The previous two examples will produce a voltage source (B1) whose voltage is a simple linear function of time. At \( t = 0 \) the voltage is 0 volts and at time \( t = 1s \) the voltage is 2 volts. Similarly, the voltage will be 4 volts at \( t = 2s \) and 6 volts at \( t = 3s \). Linear interpolation is used at times in between those tabulated values.

It is also possible to create ABM sources from files of time-value pairs by providing the name of
the file containing the pairs between quotation marks ("):

**Example:**  
```
Bfile 1 0 V="myfile"
```

The file provided must have one time-voltage pair per line, separated by spaces. Comma-separated files are not supported, and will not be parsed correctly. If the file “myfile” contains the following data:

```
0 0  
1 2  
2 4  
3 6  
```

then the “Bfile” example above will be identical to either of the “B1” examples given above. The quoted-file syntax is in fact converted internally to precisely the same TABLE format as the first B1 example, with an independent variable of TIME and the given time-value pairs inserted.

Finally, the independent variable of the table source does not have to be a simple expression. In the example shown below, the independent variable is a function of voltages and currents throughout the circuit.

**Example:**  
```
Bcomplicated 1 0 V={TABLE {V(5)-V(3)/4+I(V6)*Res1} = (0, 0) (1, 2) (2, 4) (3, 6)}
```

### 6.2.3 Alternate behavioral modeling sources

In addition to the primary nonlinear dependent source, the $B$ source, **Xyce** also supports the PSpice extensions to the standard Spice voltage- and current-controlled sources, the $E$, $F$, $G$, and $H$ sources. **Xyce** provides these sources for PSpice compatibility, and converts them internally into equivalent $B$ sources. The **Xyce** Reference Guide netlist reference chapter provides the syntax of these compatibility devices.

### 6.3 Guidance for ABM Use

#### 6.3.1 ABM devices add equations to the system of equations used by the solver

As **Xyce** solves a complex nonlinear set of equations at each time step, it is important to remember this system of equations is solved iteratively to obtain a converged solution. Specifying an ABM

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1The use of a $B$ source in this manner is similar to using the FILE option to the piecewise linear (PWL) voltage source as documented in the **Xyce** Reference Guide, but unlike the PWL source, the file-based table function does NOT support reading comma-separated files.
device in a Xyce netlist adds one or more equations to the nonlinear problem that Xyce must solve.

When the nonlinear solver has converged, the expression given in the ABM device will be satisfied to within a solver tolerance. However, during the course of the iterative solve, the unconverged values of nodal voltages and currents, which are often inputs and outputs of ABM devices, are not guaranteed to be solutions to the system of equations.

During this preconverged phase, solution variables are not guaranteed to have physically reasonable values. They could, for example, temporarily have the wrong sign. Only at the end of a successful nonlinear iterative solve are the solution variables consistent, legal values. This convergence behavior motivates the caveats on ABM usage given in the next subsection.

### 6.3.2 Expressions used in ABM devices must be valid for any possible input

While ABM devices look temptingly like calculators, it is potentially dangerous to use them as such. The previous subsection stated that during the nonlinear solution of each timestep equations, nodal voltages and currents are usually not solutions to the full set of equations, and often violate Kirchhoff’s laws. Only at the end of the nonlinear solution are all the constraints on voltages and currents satisfied. This has some important consequences to the user of ABM devices.

All expressions involving nodal voltages and currents used in ABM devices should be valid for any possible value they might see — even those that appear to be physically meaningless and those that a knowledgeable user might never expect to see in the real circuit. This is particularly important when using square roots or exponentiating to a fractional power. For example, consider the following netlist fragment:

```plaintext
*...other parts of more complex circuit deleted...
* potentially bad usage of ABM device
Vexample 1 0 5V
d1 1 0 diode_model
B1 2 0 \{sqrt(v(1))\}
r1 2 0 10k
*...other parts of more complex circuit deleted...
```

This example demonstrates a potentially dangerous usage. It is assumed, because node 1 is connected to a 5V DC source, that the argument of the square root function is always positive. However, it could be the case that during the nonlinear solution of the full circuit that an unconverged value of node 1 might be negative. Tracking down mistakes such as this can be difficult, as on most platforms B1 will result in a “Not a Number” value for the nodal voltage of node 2 but the program will not crash. This frequently results in inexplicable “timestep too small” errors.

Although such things can be avoided by protecting the arguments of functions with a limited domain, care must be taken when doing this. One obvious way to protect the example circuit fragment would be to take the absolute value of V(1) before calling the square root (sqrt) function:
There are many other ways to protect the square root function from negative arguments, such as by using the maximum of zero and V(1). Some alternatives might be more appropriate than others in different contexts.

Note, though, that it would be a mistake to attempt to generate the absolute value as shown here:

```
*...other parts of more complex circuit deleted...
* really bad misuse of ABM device
Vexample 1 0 5V
d1 1 0 diode_model
B2 3 0 V = {abs(v(1))}; watch out!
B1 2 0 V = {sqrt(v(3))}; just as bad as first example!
r1 2 0 10k
*...other parts of more complex circuit deleted...
```

There are two things wrong with this example — first, node 3 is floating and this alone could lead to convergence problems. Second, by adding the second ABM device one has merely created an equation whose solution is that node 3 contains the absolute value of the voltage on node 1. However, until convergence is reached there is no guarantee node 3 will be precisely the absolute value of V(3), nor is it guaranteed that node 3 will have a positive voltage. To re-iterate, nodes have values that are solutions to the set of equations created by the netlist only at convergence.

### 6.3.3 Infinite slope transitions can cause convergence problems

It is possible for a user to specify expressions that could have infinite-slope transitions with B-, E-, F-, G- and H-sources. This can lead to “timestep too small” errors when Xyce reaches the transition point. For example, inclusion of the following B-source expression in a circuit can cause the simulation to fail when V(IN)=3.5:

```
Bctrl OUTA 0 V = { IF( (V(IN) > 3.5), 5, 0 ) }
```

Infinite-slope transitions in expressions dependent only on the time variable are a special case, because Xyce can detect that they are going to happen, and set a “breakpoint” to capture them. Infinite-slope transitions depending on other solution variables, however, cannot be predicted in advance, and will cause the time integrator to scale back the timestep repeatedly in an attempt to
capture the feature until the timestep is too small to continue. One solution to this problem is to modify the expression to allow a continuous transition. For example, the above expression could be modified to:

\[
\text{Bctrl OUTA 0 V=\{IF( (V(IN) > 3.4), IF( (V(IN) > 3.5), 5, 50*(V(IN)-3.4) ), 0 )\}}
\]

However, this can become complicated with multiple inputs. The other solution is to specify device options or instance parameters to allow smooth transitions. The parameter smoothbsrc enables the smooth transitions. This is done by adding a RC network to the output of B sources. For example,

\[
\text{Bctrl OUTA 0 V=\{ IF( (V(IN) > 3.5), 5, 0 ) \} smoothbsrc=1}
\]

.options device smoothbsrc=1

The smoothness of the transition can be controlled by specifying the rc constant of the RC network. For example,

\[
\text{Bctrl OUTA 0 V=\{ IF( (V(IN) > 3.5), 5, 0 ) \} smoothbsrc=1}
+ rcconst = 1e-10
\]

.options device smoothbsrc=1 rcconst = 1e-10

Note that this smoothed ABM only applies to voltage sources, such as voltage B sources and E sources. The voltage behavioral source supports two instance parameters smoothbsrc and rcconst. Parameters may be provided as space separated \texttt{<parameter>=<value> specifications as needed. The default value for smoothbsrc is 0 and the default for rcconst is 1e-9.}

If the device options are specified, they apply to all voltage ABM devices in the circuit. If the device instance parameters are specified, they apply to that device. When both the device options and instance parameters are specified, the device instance parameters take precedence over the device options.

**6.3.4 ABM devices should not be used purely for output postprocessing**

Users sometimes use ABM devices to provide output postprocessing. For example, if a user was interested in the absolute value, or the log of an output voltage, then that user might create an ABM circuit element to calculate the desired output value.

Using ABM sources in this manner is bad practice though. By creating a circuit element whose only purpose is postprocessing, \texttt{Xyce} is forced to include it and the corresponding nonlinear solve
in the circuit, which can cause unnecessary solver problems. If postprocessing is the goal, it is much better to use expressions directly on the .PRINT line.

An example of a “bad use” of ABM sources can be found in the following code fragment:

```plaintext
* Bad example
B1 test1 0 V = {(abs(I(VMON)))*1.0e-10}
VIN 1 0 DC 5V
R1 1 2 2K
D1 3 0 DMOD
VMON 2 3 0
.MODEL DMOD D (IS=100FA)
.DC VIN 5 5 1
.PRINT DC I(VMON) V(3) V(test1)
```

Although the source B1 provides a postprocessing output, it doesn’t play a functional role in the circuit and Xyce would still be forced to include B1 in the problem it is attempting to solve.

A better solution to the previous problem is given here, where the post-processing is done on a .PRINT line:

```plaintext
* Good example
VIN 1 0 DC 5V
R1 1 2 2K
D1 3 0 DMOD
VMON 2 3 0
.MODEL DMOD D (IS=100FA)
.DC VIN 5 5 1
.PRINT DC I(VMON) V(3) { (abs(I(VMON)))*1.0e-10}
```

Section 9.1 and the Xyce Reference Guide [3] provide a more detailed explanation of how to use expressions in the .PRINT line.
7. Analysis Types

Chapter Overview

This chapter describes the different analysis types available in Xyce. It includes the following sections:

- Section 7.1 Introduction
- Section 7.2 DC Analysis
- Section 7.3 Transient Analysis
- Section 7.4 STEP Parametric Analysis
- Section 7.5 Harmonic Balance Analysis
- Section 7.6 AC Analysis
- Section 7.7 Noise Analysis
- Section 7.8 Sensitivity Analysis
7.1 Introduction

**Xyce** supports several simulation analysis options, including DC bias point (.DC, section 7.2), transient (.TRAN, section 7.3), AC (.AC, section 7.6), Noise (.NOISE, section 7.7), harmonic balance (.HB, section 7.5), and sensitivity (.SENS, section 7.8) analysis.

Using .STEP (section 7.4), **Xyce** can also apply an outer parametric loop to any type of analysis. This allows one (for example) to sweep a model parameter and perform a transient simulation for each parameter value.

There are some analysis types typically found in SPICE-style simulators that are still a work in progress for **Xyce**. Operating point analysis (.OP, section 7.2.3) is partially supported in **Xyce**.

7.2 Steady-State (.DC) Analysis

The DC sweep analysis capability in **Xyce** computes the DC bias point of a circuit for a range of values of input sources. DC sweep is supported for a source or device parameter, through a range of specified values. As the sweep proceeds, **Xyce** computes the bias point for each value in the specified range of the sweep.

If the variable to be swept is a voltage or current source, a DC source must be used and its value set in the netlist (see **Xyce** Reference Guide [3]). In simulating the DC response of an analog circuit, **Xyce** eliminates time dependence from the circuit by treating capacitor elements as open circuits and inductor elements as short circuits, while using only the DC values of voltage and current sources.

7.2.1 .DC Statement

To specify a .DC analysis, include a .DC line in the netlist. Some examples of typical .DC lines are:

**Example:**
```
.DC V1 7m 5m -1m
.DC I1 5u 10u 1u
.DC M1:L 7u 5u -1u
.DC OCT V0 0.125 64 2
.DC DEC R1 100 10000 3
.DC TEMP LIST 10.0 15.0 18.0 27.0 33.0
```

The examples include all four types of sweep — linear, octave, decade and list. They also demonstrate sweeping over voltage and current sources as well as device parameters. The **Xyce** Reference Guide [3] provides a complete description of each.
7.2.2 Setting Up and Running a DC Sweep

Following the example given in section 3.2, figure 7.1 shows the diode clipper circuit netlist with a DC sweep analysis specified. Here, the voltage source \( \text{Vin} \) is swept from -10 to 15 in 1-volt increments, resulting in 26 DC operating point calculations.

**NOTE:** Xyce ignores the default setting for \( \text{Vin} \) during these calculations. All other source values use the specified values (in this case, \( \text{VCC} = 5V \)).

Running Xyce on this netlist produces an output results file named clipper.cir.prn. Obtaining this file requires specifying the .PRINT DC line. Plotting this data produces the graph shown in figure 7.2.

![Diode Clipper Circuit Netlist](image)

**Figure 7.1.** Diode clipper circuit netlist for DC sweep analysis.

7.2.3 OP Analysis

Xyce also supports .OP analysis statements. In Xyce, consider .OP as a shorthand for a single-step DC sweep, in which all the default operating point values are used. One may also consider
.\OP analysis to be the operating point calculation that would occur as the initial step to a transient calculation, without the subsequent time steps.

This capability was mainly added to enable the code to handle legacy netlists using this analysis statement type. In most versions of SPICE, using .\OP results in extra output not available from a DC sweep. **Xyce** will also output some of this extra information about devices, but the capability is not fully implemented.

### 7.2.4 Output

During analysis a number of output files may be generated. The selection of which files are created depends on a variety of factors, most obvious of which is the .\PRINT command. Table [7.1] lists the format options and files created. The column labeled “Additional Columns” lists the additional data that is written, though not specified on the .\PRINT line.

### 7.3 Transient Analysis

The transient response analysis simulates the response of the circuit from \( \text{TIME}=0 \) to a specified time. Throughout a transient analysis, any or all of the independent sources may have time-dependent values.

In **Xyce** (and most other circuit simulators), the transient analysis begins by performing its own bias point calculation at the beginning of the run, using the same method as used for DC sweep. This is required to set the initial conditions for the transient solution as the initial values of the sources may differ from their DC values.
Table 7.1. Output generated for DC analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT DC</td>
<td>circuit-file.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT DC FORMAT=NOINDEX</td>
<td>circuit-file.prn</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT DC FORMAT=CSV</td>
<td>circuit-file.csv</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT DC FORMAT=RAW</td>
<td>circuit-file.raw</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT DC FORMAT=TECPLLOT</td>
<td>circuit-file.dat</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT DC FORMAT=PROBE</td>
<td>circuit-file.csd</td>
<td>TIME</td>
</tr>
<tr>
<td>Xyce -r</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>Xyce -r -a</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>.OP</td>
<td>log-file</td>
<td>Operating point information</td>
</tr>
</tbody>
</table>

7.3.1 .TRAN Statement

To run a transient simulation, the circuit netlist file must contain a .TRAN command.

Example:

```
.TRAN 100us 300ms
.TRAN 100p 12.05u 9.95u
```

The Xyce Reference Guide [3] provides a detailed explanation of the .TRAN statement. The netlist must also contain one of the following:

- Independent, transient source (see table 7.2),
- Initial condition on a reactive element, or
- Time-dependent analog behavioral modeling source (see chapter 6)

7.3.2 Defining a Time-Dependent (transient) Source

Overview of Source Elements

Source elements, either voltage or current, are entered in the netlist file as described in the Xyce Reference Guide [3]. Table 7.2 lists the time-dependent sources available in Xyce for either voltage
Table 7.2. Summary of Xyce-supported time-dependent sources

<table>
<thead>
<tr>
<th>Source Element Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP</td>
<td>Exponential Waveform</td>
</tr>
<tr>
<td>PULSE</td>
<td>Pulse Waveform</td>
</tr>
<tr>
<td>PWL</td>
<td>Piecewise Linear Waveform</td>
</tr>
<tr>
<td>SFFM</td>
<td>Frequency-modulated Waveform</td>
</tr>
<tr>
<td>SIN</td>
<td>Sinusoidal Waveform</td>
</tr>
</tbody>
</table>

or current. For voltage sources, the name is preceded by V while current sources are preceded by I.

To use time-dependent or transient sources, place the source element line in the netlist and characterize the transient behavior using the appropriate parameters. Each transient source element has a separate set of parameters dependent on its transient behavior. In this way, the user can create analog sources that produce sine wave, square pulse, exponential pulse, single-frequency FM, and piecewise linear (PWL) waveforms.

**Defining Transient Sources**

To define a transient source, select one of the supported sources: independent voltage or current, choose a transient source type from table 7.2 and provide the transient parameters (refer to the Xyce Reference Guide \[3\] to fully define the source).

The following example of an independent sinusoidal voltage source in a circuit netlist creates a voltage source between nodes 1 and 5 that oscillates sinusoidally between -5V and +5V with a frequency of 50 KHz. The arguments specify an offset of -5V, a 10V amplitude, and a 50KHz frequency, in that order.

**Example:**

```
Vexample 1 5 SIN(-5V 10V 50K)
```

### 7.3.3 Transient Time Steps

During the simulation, Xyce uses a calculated time step that is continuously adjusted for accuracy and efficiency (see \[8\] and \[9\]). Calculation time step increases during periods of circuit idleness, and decreases during dynamic portions of the waveform. Users may control the maximum internal step size by specifying the step’s ceiling value in the .TRAN command (see the Xyce Reference Guide \[3\]).

The internal calculation time steps used might not be consistent with the user-requested output time steps. By default, Xyce outputs solution results at every time step it calculates. If the user selects output timesteps via the .OPTIONS OUTPUT statement (see chapter 9), then Xyce will output
results at the interval requested, interpolating solution variables to desired output times if necessary.

7.3.4 Time Integration Methods

For a transient analysis, several time integration methods can be selected to solve the circuit model's differential algebraic equations. The following algorithms are available:

- Variable order Trapezoidal (combines Trapezoidal and Backward Euler)
- Gear method, orders 1-2.

You can set the method, maxord and minord parameters to select the time integration methods via a .OPTIONS line. The following table shows the possible settings for those three parameters. (Note: Consult the Xyce Reference Guide [3] for the exact syntax of the .OPTIONS line for each time integration method.) The default time integration method in Xyce is Trap, which is the same as SPICE, PSpice and HSPICE.

<table>
<thead>
<tr>
<th>Integration Methods</th>
<th>Option Settings</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward-Euler</td>
<td>method=trap maxord=1</td>
<td>Backward-Euler only</td>
</tr>
<tr>
<td>Trap</td>
<td>method=trap</td>
<td>combines Trapezoidal and Backward Euler (default)</td>
</tr>
<tr>
<td>Trap only</td>
<td>method=trap minord=2</td>
<td>Trapezoidal only</td>
</tr>
<tr>
<td>Gear</td>
<td>method=gear</td>
<td>combines Backward Euler and 2nd order Gear</td>
</tr>
<tr>
<td>Gear2 only</td>
<td>method=gear minord=2</td>
<td>2nd order Gear only</td>
</tr>
</tbody>
</table>

The Trapezoidal method is often the preferred method because it is accurate and fast. However, this method can exhibit artificial point-to-point ringing, which can be controlled by using tighter tolerances. If a circuit fails to converge with the Trapezoidal method then you can re-run the transient analysis using the Gear method.

The Gear method may help convergence for some circuits. The 2nd order Gear method is typically more accurate than the Backward-Euler method (1st order Gear). However, both of these methods are overly stable methods, and they can damp the actual circuit behavior when simulating high-Q resonators such as oscillators. The Backward-Euler method has more damping effect than the 2nd order Gear method. This effect can be alleviated by using tighter tolerances in the simulations. However, it is suggested to use the pure Trapezoidal method for oscillators.
7.3.5 Error Controls

There are two basic time-step error control methods in *Xyce* — Local Truncation Error (LTE) based and non-LTE based.

**Local Truncation Error (LTE) Strategy**

All time integration methods use the LTE-based strategy by default. The accuracy of the simulation can be controlled by specifying appropriate relative and absolute error tolerances (RELTOL and ABSTOL).

**Example:**

```
.OPTIONS TIMEINT RELTOL=1e-4 ABSTOL=1e-8
```

The total tolerance of LTE is

\[ Tol_{LTE} = \text{abstol} + \text{reltol} \times \text{ref} \]

The parameter \( \text{ref} \) is the reference value that the relative error is compared to. It can be controlled by setting the `newlte` option.

**Example:**

```
.OPTIONS TIMEINT NEWLTE=1
```

The choices for `newlte` option are:

- **0.** The reference value is the current value on each node. This is the most conservative and least used.
- **1.** The reference value is the maximum of all the signals at the current time. This is the default value.
- **2.** The reference value is the maximum of all the signals over all past time. This is the loosest criterion. It normally produces the best performance and should be used if the overall size of the signals is roughly the same on all nodes.
- **3.** The reference value is the maximum value on each signal over all past time. This should be used if the scale of signals varies widely in a system.

The Trapezoid integrator algorithm introduces no numerical dissipation. So, a strong ringing (artificially introduced by the numerical algorithm) will occur when sources or models introduce discontinuities. This can result in a large local truncation error estimate, ultimately leading to a “time-step too small” error. In this case, using the Gear method or a non-LTE strategy may help.
Non-LTE Strategy

The non-LTE strategy used in Xyce is based on success of the nonlinear solve, and is enabled by setting ERROPTION=1. Since the step-size selection is based only upon nonlinear iteration statistics rather than accuracy, it is highly suggested that DELMAX be specified, in a circuit-specific manner, for all three time integrators. The purpose of DELMAX is to limit the largest time step taken.

Example:

.OPTIONS TIMEINT ERROPTION=1 DELMAX=1.0e-4

For the Trapezoid and Gear integrators, the options are slightly more refined. If the number of nonlinear iterations is below NLMIN, then the step size is doubled. If the number of nonlinear iterations is above NLMAX then the step size is cut by one eighth. In between, the step size is not changed. An example using Trap (METHOD=7) is given below.

Example:

.OPTIONS TIMEINT METHOD=7 ERROPTION=1 NLMIN=3 NLMAX=8 DELMAX=1.0e-4

If the number of Newton iterations is bigger than NLmax and TIMESTEPSREVERSAL is not set, then Xyce will cut the next step. If the number of Newton iterations is bigger than NLmax and TIMESTEPSREVERSAL is set, then Xyce will reject the current step and also cut the current step.

Example:

.OPTIONS TIMEINT METHOD=7 ERROPTION=1 DELMAX=1.0e-4 TIMESTEPSREVERSAL=1

7.3.6 Breakpoints

It is often necessary or desirable for the time integrator to be forced to land on a specific time point and restart integration from that point. The most common scenario for which this is necessary is when an device (such as a PULSE or a PWL source) produces a discontinuity. If a discontinuity is present, and no breakpoint is set, then the LTE analysis will force the time integrator to take really small time steps, and this can possibly impact the robustness of the calculation.

Fortunately, Xyce handles most device-based discontinuities automatically, so it is not necessary for the user to worry about them. However, it can be desirable for the user to manually set breakpoints from the netlist. In a Xyce netlist, these are specified using the BREAKPOINTS parameter with a comma-separated list in the following .OPTIONS TIMEINT statement.

Example:

.OPTIONS TIMEINT BREAKPOINTS=1ms,2ms,3ms
7.3.7 Checkpointing and Restarting

*Xyce* was designed to simulate large, complex circuits over long simulation runs. Because complex simulations can take many hours (or even days) to complete, it can sometimes be helpful to use “checkpointing.” When checkpointing is used, *Xyce* periodically saves its complete simulation state. The saved state can be used to restart *Xyce* from one of these “checkpoints.” In the event of a computer crash, power outage, or should the simulation need to be interrupted for some other reason, checkpointing allows the user to restart a long simulation in the middle of a run without having to start over.

*Xyce* uses the `.OPTIONS RESTART` netlist command to control all checkpoint output and restarting.

Checkpointing Command Format

- `.OPTIONS RESTART [PACK=0|1] JOB=<job name> INITIAL_INTERVAL=<interval> [[<t0> <i0> [<t1> <i1> ...]]]`

  - `PACK=0|1` indicates whether restart data files will contain byte-packed (binary) data (PACK=1, the default) or unpacked (ASCII) (PACK=0). `JOB=<job name>` identifies the prefix for restart files. The actual restart files will be the job name appended with the current simulation time (e.g., `name1e-05` for `JOB=name` and simulation time `1e-05` seconds). Furthermore, the `INITIAL_INTERVAL=<interval>` identifies the initial interval time used for restart output; this parameter must be given. The `<tx ix>` intervals identify times (tx) at which the output interval (ix) will change. This functionality is identical to that described for the `.OPTIONS OUTPUT` command (section 9.1).

  - **Example — Generate checkpoints every 0.1 µs:**

    `.OPTIONS RESTART JOB=checkpt INITIAL_INTERVAL=0.1us`

  - **Example — Generate unpacked checkpoints every 0.1 µs:**

    `.OPTIONS RESTART PACK=0 JOB=checkpt INITIAL_INTERVAL=0.1us`

  - **Example — Initial interval of 0.1 µs, at 1 µs in the simulation, change to interval of 0.5 µs, and at 10 µs change to an interval of 0.1 µs:**

    `.OPTIONS RESTART JOB=checkpt INITIAL_INTERVAL=0.1us 1us 0.5us + 10us 0.1us`

Restarting Command Format

- `.OPTIONS RESTART <FILE=<filename> | JOB=<job name> START_TIME=<time>> + [INITIAL_INTERVAL=<interval> [<t0> <i0> [<t1> <i1> ...]]]`

80
To restart from an existing restart file, specify the file by using either the FILE=<filename> parameter to explicitly request a file or JOB=<job name> START_TIME=<time> to specify a file prefix and a specific time. The time must exactly match an output file time for the simulator to correctly load the file.

To continue checkpointing the simulation in a restarted run, append INITIAL_INTERVAL=<interval> and the following intervals to the command in the same format as previously described. Without these additional parameters, the simulation will restart as requested, but will not generate further checkpoint files.

- Example — Restart from checkpoint file at 0.133 \(\mu s\):
  .OPTIONS RESTART JOB=checkpt START_TIME=0.133us

- Example — Restart from checkpoint file at 0.133 \(\mu s\):
  .OPTIONS RESTART FILE=checkpt0.000000133

- Example — Restart from 0.133 \(\mu s\) and continue checkpointing at 0.1 \(\mu s\) intervals:
  .OPTIONS RESTART FILE=checkpt0.000000133 JOB=checkpt_again
  + INITIAL_INTERVAL=0.1us

### 7.3.8 Output

During analysis a number of output files may be generated. The selection of which files are created depends on a variety of factors, most obvious of which is the .PRINT command. Table 7.4 lists the format options and files created. The column labeled “Additional Columns” lists the additional data that is written, though not specified on the .PRINT line.
Table 7.4. Output generated for Transient analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT TRAN</td>
<td>circuit-file.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT TRAN FORMAT=NOINDEX</td>
<td>circuit-file.prn</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT TRAN FORMAT=CSV</td>
<td>circuit-file.csv</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT TRAN FORMAT=RAW</td>
<td>circuit-file.raw</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT TRAN FORMAT=TECPLT</td>
<td>circuit-file.dat</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT TRAN FORMAT=PROBE</td>
<td>circuit-file.csd</td>
<td>TIME</td>
</tr>
<tr>
<td>Xyce -r</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>Xyce -r -a</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>.OP</td>
<td>log-file</td>
<td>Operating point information</td>
</tr>
</tbody>
</table>
7.4  STEP Parametric Analysis

The .STEP command performs a parametric sweep for all the analyses of the circuit. When the .STEP command is invoked, typical analyses, such as .DC, .AC, and .TRAN are performed for each value of the stepped parameter.

This capability is very similar, but not identical, to the STEP capability in PSpice [4]. Xyce can use .STEP to sweep over any device instance or device model parameter, as well as the circuit temperature. It is not legal to sweep parameters defined in .PARAM statements, but it is legal to sweep global parameters defined in .global.param statements. Section [4.3] discusses these two distinct parameter definitions.

7.4.1 .STEP Statement

A .STEP analysis may be specified by simply adding a .STEP line to a netlist. Unlike .DC, .STEP by itself is not an adequate analysis specification, as it merely specifies an outer loop around the normal analysis. A standard analysis line, either specifying .TRAN, .AC and .DC analysis, is still required.

Some examples of typical .STEP lines are:

Example:

```
.STEP M1:L 7u 5u -1u
.STEP OCT V0 0.125 64 2
.STEP DEC R1 100 10000 3
.STEP TEMP LIST 10.0 15.0 18.0 27.0 33.0
```

.STEP has a format similar to that of the .DC format specification. In the first example, M1:L is the name of the parameter (in this instance, the length parameter of the MOSFET M1), 7u is the initial value of the parameter, 5u is the final value of the parameter, and -1u is the step size. Like .DC, .STEP in Xyce can also handle sweeps by decade, octave, or specified lists of values. Consult the Xyce Reference Guide [3] for complete explanations of each sweep type.

7.4.2 Sweeping over a Device Instance Parameter

The first example uses M1:L as the parameter, but it could have used any model or instance parameter existing in the circuit. Internally, Xyce handles the parameters for all device models and device instances in the same way. Users can uniquely identify any parameter by specifying the device instance name, followed by a colon (:), followed by the specific parameter name. For example, all the MOSFET models have an instance parameter for the channel length, L. For a MOSFET instance specified in a netlist, named M1, the full name for the M1 channel length parameter is M1:L.

Figure [7.3] provides a simple application of .STEP to a device instance. This is the same diode clipper circuit as was used in the transient analysis chapter, except that a single line (in red) has
been added. This .STEP line will cause **Xyce** to sweep the resistance of the resistor, R4, from 3.0 KOhms to 15.0 KOhms, in 2.0 KOhms increments, meaning seven transient simulations will be performed, each one with a different value for R4.

As the circuit is executed multiple times, the resulting output file is a little more sophisticated. The .PRINT statement is still used in much the same way as before. However, the .prn output file contains the concatenated output of each .STEP increment. The end of this section provides more details of how .STEP changes output files.

```plaintext
Transient Diode Clipper Circuit with Step Analysis
* Voltage Sources
VCC 1 0 5V
VIN 3 0 SIN(0V 10V 1kHz)
* Analysis Command
.TRAN 2ns 2ms
* Output
.PRINT TRAN V(3) V(2) V(4)
* Step statement
.STEP R4:R 3.0K 15.0K 2.0K
* Diodes
D1 2 1 D1N3940
D2 0 2 D1N3940
* Resistors
R1 2 3 1K
R2 1 2 3.3K
R3 2 0 3.3K
R4 4 0 5.6K
* Capacitor
C1 2 4 0.47u
.MODEL D1N3940 D(
+ IS=4E-10 RS=.105 N=1.48 TT=8E-7
+ CJO=1.95E-11 VJ=.4 M=.38 EG=1.36
+ XTI=-8 KF=0 AF=1 FC=.9
+ BV=600 IBV=1E-4)
.END
```

**Figure 7.3.** Diode clipper circuit netlist for step transient analysis

### 7.4.3 Sweeping over a Device Model Parameter

Sweeping a model parameter can be done in an identical manner to an instance parameter. Figure 7.4 contains the same circuit as in figure 7.3 but with additional .STEP line referring to a model parameter, D1N3940:IS.

**NOTE:** .STEP line syntax differs from .DC line syntax in that multiple parameters require separate
Transient Diode Clipper Circuit with Step Analysis

* Voltage Sources
VCC 1 0 5V
VIN 3 0 SIN(0V 10V 1kHz)

* Analysis Command
.Tran 2ns 2ms

* Output
.Print tran V(3) V(2) V(4)

* Step statements
.Step R4:R 3.0K 15.0K 2.0K
.Step D1N3940:IS 2.0e-10 6.0e-10 2.0e-10

* Diodes
D1 2 1 D1N3940
D2 0 2 D1N3940

* Resistors
R1 2 3 1K
R2 1 2 3.3K
R3 2 0 3.3K
R4 4 0 5.6K

* Capacitor
C1 2 4 0.47u
.Model D1N3940 D(
  + IS=4E-10 RS=.105 N=1.48 TT=8E-7
  + CJ0=1.95E-11 VJ=.4 M=.38 EG=1.36
  + XTI=-8 KF=0 AF=1 FC=.9
  + BV=600 IBV=1E-4)
.End

Figure 7.4. Diode clipper circuit netlist for 2-step transient analysis

7.4.4 Sweeping over Temperature

It is also possible to sweep over temperature. To do so, simply specify temp as the parameter name. It will work in the same manner as .STEP when applied to model and instance parameters.

7.4.5 Special cases: Sweeping Independent Sources, Resistors, Capacitors and Inductors

For some devices, there is generally only one parameter that one would want to sweep. For example, a linear resistor's only parameter of interest is resistance, R. Similarly, for a DC voltage
or current source, one is usually only interested in the magnitude of the source, DCV0. Finally, linear capacitors generally only have capacitance, C, as a parameter of interest, while inductors generally only have inductance, L, as a parameter of interest.

For these simple devices, it is not necessary to specify both the parameter and device on the .STEP line: only the device name is strictly required, as these devices have default parameters that are assumed if no parameter name is given explicitly.

Examples of usage are given below. The first two lines are equivalent — in the first line, the resistance parameter of R4 is named explicitly, and in the second line the resistance parameter is implicit. A similar example is then shown for the DC voltage of the voltage source VCC. In the remaining lines, parameter names are all implicit, and the default parameters of the associated devices are used.

Example:

```plaintext
.STEP R4:R 3.0K 15.0K 2.0K
.STEP R4 3.0K 15.0K 2.0K
.STEP VCC:DCV0 4.0 6.0 1.0
.STEP VCC 4.0 6.0 1.0
.STEP ICC 4.0 6.0 1.0
.STEP C1 0.45u 0.50u 0.1u
.STEP L1 0.5m 1.0m 0.5m
```

Independent sources require further explanation. Their default parameter, DCV0, only applies to .DC analyses. They do not have default parameters for their transient forms, such as SIN or PULSE.

### 7.4.6 Output files

Users can think of .STEP simulations as several distinct executions of the same circuit netlist. The output data, as specified by a .PRINT line, however, goes to a single (*.prn) file. For convenience, Xyce also creates a second auxiliary file with the *.res suffix.

Figure 7.3 shows an example file named clip.cir, which when run will produce files clip.cir.res and clip.cir.prn. The file clip.cir.res contains one line for each step, showing what parameter value was used on that step. clip.cir.prn is the familiar output format, but the INDEX field recycles to zero each time a new step begins. As the default behavior distinguishes each step's output only by recycling the INDEX field to zero, it can be beneficial to add the sweep parameters to the .PRINT line. For the default file format (format=std), Xyce will not automatically include these sweep parameters, so for plotting it is usually best to specify them by hand.

If using the default .prn file format (format=std), the resulting .STEP simulation output file will be a simple concatenation of each step's underlying analysis output. If using format=probe, the data for each execution of the circuit will be in distinct sections of the file, and it should be easy to plot the results using PROBE. If using format=tecplot, the results of each .STEP simulation will be in a distinct tecplot zone. Finally, format=raw will place the results for each .STEP simulation in a distinct “plot” region.
7.5 Harmonic Balance Analysis

Harmonic balance (HB) is a technique that solves for the steady state solution of nonlinear circuits in the frequency domain. In harmonic balance simulation, voltages and currents in a nonlinear circuit are represented by truncated Fourier series. HB directly computes the frequency spectrum of voltages and currents at the steady state solution. This can be more efficient than transient analysis in applications where a transient analysis may take a long time to reach the steady state solution. In particular, HB is well suited for simulating analog RF and microwave circuits.

HB supports an unlimited number of independent input tones for driven circuits in both serial and parallel builds of Xyce. The output of HB analysis is the real and imaginary components of voltages and currents in the frequency domain. Xyce also provides time domain responses of a circuit. By default, the numbers of samples in both time and frequency domain outputs are the same. However, the number of time domain samples can be much larger than the number of frequency domain samples by setting numtpts in .options hbint. This enables the users to use a small number of harmonics for each tone and produce well-resolved results in time domain.

For HB analysis, an initial guess of the solution is required. Often, a good initial guess is necessary for HB to converge. By default, Xyce uses transient analysis to determine the initial guess, often called “Transient Assisted HB”. This option is controlled by the parameter, TAHB, which is enabled if TAHB=1 and disabled if TAHB=0 in .options hbint. If enabled, the starting time of the transient analysis can be modified by specifying the parameter STARTUPPERIODS in .options hbint. The Xyce Reference Guide provides a detailed explanation of the HB options.

7.5.1 .HB Statement

To run a HB simulation, the circuit netlist file must contain a .HB command.

Example:

```
.HB 1e4
.HB 1e4 2e2
```

The parameters following .HB are the fundamental frequencies and must be specified by the user. The Xyce Reference Guide provides a detailed explanation of the .HB statement.

7.5.2 HB Options

Key parameters for .HB simulation can be specified by .options hbint.

Example:

```
.options hbint numfreq=5,3 STARTUPPERIODS=2 tahb=1 intmodmax=3 numtpts=100
.HB 1e4 2e2
```
As shown in the example, `numfreq` specifies the number of harmonics to be calculated for each tone. It must have the same number of entries as the fundamental frequencies in the `.HB` statement. This example shows the options for a two tone HB analysis. The `.HB` statement is `.HB f1 f2`. For the first tone $f_1$, 5 harmonics are used and for the second tone $f_2$, 3 harmonics are used.

The `intmodmax` option is the maximum intermodulation product order used in the spectrum.

As stated above, `TAHB` is the Transient Assisted HB option. In the case of multi-tone HB analysis, the initial guess is generated by a single tone transient simulation. The single tone that is used is the first tone in the `.HB` statement. So, when ordering the fundamental frequencies in the `.HB` statement, the first tone should be the frequency that produces the most nonlinear response by the circuit.

As stated above, the `STARTUPPERIODS` option specifies the number of time periods that Xyce will integrate through using normal transient analysis before generating the initial conditions for HB analysis. For this example, Xyce will integrate through two periods before computing the initial conditions, which requires an additional period. Thus, Xyce will integrate through a total of three periods to compute the initial guess for HB analysis.

The `numtpts` option specifies the number of time points in the output. The number of samples in the time domain output is an odd number. If an even number is specified, the number of time points will be `numtpts` plus one. For this example, the time domain output has 101 samples.

**Example:**
`.options hbint numfreq=20 STARTUPPERIODS=2`

For the single tone example given above, this statement will return 20 negative and 20 positive harmonics plus the DC component.


**Nonlinear Solver Options**

The HB analysis uses a different set of default nonlinear solver parameters than that of transient and DC analysis. Nonlinear solver parameters for HB analysis can be specified by using `.options nonlin-hb`.

**Example:**
`.options nonlin-hb abstol=1e-6`


**Linear Solver Options**

The HB analysis provided by Xyce can employ both iterative and direct solvers. If iterative solvers are used, then the HB Jacobian matrix is not assembled and only HB-specific preconditioners
can be used for this matrix-free approach. If direct solvers are used, then the HB Jacobian is assembled and the complex-valued matrix is solved using the selected method. Direct solvers are memory intensive and computationally expensive, so it is suggested that they are only used when iterative methods fail during HB analysis. You can set iterative solver and preconditioner options using the .options linsol-hb statement.

**Example:**

```
.options linsol-hb type=aztecoo prec_type=block_jacobi AZ_tol=1e-9
```

In this example, `type` specifies the iterative solver to use in the HB analysis and `AZ_tol` is the relative tolerance for the iterative solver. Any of the iterative solver options in section [10.4](#) are valid. However, `prec_type` specifies which HB-specific preconditioner to use. The choices for this option are `none` and `block_jacobi` (default).

### 7.5.3 Output

HB analysis can generate a variety of output files. The selection of which files are generated most often depends on what is specified for the `.PRINT HB` command. Table [7.5](#) lists the format options and files created. The column labeled “Additional Columns” lists the additional data that is written, though not specified on the `.PRINT HB` line.

### 7.5.4 User Guidance

One of the most common errors in the HB simulation setup is the use of too few harmonic frequencies (i.e., `numfreq` is too small). One way to determine the optimum number of harmonic frequencies is to first simulate the circuit with a small `numfreq`, then increase the `numfreq` until the solution stops changing within a significant bound. Requesting too many harmonic frequencies is wasteful of memory and simulation time, so it is not practical to request a very high `numfreq` either.

### 7.6 AC Analysis

The AC small-signal analysis of Xyce computes AC output variables as a function of frequency. The program first computes the DC operating point of the circuit and linearizes the circuit. The resultant linear circuit is then analyzed over a user-specified range of frequencies. The desired output of an AC small-signal analysis is usually a transfer function (voltage gain, transimpedance, etc). If the circuit has one AC input, it is convenient to set that input to unity and zero phase so output variables have the same value as the transfer function of the output variable with respect to input.

#### 7.6.1 .AC Statement

One may specify `.AC` analyses by adding a `.AC` line in the netlist. Some examples of typical `.AC` lines include:
Table 7.5. Output generated for HB analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
</table>
| .PRINT HB | circuit-file.HB.TD.prn  
circuit-file.HB.FD.prn | INDEX TIME  
INDEX FREQUENCY |
| .PRINT HB_TD FORMAT=NOINDEX  
.PRINT HB_FD FORMAT=NOINDEX | circuit-file.HB.TD.prn  
circuit-file.HB.FD.prn | TIME  
FREQUENCY |
| .PRINT HB_TD FORMAT=CSV  
.PRINT HB_FD FORMAT=CSV | circuit-file.HB.csv  
circuit-file.HB.FD.csv | TIME  
FREQUENCY |
| .PRINT HB_TD FORMAT=RAW  
.PRINT HB_FD FORMAT=RAW | circuit-file.raw | |
| .PRINT HB_TD FORMAT=TECPLLOT  
.PRINT HB_FD FORMAT=TECPLLOT | circuit-file.HB.TD.dat  
circuit-file.HB.FD.dat | TIME  
FREQUENCY |
| Xyce -r | | All circuit variables printed |
| Xyce -r -a | | All circuit variables printed |
| .options hbint STARTUPPERIODS=n | | Falls back to .PRINT HB variables |
| .PRINT HB_STARTUP  
.options hbint STARTUPPERIODS=n | circuit-file.startup.prn | INDEX TIME |
| .PRINT HB_STARTUP FORMAT=CSV  
.options hbint STARTUPPERIODS=n | circuit-file.startup.csv | TIME |
| .PRINT HB_STARTUP FORMAT=TECPLLOT  
.options hbint STARTUPPERIODS=n  
.options hbint SAVEICDATA=1 | circuit-file.startup.dat | TIME |
| .options hbint SAVEICDATA=1 | | Falls back to .PRINT HB variables |
| .PRINT HB.IC  
.options hbint SAVEICDATA=1 | circuit-file.hb.ic.prn | INDEX TIME |
| .PRINT HB.IC FORMAT=CSV  
.options hbint SAVEICDATA=1 | circuit-file.hb.ic.csv | TIME |
| .PRINT HB.IC FORMAT=TECPLLOT  
.options hbint SAVEICDATA=1 | circuit-file.hb.ic.dat | TIME |
| .OP | log-file | Operating point information |
Example:
.AC DEC 10 1K 100MEG
.AC DEC 10 1 10K
.AC LIN 100 1 100HZ

These examples include some types of sweep (linear and decade). The Xyce Reference Guide provides a complete description of all types of sweep.

7.6.2 AC Voltage and Current Sources

Xyce assumes the AC source to be a cosine waveform at a specified phase angle. Its frequency must be defined in a separate \".AC\" command defining the frequency for all the sources in the circuit. The unique information for the individual source is the name (which must start with \"V\" or \"I\"), the node numbers, the magnitude of the source, and its phase angle. Some examples are as follows:

Example:
Vac 4 1 AC 120V 30
Vin 1 0 1.44 ac .1
Iin 1 0 1.44e-5 ac 0.1e-5 sin(0 1 1e+5 0 0)

NOTE: The type, AC, must be specified because the default is DC. If not specified, Xyce assumes the phase angle to be zero degrees. The units of the phase angle are in degrees.

7.6.3 Output

During analysis a number of output files may be generated. The selection of which files are created depends on a variety of factors, most obvious of which is the \PRINT command. Table lists the format options and files created. The column labeled \"Additional Columns\" lists the additional data that is written, though not specified on the \PRINT line.

Running Xyce on AC analysis produces an output results file named \cir.FD.prn. Obtaining this file requires that the \PRINT AC line be specified.

Xyce supports printing the real and imaginary parts of phasor values (complex numbers) for AC analysis output as voltages or currents. For instance, specify \"V(1)\" to print the real part and imaginary part of a voltage at node 1. Additional output variable formats are also available:

- \VR(<circuit node>) output the real component of the voltage response
- \VI(<circuit node>) output the imaginary component of voltage response
- \VM(<circuit node>) output the magnitude of voltage response
- \VDB(<circuit node>) output the magnitude of voltage response in decibels
- \VP(<circuit node>) output the phase of voltage response
### Table 7.6. Output generated for AC analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT AC</td>
<td>circuit-file.FD.prn</td>
<td>INDEX FREQUENCY</td>
</tr>
<tr>
<td>.PRINT AC FORMAT=NOINDEX</td>
<td>circuit-file.FD.prn</td>
<td>INDEX FREQUENCY</td>
</tr>
<tr>
<td>.PRINT AC FORMAT=CSV</td>
<td>circuit-file.FD.csv</td>
<td>FREQUENCY</td>
</tr>
<tr>
<td>.PRINT AC FORMAT=RAW</td>
<td>circuit-file.raw</td>
<td>FREQUENCY</td>
</tr>
<tr>
<td>.PRINT AC FORMAT=TECPLT</td>
<td>circuit-file.FD.dat</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT AC FORMAT=PROBE</td>
<td>circuit-file.csd</td>
<td>TIME</td>
</tr>
<tr>
<td>Xyce -r</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>Xyce -r -a</td>
<td>circuit-file.raw</td>
<td>All circuit variables printed</td>
</tr>
<tr>
<td>.OP</td>
<td>falls back to .PRINT AC</td>
<td></td>
</tr>
<tr>
<td>.PRINT AC IC FORMAT=NOINDEX</td>
<td>circuit-file.TD.prn</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT AC IC FORMAT=CSV</td>
<td>circuit-file.TD.csv</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT AC IC FORMAT=RAW</td>
<td>circuit-file.raw</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT AC IC FORMAT=TECPLT</td>
<td>circuit-file.TD.dat</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT AC IC FORMAT=PROBE</td>
<td>circuit-file.TD.csd</td>
<td>TIME</td>
</tr>
<tr>
<td>.OPTIONS NONLIN CONTINUATION=&lt;method&gt;...</td>
<td>falls back to AC</td>
<td></td>
</tr>
<tr>
<td>.PRINT HOMOTOPY FORMAT=NOINDEX</td>
<td>circuit-file.HOMOTOPY.prn</td>
<td>INDEX TIME</td>
</tr>
</tbody>
</table>
Some examples are as follows:

**Example:**
```plaintext
.print AC V(3)
.print AC VI(15)
.print AC VP(OUTPUT)
```

## 7.7 NOISE Analysis

**Xyce** supports small-signal noise analysis, which is closely related to AC analysis. For noise analysis, input and output noise is computed for a specified output node, relative to an input source, as a function of frequency.

The program first computes the DC operating point of the circuit and linearizes the circuit. Next, at each frequency, an AC calculation is performed to obtain the AC gain. This gain is used later to compute the equivalent input noise from the output noise. After the AC gain is computed, the noise calculation is performed at the current frequency using the adjoint method. This involves solving the transpose of the AC matrix.

If the circuit has one NOISE input, it is convenient to set that input to unity and zero phase so output variables have the same value as the transfer function of the output variable with respect to the input.

### 7.7.1 .NOISE Statement

One may specify .NOISE analyses by adding a .NOISE line in the netlist. Some examples of typical .NOISE lines include:

**Example:**
```plaintext
.NOISE V(5) VIN LIN 101 100Hz 200Hz
.NOISE V(5,3) V1 OCT 10 1kHz 16kHz
.NOISE V(4) V2 DEC 20 1MEG 100MEG
```

The sweep type can be set to LIN, OCT or DEC. See the **Xyce** Reference Guide [3] for details.

### 7.7.2 NOISE Voltage and Current Sources

Noise analysis requires a reference AC source. **Xyce** assumes the AC source to be a cosine waveform at a specified phase angle. Its frequency must be defined in a separate “.NOISE” command defining the frequency for all the sources in the circuit. The unique information for the individual source is the name (which must start with “V” or “I”), the node numbers, the magnitude of the source, and its phase angle. Some examples are as follows:
Example:
\[
\begin{align*}
\text{Vac} & \quad 4 \quad 1 \quad \text{AC} \quad 120V \quad 30 \\
\text{Vin} & \quad 1 \quad 0 \quad 1.44 \quad \text{ac} \quad .1 \\
\text{Iin} & \quad 1 \quad 0 \quad 1.44e-5 \quad \text{ac} \quad 0.1e-5 \quad \sin(0 \quad 1 \quad 1e+5 \quad 0 \quad 0)
\end{align*}
\]

NOTE: The type, AC, must be specified because the default is DC. If not specified, Xyce assumes the phase angle to be zero degrees. The units of the phase angle are in degrees.

7.7.3 Example

An example noise analysis netlist is given in figure 7.5. In this example, the only noise source is the resistor, rlp1. The input source is v1 and the output node is v(4).

```
* Noise Analysis example
v1 1 0 DC 5.0 AC 1.0
r1 1 2 100K
r2 2 0 100K
eamp 3 0 2 0 1
rlp1 3 4 100
clp1 4 0 1.59nf

* Noise commands
.noise v(4) v1 dec 5 100 100meg 1

* Noise file output
.print noise inoise onoise
.end
```

Figure 7.5. Noise Example Netlist

7.7.4 Output

During analysis a number of output files may be generated. The selection of which files are created depends on a variety of factors, most obvious of which is the .PRINT command. Table 7.7 lists the format options and files created. The column labeled “Additional Columns” lists the additional data that is written, though not specified on the .PRINT line.

Running Xyce NOISE analysis produces an output results file named .cir.NOISE.prn. Obtaining this file requires that the .PRINT NOISE line be specified. Using the .PRINT line, Xyce supports printing the total noise spectral density curves. The output units for spectral densities are $V^2/Hz$ and $A^2/Hz$. Some examples are as follows:
Table 7.7. Output generated for NOISE analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT NOISE</td>
<td>circuit-file.NOISE.prn</td>
<td>INDEX FREQUENCY</td>
</tr>
<tr>
<td>.PRINT NOISE FORMAT=NOINDEX</td>
<td>circuit-file.NOISE.prn</td>
<td>FREQUENCY</td>
</tr>
<tr>
<td>.PRINT NOISE FORMAT=CSV</td>
<td>circuit-file.NOISE.csv</td>
<td>FREQUENCY</td>
</tr>
<tr>
<td>.PRINT NOISE FORMAT=TECPlot</td>
<td>circuit-file.NOISE.dat</td>
<td>FREQUENCY</td>
</tr>
</tbody>
</table>

Example:

```plaintext
.print noise inoise onoise
.print noise log(inoise) log(onoise)
```

**Xyce** will also compute the total integrated output noise, and the total integrated input noise for the specified output node. This information is sent to standard output, or to the user-specified log file. A typical output (which in this case was generated by the netlist given in figure 7.5) will look like this:

Example:

```
Total Output Noise = 1.28592e-09
Total Input Noise = 5.22876e-07
```

If `.STEP` is used with a noise analysis then the **Xyce** standard output will contain the values of the stepped parameters, along with the values for the total integrated output noise and the total integrated input noise for the specified output node.

### 7.7.5 Device Model Support

Note that stationary noise is not supported in every **Xyce** device. A list of **Xyce** devices, and which of them support stationary noise, is given in the **Xyce** Reference Guide [3].
7.8 Sensitivity Analysis

The .SENS command instructs Xyce to calculate the sensitivities of an output expression with respect to a specified list of circuit parameters. This capability works in either steady-state (.DC) or transient (.TRAN).

General Format:

```
.SENS objfunc={<output expression(s)>} param=<circuit parameter(s)>
.options SENSITIVITY [direct=<1 or 0>] [adjoint=<1 or 0>]
```

At least one objective function parameter, objfunc, is required. It is possible to specify a comma-separated list of objective functions. The list of circuit parameters must have at least one entry as well. If there is more than one, the parameters are specified as a comma-separated list. Xyce will not assume any particular parameter list. Unlike the Spice version of .SENS, Xyce will not automatically compute the sensitivity of every parameter; only the parameters the user requested.

7.8.1 Steady-State (DC) sensitivities

For DC analysis, Xyce can compute a direct sensitivity, an adjoint sensitivity, or both. In general, adjoint sensitivities are much more efficient when computing the derivatives with respect to really large numbers of parameters, but a small number of objective functions. Direct sensitivities are most efficient for small numbers of parameters, but large numbers of objective functions. Xyce allows the user to specify multiple objective functions, as well as multiple parameters, so either scenario could apply.

An example of using .SENS on a DC problem is shown in the following netlist: The output to stdout,

```
Example Circuit using sensitivity analysis
R1 A B 10.0
R2 B 0 10.0
Va A 0 5

.dc Va 5 5 1
.print dc v(A) v(B)

.print sens
.SENS objfunc={0.5*(V(B)-3.0)**2.0} param=R1:R,R2:R
.options SENSITIVITY direct=1 adjoint=1 stdout=1
.END
```

Figure 7.6. Steady-State Sensitivity Example Netlist

which was requested by setting stdout=1, for this example is:
Direct Sensitivities of objective function: {0.5*(V(B)-3.0)**2.0}

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Sensitivity</th>
<th>Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1:R</td>
<td>1.0000e+01</td>
<td>6.2500e-02</td>
<td>6.2500e-03</td>
</tr>
<tr>
<td>R2:R</td>
<td>1.0000e+01</td>
<td>-6.2500e-02</td>
<td>-6.2500e-03</td>
</tr>
</tbody>
</table>

Adjoint Sensitivities of objective function: {0.5*(V(B)-3.0)**2.0}

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Sensitivity</th>
<th>Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1:R</td>
<td>1.0000e+01</td>
<td>6.2500e-02</td>
<td>6.2500e-03</td>
</tr>
<tr>
<td>R2:R</td>
<td>1.0000e+01</td>
<td>-6.2500e-02</td>
<td>-6.2500e-03</td>
</tr>
</tbody>
</table>

In the above example, both adjoint and direct sensitivities are computed. This is a linear problem, so it is easy to compare them to the analytic solution.

### 7.8.2 Transient sensitivities

Sensitivities can also be computed for transient analysis. As with steady-state (DC) analysis, both direct and adjoint sensitivities are supported.

#### Transient Direct Sensitivities

Transient direct sensitivities are a good choice if the number of parameters is modest. Also, if the output of interest is a full waveform sensitivity, they will usually outperform adjoint sensitivities, as from the perspective of adjoint calculations, each time point constitutes a separate objective function, requiring a separate integration.

Set `direct=1 adjoint=0` to specify transient direct simulations. The transient direct formulation in Xyce is based on the one described by Hocevar [10]. An example netlist for a transient sensitivity calculation is given in figure 7.7. This is a simple linear problem (RC decay), so it has an analytic solution. Results for the transient example are given in figure 7.8. The analytic sensitivity solution is given by the solid line and the computed numerical sensitivity is given by the dashed line. The results match very well in this case, with the two lines right on top of each other.
* Transient sensitivity example
.param cap=1u
.param res=1K
c1 1 0 cap
R1 1 0 res
.IC V(1)=1.0
* Transient commands
.tran 0 5ms uic
.options timeint reltol=1e-6 abstol=1e-6

* Conventional file output
.print tran format=tecplot v(1)
* Sensitivity file output.
.print sens format=tecplot
+ exp(-time/(res*cap)) ; analytic solution (V(1))
+ (time/(res*res*cap))*exp(-time/(res*cap)) ; analytic dV(1)/dR
+ (time/(res*cap*cap))*exp(-time/(res*cap)) ; analytic dV(1)/dC
* Sensitivity commands
.SENS objfunc={V(1)} param=R1::R,C1::C
.options SENSITIVITY direct=1 adjoint=0
.end

Figure 7.7. Direct Transient Sensitivity Example Netlist
Figure 7.8. Transient direct sensitivity result.
Transient Adjoint Sensitivities

Transient adjoint sensitivities are a good choice for really large numbers of parameters, and when the number of objective functions is modest. For transient calculations, each time point is considered a separate objective function, so it is best to use adjoints when the sensitivity of interest concerns only one or a handful of time points.

Set `direct=0 adjoint=1` to specify transient adjoint simulations. The transient adjoint formulation in **Xyce** has similarities to the ones described by Liu [11] and Meir [12]. An example netlist for a transient adjoint sensitivity calculation is given in figure 7.9. This is a simple linear problem (RC driven by a sinewave), so it has an analytic solution. Results for the transient adjoint example are given in figure 7.9. The analytic sensitivity solution is given by the dashed line and the computed numerical sensitivity is given by the solid line. The results match very well in this case, with the two lines right on top of each other.

```
*Test of transient adjoint sensitivities
.param cap=1e-6
.param res=1e3
V1 1 0 0.0 sin (0.0 1.0 200 0.0 0.0 0.0 )
R1 1 2 res
C1 2 0 cap
.tran 1.0e-6 0.5e-2
.print tran format=tecplot V(1) V(2)
.print TRANADJOINT format=tecplot
.options timeint method=gear reltol=1.0e-6 abstol=1e-6

* Sensitivity commands
.SENS objfunc=V(2) param=R1:R,C1:C
.options SENSITIVITY direct=0 adjoint=1
.end
```

**Figure 7.9.** Adjoint Transient Sensitivity Example Netlist
Figure 7.10. Transient adjoint sensitivity result.
7.8.3 Output

For a full list and explanation of options related to .SENS output see the Xyce Reference Guide [3].

Sensitivity output can be sent to standard output, or to a user-specified log file. The format for this output is similar to that generated by the circuit given in figure 7.6. This feature is mainly made available in Xyce so as to be similar to the sensitivity analysis of older circuit simulators. However, for most uses it isn’t the most practical output, so it is disabled by default. To enable standard output, one should set the following:

```
.options SENSITIVITY STDOUTPUT=1
```

In addition to the screen output, Xyce can also produce a plottable file containing all the requested sensitivities. This file can be requested by adding either a .PRINT SENS or a .PRINT TRANADJOINT command to the input file. Steady-state sensitivities (adjoint or direct) and transient direct sensitivities will be handled by the .PRINT SENS command. Transient adjoint, on the other hand, is handled by the .PRINT TRANADJOINT command.

Unlike the traditional .PRINT line, both .PRINT SENS and .PRINT TRANADJOINT will assume that the user wants all the sensitivities specified on the .SENS line. As such it is not necessary (or possible) to specify specific sensitivities on the .PRINT SENS line. If the line exists, that is sufficient to produce the file, and it will contain a column for every objective function and every derivative. The file name is the same as the one produced with .PRINT, but with “.SENS” included just before the suffix. Similarly, for transient adjoint, the output file name has the string “.TRADJ” included before the suffix. Note also, that most of the same output formats (std, tecplot, etc.) are available for .PRINT SENS and .PRINT TRANADJOINT as they are for conventional .PRINT. The available formats are listed in table 7.8 and 7.9.

```
Table 7.8. Output generated for SENS analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT SENS</td>
<td>circuit-file.SENS.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT SENS FORMAT=GNUPLOT</td>
<td>circuit-file.SENS.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT SENS FORMAT=NOINDEX</td>
<td>circuit-file.SENS.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT SENS FORMAT=CSV</td>
<td>circuit-file.SENS.csv</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT SENS FORMAT=TECPLOT</td>
<td>circuit-file.SENS.dat</td>
<td>TIME</td>
</tr>
</tbody>
</table>
```

SENS. This is because the transient adjoint calculation is performed as a post-process, after the original forward calculation has been completed, and Xyce’s forward outputters are no longer active. To specify transient adjoint output, one must use .PRINT TRANADJOINT instead. As it is possible to perform both a transient direct and a transient adjoint calculation as part of the same computation, and most of Xyce’s output files are in column format, there wasn’t an easy way to have them use the same outputter.
Table 7.9. Output generated for transient adjoint SENS analysis

<table>
<thead>
<tr>
<th>Command</th>
<th>Files</th>
<th>Additional Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>.PRINT TRANADJOINT</td>
<td>circuit-file.TRADJ.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT TRANADJOINT FORMAT=NOINDEX</td>
<td>circuit-file.TRADJ.prn</td>
<td>INDEX TIME</td>
</tr>
<tr>
<td>.PRINT TRANADJOINT FORMAT=CSV</td>
<td>circuit-file.TRADJ.csv</td>
<td>TIME</td>
</tr>
<tr>
<td>.PRINT TRANADJOINT FORMAT=TECPLT</td>
<td>circuit-file.TRADJ.dat</td>
<td>TIME</td>
</tr>
</tbody>
</table>
7.8.4 Notes about .SENS accuracy and formulation

The sensitivity calculation in Xyce is based on a chain rule calculation. Ultimately, the calculation will produce $\frac{dO}{dp}$, where $O$ is a user-specified objective function, and $p$ is a user-specified parameter. $\frac{dO}{dp}$ is equal to:

$$\frac{dO}{dp} = \frac{\partial O}{\partial x} \frac{\partial x}{\partial p} + \frac{\partial O}{\partial p}$$  \hspace{1cm} (7.1)

where $x$ is a solution vector and $\frac{\partial x}{\partial p}$ is the sensitivity of that solution vector with respect to the parameter. Evaluating $\frac{\partial x}{\partial p}$ requires that $\frac{\partial x}{\partial p}$ be computed first. The direct sensitivity calculation for $\frac{\partial x}{\partial p}$ can be derived by considering the DAE form of the residual equation:

$$F(x, t) = \dot{q}(x, t) + j(x, t) - b(t) = 0$$  \hspace{1cm} (7.2)

In this equation, $q$ represents quantities that must be differentiated with respect to time (such as capacitor charge), and $j$ represents algebraic terms that depend on the solution $x$ (such as DC currents), and $b$ are independent sources that only depend on time. Equation 7.2 is solved to obtain the solution, $x$. To obtain sensitivities, one must differentiate this equation with respect to a parameter, $p$.

$$\frac{dF}{dp} = \frac{d}{dp} (\dot{q} + j - b) = 0$$  \hspace{1cm} (7.3)

In steady-state, equation 7.3 simplifies to:

$$\frac{dF}{dp} = \frac{dj}{dp} - \frac{db}{dp} = 0$$  \hspace{1cm} (7.4)

As $j$ is dependent upon $x$, the $\frac{dj}{dp}$ term must be expanded via chain rule, and the resulting equation must be re-arranged to set up a matrix equation that can be solved to obtain $\frac{dx}{dp}$:

$$\frac{dj}{dx} \frac{dx}{dp} = -\frac{dj}{dp} + \frac{db}{dp}$$  \hspace{1cm} (7.5)

In equation 7.5, the terms on the right hand side are computed by the individual device models once the Newton loop the circuit analysis has converged. The Jacobian matrix on the left hand side ($\frac{dj}{dx}$) is the same matrix used by the original analysis. Once the linear system is solved, then $\frac{dx}{dp}$ is available for the given parameter, and it can then be applied to equation 7.1. For transient, a similar linear system is solved, which depends on the specific time integration method used. For Backward-Euler the linear system is:

$$\frac{1}{h} \frac{d\dot{q}}{dx} \frac{dx}{dp_{n+1}} = -\frac{1}{h} \left[ \frac{d\dot{q}}{dp_{n+1}} \frac{dx}{dp_{n+1}} - \frac{d\dot{q}}{dp_{n}} \right] - \frac{dj}{dp} + \frac{db}{dp} + \frac{1}{h} \left[ \frac{dq}{dx} \right] \frac{dx}{dp_{n}}$$  \hspace{1cm} (7.6)
Where \( h \) is the time step size. As with \( 7.5 \), the left hand side of the equation contains the original Jacobian matrix.

In general, the accuracy of the above calculation is dependent on the accuracy of the individual derivatives that comprise equations \( 7.1 \) and \( 7.5 \) or \( 7.6 \). In Xyce, the Jacobian derivatives \( (dj/dx \) and \( dq/dx \) are always analytic. Similarly, the objective function derivatives \( (dO/dx) \) are also always analytic. However, the derivatives on the right hand side of \( 7.6 \) \( (dj/dp, db/dp \) and \( dq/dp) \) depend on particular device implementations. If the device was implemented with analytic parameter sensitivities, then those sensitivities are used. If analytic derivatives were not available, then the \( dj/dp, dq/dp \) and \( db/dp \) derivatives are computed using finite differences. A list of Xyce devices, and which of them support analytic sensitivities, is given in the Xyce Reference Guide [3].

For some problems, finite difference derivatives will work fine, but some devices and/or circuit problems have wide ranges of solution and/or parameter scalings, and this can render inaccurate finite difference derivatives. As this capability develops, most devices should eventually provide analytic derivatives.

The above derivation and arguments were given for direct sensitivities (as that is the only form supported for both DC and transient), but the same ideas with regard to accuracy apply for adjoint sensitivities.

For transient, note that the transient direct calculation uses the same time steps that are used for the original circuit analysis. It does not impose any additional error control that is specific to the accuracy of \( dx/dp \).
8. Homotopy and Continuation Methods

Chapter Overview

This chapter includes the following sections:

- Section 8.1 Continuation Algorithms Overview
- Section 8.2 Natural Parameter Continuation
- Section 8.3 Natural Multiparameter Continuation
- Section 8.4 GMIN Stepping Continuation
- Section 8.5 Source Stepping Continuation
- Section 8.6 MOSFET Continuation
- Section 8.7 Pseudo Transient
- Section 8.8 Arc Length Continuation
8.1 Continuation Algorithms Overview

Often, circuit convergence problems are most prominent during the DC operating point calculation. Unlike transient solves, DC operating point analysis cannot rely on a good initial guess from a previous step, and cannot simply reduce the step size when the solver fails. Additionally, operating points often have multiple solutions, with no capability to interpret the user’s intent. Multiple solutions can, even for converged circuit problems, result in a standard Newton solve being unreliable. For example, the operating point solution to a Schmidt trigger circuit has been observed to change with the computational platform.

Continuation methods can often provide solutions to difficult nonlinear problems, including circuit analysis, even when conventional methods (e.g., Newton’s method) fail [13] [14]. This chapter gives an introduction to using continuation algorithms (sometimes called homotopy algorithms) in Xyce. The Xyce Reference Guide [3] provides a more complete description of solver options.

The underlying numerical library used by Xyce to support continuation methods is LOCA (Library of Continuation Algorithms) [15, 16]. For a description of the numerical details see the LOCA theory and implementation manual [17].

8.1.1 Continuation Algorithms Available in Xyce

Xyce invokes a well-known SPICE method, “GMIN stepping,” automatically when a DC operating point fails to converge without it. It is a special case where the parameter being swept is artificial. GMIN stepping can also be invoked with .options nonlin continuation=3 or .options nonlin continuation=gmin. See Section 8.4 for more information and an example of GMIN stepping.

Xyce also invokes the SPICE “source stepping” method automatically when a DC operating point calculation fails both normal Newton’s method and the automatic GMIN stepping attempt. This is an example of natural parameter continuation that steps through a scale factor that is applied to all DC voltage sources in the circuit. It is described in Section 8.5.

Another basic type of continuation in Xyce is accessed by setting .options nonlin continuation=1. This allows the user to sweep existing device parameters (models and instances), as well as a few reserved artificial parameter cases. The most obvious natural parameter to use is the magnitude(s) of independent voltage or current sources, the choice of which is equivalent to “source stepping” in SPICE. Section 8.2 provides a Xyce source-stepping example. For some circuits (as in the aforementioned Schmidt trigger), source stepping leads to turning points in the continuation.

A special type of continuation, an algorithm designed specifically for MOSFET circuits [18], involves two internal MOSFET model parameters—one for the MOSFET gain, and the other for the nonlinearity of the current-voltage relationship. This algorithm is invoked with .options nonlin continuation=2, and has proven to be effective in some large MOSFET circuits. Section 8.6 provides a detailed example.
8.2 Natural Parameter Continuation

Figure 8.1 shows a natural parameter continuation netlist with parameters pertinent to the continuation algorithm highlighted in red. For this example, the parameter being swept is the DC value of the voltage source $V_{DDdev}$. This example demonstrates a version of “source stepping” that is similar to SPICE, but only applied to the single voltage source $V_{DDdev}$ rather than to all voltage sources. For an example of source stepping in which every source in simultaneously swept, see sections 8.2.2 and 8.5.

Using continuation on the magnitudes of independent voltage and current sources is a fairly obvious technique when a DC operating point calculation fails to converge. However, a naïve application of natural parameter continuation to single voltage and current sources does not often enable convergence in practice. Xyce will apply source stepping automatically during the DC operating point calculation if both the standard Newton’s method and GMIN stepping fail. So, normally, this technique of manually forcing stepping of a single source is unnecessary.

```
MOS level 1 model CMOS inverter
.TRAN 20ns 30us 0 5ns
.PRINT tran v(vout) v(in) v(1)
.options timeint reltol=5e-3 abstol=1e-3
* Continuation Options

.options nonlin continuation=1
.options loca stepper=0 predictor=0 stepcontrol=1
+ conparam=VDDdev
+ initialvalue=0.0 minvalue=-1.0 maxvalue=5.0
+ initialstepsize=0.2 minstepsize=1.0e-4
+ maxstepsize=5.0 aggressiveness=1.0
+ maxsteps=100 maxnliters=200

VDDdev VDD 0 5V
RIN IN 1 1K
VIN1 1 0 5V PULSE (5V 0V 1.5ns 5ns 5ns 1.5us 3us)
R1 VOUT 0 10K
C2 VOUT 0 0.1p
MN1 VOUT IN 0 0 CD4012_NMOS L=5u W=175u
MP1 VOUT IN VDD VDD CD4012_PMOS L=5u W=270u
.MODEL cd4012_pmos PMOS
.MODEL cd4012_nmos NMOS
.END
```

Figure 8.1. Example natural parameter continuation netlist. This example of source stepping shows a circuit that does not require continuation to run. Most circuits complex enough to require continuation would not fit on a single page.
8.2.1 Explanation of Parameters, Best Practice

Figure 8.1 also illustrates the following "best practice" rules:

- .options nonlin continuation=1. Sets the algorithm to use natural parameter continuation.
- .options loca conparam=VDDdev. If using natural parameter continuation, it is necessary include a setting for conparam. It sets which input parameter to use to perform continuation. The parameter name is subject to the same rules as parameter used by the .STEP capability. (Section 7.4.2). In this case, the parameter is the magnitude of the DC voltage source, VDDdev. For this type of voltage source, it was possible to use the default device parameter (Section 7.4.5).
- .options loca initialvalue=0.0. This is required.
- .options loca maxvalue=5.0. This is required.
- .options loca stepcontrol=1 or .options loca stepcontrol=adaptive. This specifies the continuation steps to be adaptive, rather than constant. This is recommended.
- .options loca maxsteps=100. This sets the maximum number of continuation steps for each parameter.
- .options loca maxnliters=200. This is the maximum number of nonlinear iterations, and has precedence over the similar number that can be set on the .options nonlin line.
- .options loca aggressiveness=1.0. This refers to the step size control algorithm, and the value of this parameter can be anything from 0.0 to 1.0. 1.0 is the most aggressive. In practice, try starting with this set to 1.0. If the solver fails, then reset to a smaller number.

8.2.2 Voltage Source Scaling Continuation

Figure 8.2 shows a natural parameter continuation netlist with parameters pertinent to the continuation algorithm highlighted in red. For this example, a special parameter VSRCSCALE is being swept from zero to one. This parameter is applied as a scaling factor for all DC voltage sources in the netlist. As a result, this example demonstrates an explicit invocation of "source stepping" like the one that both Xyce and SPICE apply automatically as part of their DC operating point solution strategies if Newton's method and GMIN stepping both fail.
*Simple netlist demonstrating source-stepping continuation
*This source will be swept with .DC
V1 1 0 DC 1
R1 1 0 100
*This source will be not swept with .DC
V2 2 0 DC 8
R2 2 0 100
.DC V1 1 8 1
.print DC V(1) V(2)
.print HOMOTOPY V(1) V(2)
* Continuation Options
.options nonlin continuation=1
.options loca stepper=0 predictor=0 stepcontrol=0
+ conparam=vsrcscale
+ initialvalue=0.0 minvalue=-1.0 maxvalue=1.0
+ initialstepsize=0.2 minstepsize=1.0e-4 maxstepsize=0.2
+ aggressiveness=1.0
+ maxsteps=5000 maxnliters=200

.END

Figure 8.2. Example natural parameter continuation netlist implementing source stepping over all DC voltage sources. This example of source stepping shows a circuit that does not require continuation to run. Most circuits complex enough to require source stepping would not fit on a single page.
8.3 Natural Multiparameter Continuation

It is possible to use the natural parameter continuation specification to have Xyce sweep multiple parameters in sequential order. This requires specifying many of the parameters in the .options loca statement as vectors, delineated by commas, rather than as single parameters.

This is a usage example — the circuit itself does not require continuation to run. Most circuits complex enough to require continuation would not fit on a single page.

8.3.1 Explanation of Parameters, Best Practice

The solver parameters set in figure 8.3 are the same as those from figure 8.1, but many of them are in vector form. Specify any parameters specific to the continuation variable as a vector, including conparam, initialvalue, minvalue, maxvalue, initialstepsize, minstepsize, maxstepsize, and aggressiveness. Otherwise, the specification is identical.
MOS level 1 model CMOS inverter
.TRAN 20ns 30us 0 5ns
.PRINT tran v(vout) v(in) v(1)
.options timeint reltol=5e-3 abstol=1e-3
* Continuation Options
.options nonlin continuation=1
.options loca stepper=0 predictor=0 stepcontrol=adaptive
+ conparam=mosfet:gainscale,mosfet:nlttermscale
+ initialvalue=0.0,0.0
+ minvalue=-1.0,-1.0
+ maxvalue=1.0,1.0
+ initialstepsize=0.2,0.2
+ minstepsize=1.0e-4,1.0e-4
+ maxstepsize=5.0,5.0
+ aggressiveness=1.0,1.0

VDDdev VDD 0 5V
RIN IN 1 1K
VIN1 1 0 5V PULSE (5V 0V 1.5us 5ns 5ns 1.5us 3us)
R1 VOUT 0 10K
C2 VOUT 0 0.1p
MN1 VOUT IN 0 0 CD4012_NMOS L=5u W=175u
MP1 VOUT IN VDD VDD CD4012_PMOS L=5u W=270u
.MODEL cd4012_pmos PMOS
.MODEL cd4012_nmos NMOS
.END

**Figure 8.3.** Example multiparameter continuation netlist.
This netlist reproduces MOSFET continuation with a manual specification.
8.4 GMIN Stepping

GMIN stepping is a type of continuation commonly available in circuit simulators. Like SPICE, Xyce automatically attempts GMIN stepping if the initial operating point fails, and if the attempt at GMIN stepping fails, it will subsequently attempt source stepping. As such, it is not typically necessary to manually specify GMIN stepping in a Xyce netlist.

However, GMIN stepping may be manually specified by setting continuation=3 or more conveniently, continuation=gmin. If it is manually specified, Xyce will not attempt to find a DC operating point using any other method; it will attempt GMIN stepping, and if that fails it will exit with error, not attempting any other method. Figure 8.4 provides a netlist example of GMIN stepping, in which the method has been explicitly requested.

```
Simple GMIN stepping example.
.TRAN 20ns 30us 0 5ns
.PRINT tran v(vout) v(in) v(1)
.options timeint reltol=5e-3 abstol=1e-3

* Continuation Options
.options nonlin continuation=gmin

VDDdev VDD 0 5V
RIN IN 1 1K
VIN1 1 0 5V PULSE (5V 0V 1.5us 5ns 5ns 1.5us 3us)
R1 VOUT 0 10K
C2 VOUT 0 0.1p
MN1 VOUT IN 0 0 CD4012_NMOS L=5u W=175u
MP1 VOUT IN VDD VDD CD4012_PMOS L=5u W=270u
.MODEL cd4012_pmos PMOS
.MODEL cd4012_nmos NMOS
.END
```

Figure 8.4. Example GMIN stepping netlist. The continuation parameter is gmin. It can also be specified using continuation=3.

The name "GMIN stepping" can be somewhat confusing, as "GMIN" is also a user-specified device package parameter (unrelated to this algorithm) that one may set. In the device context, "GMIN" refers to a minimum conductance applied to many device models to enhance convergence. In the continuation context, it refers to the conductance of resistors attached from every circuit node to ground.

The conductance, which is the continuation parameter, is initially very large, and is iteratively reduced until the artificial resistors have a very high resistance. At the end of the continuation, the resistors are removed from the problem. At this point, assuming the continuation has been successful, the original user-specified problem has been solved.
Source stepping is a type of continuation commonly available in circuit simulators. Like SPICE, Xyce automatically attempts source stepping if the initial operating point fails, and if the subsequent attempt at GMIN stepping also fails. As such, it is not typically necessary to manually specify source stepping in a Xyce netlist.

However, source stepping may be manually specified by setting continuation=34 or more conveniently, continuation=sourcestep. If it is manually specified, Xyce will not attempt to find a DC operating point using any other method; it will attempt source stepping, and if that fails it will exit with error, not attempting any other method. Figure 8.5 provides a netlist example of source stepping.

```plaintext
Simple test of explicit source stepping
***************************************************
R1 1 0 1K
V1 1 0 5V

.OP
.PRINT DC V(1) I(V1)
.PRINT HOMOTOPY V(1) I(V1)
* Continuation Options
.options nonlin continuation=sourcestep

.END
```

Figure 8.5. Example source stepping netlist.
8.6 MOSFET Continuation

Figure 8.6 contains a MOSFET continuation example netlist, and is the same circuit as was used in figure 8.6, except some of the parameters are different. As before, the lines pertinent to the continuation algorithm are highlighted in red.

```plaintext
THIS CIRCUIT IS A MOS LEVEL 1 MODEL CMOS INVERTER
.TRAN 20ns 30us 0 5ns
.PRINT tran v(vout) v(in) v(1)
.options timeint reltol=5e-3 abstol=1e-3

* Continuation Options
.options nonlin continuation=mos

VDDdev VDD 0 5V
RIN IN 1 1K
VIN1 1 0 5V PULSE (5V 0V 1.5us 5ns 5ns 1.5us 3us)
R1 VOUT 0 10K
C2 VOUT 0 0.1p
MN1 VOUT IN 0 0 CD4012_NMOS L=5u W=175u
MP1 VOUT IN VDD VDD CD4012_PMOS L=5u W=270u
.MODEL cd4012_pmos PMOS
.MODEL cd4012_nmos NMOS
.END
```

Figure 8.6. MOSFET continuation netlist example. This is a usage example — the circuit itself does not require continuation to run. Most circuits complex enough to require continuation would not fit on a single page.

8.6.1 Explanation of Parameters, Best Practice

There are a few differences between the netlist in figures 8.1 and 8.6. This example shows one set of options, but there are numerous options of working combinations.

MOSFET continuation requires only .options nonlin continuation=2 or .options nonlin continuation=mos parameters, which specifies use of the special MOSFET continuation. This is a two-pass continuation, in which first a parameter concerning gain is swept from 0 to 1, and then a parameter relating to the nonlinearity of the transfer curve is swept from 0 to 1. The default parameters will work for a variety of MOSFET circuits, so it often will be unnecessary to override them using an .options loca line. However, it is possible to override the default parameters using the same .options loca parameters described in Section 8.2.1.
8.7 Pseudo Transient

Pseudo transient continuation is very similar to GMIN stepping, in that both algorithms involve placing large artificial terms on the Jacobian matrix diagonal, and progressively making these terms smaller until the original circuit problem is recovered. One difference is, rather than doing a series on Newton solves, pseudo transient does a single nonlinear solve while progressively modifying the pseudo transient parameter. Figure 8.7 provides an example of pseudo transient continuation options.

```plaintext
* Continuation Options
  .options nonlin continuation=9

  .options loca
  + stepper=natural
  + predictor=constant
  + stepcontrol=adaptive
  + initialvalue=0.0
  + minvalue=0.0
  + maxvalue=1.0e12
  + initialstepsize=1.0e-6
  + minstepsize=1.0e-6
  + maxstepsize=1.0e6
  + aggressiveness=0.1
  + maxsteps=200
  + maxnliters=200
  + voltagescalefactor=1.0
```

**Figure 8.7.** Pseudo transient solver options example. The continuation parameter is set to 9.

8.7.1 Explanation of Parameters, Best Practice

Pseudo transient has not been observed to be as successful as MOSFET-continuation for large MOSFET circuits. However, it may be a good candidate for difficult non-MOSFET circuits as it tends to be faster because the total number of matrix solves is smaller.
8.8 Arc Length Continuation

Most of the forms of continuation described in this chapter are low-order, and thus cannot be used to track turning points in the solution. However, the ability to track turning points is a capability that can be enabled in Xyce. A simple example netlist, which is based on a third order polynomial (which thus has multiple DCOP solutions) is given in figure 8.8. The solution, which exhibits this turning point behavior is given in figure 8.9.

```
Test for turning points using arclength continuation
* polynomial coefficients:
.param A=3.0
.param B=-2.0
.param C=1.0
.param I=1.0
Vtest 1 0 5.0
Btest 1 0 V=A*(I(Vtest)-I)**3 + B*(I(Vtest)-I) + C
.DC Vtest 1 1 1

* natural parameter continuation options (via loca)
.options nonlin continuation=1

* stepper sets what order of continuation this is.
* stepper=0 or stepper= NAT is natural continuation
* stepper=1 or stepper=ARC is arclength continuation
*
* predictor must be set to secant to see turning points
* predictor=0 tangent
* predictor=1 secant
* predictor=2 random
* predictor=3 constant
.options loca stepper=1
+ predictor=1 stepcontrol=1
+ conparam=Vtest
+ initialvalue=0.0 minvalue=0.0 maxvalue=2.0
+ initialstepsize=0.01 minstepsize=1.0e-8 maxstepsize=0.1
+ aggressiveness=0.1
.print homotopy I(Vtest)
```

**Figure 8.8.** Arclength continuation example. An explanation of some of the important parameters is given in the comments.
8.8.1 Explanation of Parameters, Best Practice

Most of the parameters specified in the netlist \[8.8\] are the same as the ones described in the natural parameter section \[8.2.1\]. However, two of them must be specified to non-default values to enable an arclength calculation. Specifically, the stepper parameter must be set to 1 or ARC, and the predictor parameter must be set to 2 or SECANT.
9. Results Output and Evaluation Options

Chapter Overview

This chapter illustrates how to output simulation results to data or output files and includes the following sections:

- Section 9.1 | Control of Results Output
- Section 9.1.2 | Additional Output Options
- Section 9.2 | Output Analysis
- Section 9.3 | Graphical Display of Solution Results
9.1 Control of Results Output

\textbf{Xyce} supports one solution output command, \texttt{.PRINT}, which is quite flexible, and supports several output formats.

9.1.1 \texttt{.PRINT} Command

The \texttt{.PRINT} command sends the analysis results to an output file. \textbf{Xyce} supports several options on the \texttt{.PRINT} line of netlists that control the format of the output.

Multiple \texttt{.PRINT} lines may be present in the netlist. Only \texttt{.PRINT} lines appropriate for the analysis being executed are activated. Each analysis type has a set of analysis print types. These analysis print types are used to specify the variables desired for each of the different output files which may be generated by an analysis type. If an additional analysis print type is activated and no \texttt{.PRINT} for that analysis print type is present, the variable list and options fall back to the \texttt{.PRINT} of that analysis type.

General Format:

\texttt{.PRINT <print type> [options] <output variable> [<output variable>]*}

Table 9.1 lists the available print types for the analyses.

Table 9.2 gives the various options available to the \texttt{.PRINT} command.

Table 9.3 gives the various output formats available to the \texttt{.PRINT} command.

The \texttt{<output variable>} parameter can be a variety of requested outputs, including nodal voltages, \texttt{V(...)}, or device currents, \texttt{I(...)}, and power, \texttt{P(...)} or \texttt{W(...)}, as given by

- \texttt{V(<node name>)}
- \texttt{V(<node name>,<node name>)} (the voltage difference between the first and second nodes)
- \texttt{I(<two-terminal device>)}
- \texttt{Ik(<three-or-more-terminal device>)} (the \texttt{k} indicates the device node from which to acquire the value, which is device specific; see the \textbf{Xyce} Reference Guide [3] for details)
- \texttt{P(two-terminal device)}
- \texttt{W(two-terminal device)}

At this time, power calculations are only supported for \texttt{.DC} and \texttt{.TRAN} analysis types. Power calculations may also not be supported for all \textbf{Xyce} devices yet. Consult the \textbf{Xyce} Reference Guide [3] for more details. As an example, the power supplied or dissipated by the voltage source \texttt{V} is calculated as \texttt{I \cdot \Delta V} where the voltage drop is calculated as \texttt{(V_+ - V_-)} and positive current
Table 9.1. .PRINT Print Types

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Print Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.AC</td>
<td>AC</td>
<td>Sets default variable list and formats for print subtypes</td>
</tr>
<tr>
<td>.AC</td>
<td>AC_IC</td>
<td>Overrides variable list and format for AC initial conditions</td>
</tr>
<tr>
<td>.DC</td>
<td>DC</td>
<td></td>
</tr>
<tr>
<td>.HB</td>
<td>HB</td>
<td>Overrides variable list and format for HB initial conditions</td>
</tr>
<tr>
<td>.HB</td>
<td>HB_FDD</td>
<td>Overrides variable list and format for HB frequency domain</td>
</tr>
<tr>
<td>.HB</td>
<td>HB_IC</td>
<td>Overrides variable list and format for HB initial conditions</td>
</tr>
<tr>
<td>.HB</td>
<td>HB_STARTUP</td>
<td>Overrides variable list and format for HB start up</td>
</tr>
<tr>
<td>.HB</td>
<td>HB_TD</td>
<td>Overrides variable list and format for HB time domain</td>
</tr>
<tr>
<td>.NOISE</td>
<td>Noise</td>
<td>Outputs Noise spectral density curves</td>
</tr>
<tr>
<td>.TRAN</td>
<td>TRAN</td>
<td></td>
</tr>
</tbody>
</table>

Specialized Output Commands

| HOMOTOPY | Sets variable list and format for homotopy |
| SENS     | Sets variable list and format for sensitivity |

flows from $V_+$ to $V_-$. Dissipated power has a positive sign, while supplied power has a negative sign. An important note is that the power calculations are a post-processing step, which places a limit on the accuracy of circuit-wide “energy conservation” calculations (e.g., total power supplied by sources - total power dissipated in non-source devices) in Xyce. The accuracy of the inputs ($V$ and $I$) to the power calculations is limited by the nonlinear solver tolerances, and the error in the power calculations is upper-bounded by the sum of the product-terms of $V*(error\ in\ I)$ and $I*(error\ in\ V)$.

Voltage variables specified in the frequency domain have special processing to handle complex results. For file formats which have a complex output capability, the complex value is written. However, for file formats, such as STD and CSV, the complex value is written as two columns of data, the real part followed by the imaginary part. Pseudo names may also be used to compute scalar values from a complex voltage variable. These are given in Table 9.4.

In addition to the above, internal device variables can be specified as an `<output variable>`. These take the form, $N$(device variable). The format of the device variable called by $N$ is device-specific, and exact forms can be found in the Xyce Reference Guide [3].
Table 9.2. .PRINT command options.

<table>
<thead>
<tr>
<th>Option...</th>
<th>Action...</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORMAT=&lt;STD</td>
<td>NOINDEX</td>
</tr>
<tr>
<td>FILE=&lt;filename&gt;</td>
<td>Output filename. The default is the netlist filename with &quot;.prn&quot; appended. foo.cir.prn, where foo.cir is the input netlist filename. The suffix depends on the format. The default suffixes for FORMAT=STD</td>
</tr>
<tr>
<td>WIDTH=&lt;field-width&gt;</td>
<td>Column width for the output data</td>
</tr>
<tr>
<td>PRECISION=&lt;floating-point-precision&gt;</td>
<td>Number of significant digits past the decimal point</td>
</tr>
<tr>
<td>FILTER=&lt;floor-value&gt;</td>
<td>Absolute value below which output variables will be printed as 0.0</td>
</tr>
<tr>
<td>DELIMITER=&lt;TAB</td>
<td>COMMA&gt;</td>
</tr>
</tbody>
</table>

Table 9.3. .PRINT FORMAT options.

<table>
<thead>
<tr>
<th>Format...</th>
<th>Action...</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>Outputs data in standard columns</td>
</tr>
<tr>
<td>NOINDEX</td>
<td>Outputs the same as the STD except the index column is omitted.</td>
</tr>
<tr>
<td>PROBE</td>
<td>Output is formatted to be compatible with the PSpice Probe plotting utility.</td>
</tr>
<tr>
<td>RAW</td>
<td>Output conforms to the Spice binary rawfile. Use the -a command line option to produce an ascii rawfile.</td>
</tr>
<tr>
<td>TECPLOT</td>
<td>Output for use in the TecPlot graphics package.</td>
</tr>
<tr>
<td>CSV</td>
<td>Produces a comma-separated value format.</td>
</tr>
<tr>
<td>GNUPLOT</td>
<td>Output data in standard columns, with improved Gnuplot compatibility for .STEP data.</td>
</tr>
</tbody>
</table>

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### Table 9.4. Pseudo Variables for Complex Output

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR(node)</td>
<td>Voltage Real Component</td>
</tr>
<tr>
<td>VI(node)</td>
<td>Voltage Imaginary Component</td>
</tr>
<tr>
<td>VM(node)</td>
<td>Voltage Magnitude</td>
</tr>
<tr>
<td>VP(node)</td>
<td>Voltage Phase, Radians</td>
</tr>
<tr>
<td>VDB(node)</td>
<td>Voltage Magnitude, Decibels</td>
</tr>
<tr>
<td>VR(node1,node2)</td>
<td>Difference of Voltage Real Component</td>
</tr>
<tr>
<td>VI(node1,node2)</td>
<td>Difference of Voltage Imaginary Component</td>
</tr>
<tr>
<td>VM(node1,node2)</td>
<td>Difference of Voltage Magnitude</td>
</tr>
<tr>
<td>VP(node1,node2)</td>
<td>Difference of Voltage Phase, Radians</td>
</tr>
<tr>
<td>VDB(node1,node2)</td>
<td>Difference of Voltage Magnitude, Decibels</td>
</tr>
<tr>
<td>IR(device)</td>
<td>Current Real Component</td>
</tr>
<tr>
<td>II(device)</td>
<td>Current Imaginary Component</td>
</tr>
<tr>
<td>IM(device)</td>
<td>Current Magnitude</td>
</tr>
<tr>
<td>IP(device)</td>
<td>Current Phase, Radians</td>
</tr>
<tr>
<td>IDB(device)</td>
<td>Current Magnitude, Decibels</td>
</tr>
</tbody>
</table>

It is also possible to output a device or model parameter directly, such as the resistance of a resistor R5, specified as R5:R on the .PRINT line. It is necessary to specify both the device name and parameter name, separated by a colon.

Finally, an expression may also be specified as an `<output variable>`. To do so, enclose the expression within curly braces ({}). See Section 4.3 for a description of expressions.

**Example:**

```plaintext
.PRINT TRAN FILE=Output.prn V(3) I(R3) ID(M5) V(4)
.PRINT DC FORMAT=TECPLOT FILE=Output.dat V(2) {I(C3)+abs(V(4))*5.0}
.PRINT HB RA:R V(Vsrc) VM(Vsrc)
.PRINT HB_TD RA:R V(Vsrc)
.PRINT TRAN FORMAT=CSV R1:R R1:TEMP I(R1) R2:R R2:TEMP
.PRINT AC v(3) .PRINT AC FILE=AUX.FD.prn v(1) .OP
.PRINT AC_IC v(1) v(2)
```
9.1.2 Additional Output Options

Additional control of .PRINT line output can be set using the .OPTIONS OUTPUT specification.

Output Intervals

An important feature of the .OPTIONS OUTPUT command is to provide control of the interval at which transient data is written to files specified by .PRINT TRAN commands. This can be especially useful in controlling the size of the results file for simulations that require a large number of time steps. The default behavior is for Xyce to output results at every time step, so using this feature to reduce output frequency will result in improved performance.

**General Format:**

```
.OPTIONS OUTPUT INITIAL_INTERVAL=<interval> [<t0> <i0> [<t1> <i1> ...]]
```

`INITIAL_INTERVAL=<interval>` specifies the starting interval time for output and `<tx ix>` specifies later simulation times (`tx`) where the output interval will change to (`ix`).

The following example shows the output being requested (via the netlist .OPTIONS OUTPUT command) every .1µs for the first 10µs, every 1µs for the next 10µs, and every 5µs for the remainder of the simulation:

**Example:**

```
.OPTIONS OUTPUT INITIAL_INTERVAL=.1us 10us 1us 20us 5us
```

Suppressing output file header and footer

It can be convenient to have an output file that contains only numerical data with minimal formatting. There are two options, PRINTHEADER and PRINTFOOTER available on the .OPTIONS OUTPUT line to facilitate this. The format is given by:

**General Format:**

```
.OPTIONS OUTPUT PRINTHEADER=<boolean> PRINTFOOTER=<boolean>
```

So, to produce an output file that has no header and no footer, simply set:

**Example:**

```
.OPTIONS OUTPUT PRINTHEADER=false PRINTFOOTER=false
```

Note that this is only supported for .PRINT FORMAT=STD, the default format.

9.2 Output Analysis
9.2.1 .MEASURE

_Xyce_ supports analysis of the data from a simulation through the .MEASURE command. Using .MEASURE one can locate extrema in a voltage or current node, calculate integrals, derivatives, Fourier transforms, and locate transient events.

**General Format:**

```
.MEASURE <analysis type> <measure name> <measure type> <simulation variable>
+ [qualifiers]
```

<analysis type> is the analysis under which the measure should be calculated. Currently only transient (.TRAN) and dc (.DC) analyses are supported. However, .MEASURE can be used with .STEP in both cases. The specified measure is referenced by <measure name>. That name is used in the summary output at the end of the simulation to report the value of that measure, and can also be used in .PRINT statements. The <measure type> is the type of calculation to be done. For .TRAN analyses, the supported measure types are:

- **AVG**: Computes the arithmetic mean.
- **DERIV**: Computes the derivative of a simulation variable, either at a user-specified time or when the simulation variable hits a user-specified value.
- **DUTY**: Fraction of time that a given simulation variable is greater than ON and does not fall below OFF (ON and OFF are defined later in this section).
- **EQN**: Calculates the value of a _Xyce_ expression during the simulation.
- **ERROR**: Calculates the norm between the measured waveform and a “comparison waveform” specified in a file. The supported norms are L1, L2 and INFNORM. The default norm is the L2 norm. The descriptive output for each ERROR measure, that is printed to standard output, will explicitly state which norm was used for each ERROR measure.
- **FIND-WHEN**: Returns the value of a solution variable when the solution variable specified in the WHEN clause reaches a specified fixed value or is equal to another solution variable. If the conditions specified for finding the value specified in the WHEN clause are not found during the simulation then the measure will return the default value of -1 (or the user-specified default value).
- **FOUR**: Calculates the Fourier transform of the solution variable for the .TRAN analysis type using the fundamental frequency AT. By default, the DC component and first nine harmonics are computed; more can be reported by setting NUMFREQ to the desired value. More interpolation points can be used in the Fourier analysis by setting GRIDSIZE, which is 200 by default.
- **FREQ**: An estimate of the frequency of a solution variable found by cycle counting during the simulation. Thresholds are defined through the values of ON and OFF.
- **INTEG**: Calculates the integral of a solution variable through second order numerical integration.
- **MAX**: Returns the maximum value of a solution variable.

- **MIN**: Returns the minimum value of a solution variable.

- **OFF_TIME**: Returns the time that a solution variable is below OFF, and not greater than ON for the simulation, normalized by the number of cycles of the waveform during the simulation.

- **ON_TIME**: Returns the time that a solution variable is above ON, and not less than OFF for the simulation, normalized by the number of cycles of the waveform during the simulation.

- **PP**: Returns the difference between the maximum value and the minimum value of a solution variable during the simulation.

- **RMS**: Computes the root-mean-squared value of a solution variable.

- **TRIG-TARG**: Measures the time between a trigger event and a target event.

- **WHEN**: Returns the time when a solution variable reaches a specified fixed value or is equal to another solution variable. If the conditions specified for finding the value specified in the WHEN clause are not found during the simulation then the measure will return the default value of -1 (or a user-specified default value).

For **.DC** analyses, only the **EQN**, **ERROR**, **MIN**, **MAX** and **PP** measure types are currently supported.

The `<simulation variable>` specifies a voltage or current node that will be used in this measure, such as V(a). The measure **WHEN** is different from the other measures in that it can take one or two solution variables. For example, **WHEN** V(a)=5 returns the time when V(a) equals 5. Or, if **WHEN** V(a) = V(b) is specified, the time when V(a) equals V(b) is returned.

The **.MEASURE** command can also take optional [qualifiers] that limit the time window (or DC sweep values) when **.MEASURE** is applied. The [qualifiers] also place numeric limits on what state a value is considered to be in (e.g., **ON** and **OFF**), and provide numeric qualification on comparisons of values (e.g., **MINVAL**). A partial list of the supported qualifiers is as follows. See the *Xyce* Reference Guide [3] for more details on these qualifiers, and for the complete list of supported qualifiers for each combination of analysis type and measure type.

- **FROM=value** A time (or DC sweep value) after which the measurement calculation will start.

- **TO=value** A time (or DC sweep value) after which the measurement calculation will end.

- **TD=value** A time delay before which the measurement should be taken or checked.

- **RISE=r | LAST** The number of rises after which the measurement should be checked. If **LAST** is specified, then the last rise found in the simulation will be used.

- **FALL=f | LAST** The number of falls after which the measurement should be checked. If **LAST** is specified, then the last fall found in the simulation will be used.

- **CROSS=c | LAST** The number of zero crossings after which the measurement should be checked. If **LAST** is specified, then the last zero crossing found in the simulation will be used.
■ MINVALUE=value  An allowed absolute difference between the simulation variable and the variable to which it is being compared. This has a default value of 1.0e-12. One may need to specify a larger value to avoid missing the test condition in a transient run.

■ ON=value  The value at which a signal is considered to be on for frequency, duty and on time calculations.

■ OFF=value  The value at which a signal is considered to be off for frequency, duty and off time calculations.

An example of using .measure during a transient analysis is shown in the following netlist:

```
VS 1 0 SIN(0 1.0 1KHZ 0 0)
VP 2 0 PULSE( 0 1 0.2ms 0.2ms 0.2ms 1ms 2ms )

R1 1 0 100
R2 2 0 100

.TRAN 0 10ms
.PRINT TRAN FORMAT=NOINDEX V(1) V(2)

.MEASURE TRAN avg1 AVG V(1)
.MEASURE TRAN avg2 AVG V(2)

.MEASURE TRAN duty1 DUTY V(1) ON=0.75 OFF=0.25
```

The measure avg1 returns the average of \( v(1) \), and avg2 returns the average of \( v(2) \). Additionally, duty1 computes the fraction of time that \( v(1) \) is above 0.75 V, without falling below 0.25 V.

The next netlist provides an example of using the when measure during a transient analysis:

```
VS 1 0 SIN(0 1.0 1KHZ 0 0)
VP 2 0 PULSE( 0 100 0.2ms 0.2ms 0.2ms 1ms 2ms )

R1 1 0 100
R2 2 0 100

.TRAN 0 10ms 0 1.0e-5
.PRINT TRAN FORMAT=NOINDEX V(1) V(2)

.MEASURE TRAN hit1_75 WHEN V(1)=0.75 MINVAL=0.02
.MEASURE TRAN hit2_75 WHEN V(1)=0.75 MINVAL=0.08 RISE=2
```

In the above netlist, the measure called hit1_75 will return the simulation time where \( v(1) \) reaches a value of 0.75, while hit2_75 returns the second time that \( v(1) \) reaches a value of 0.75. The
MINVAL option acts at an absolute tolerance in this case. So, the above measure statements are more exactly interpreted as hit1.75 is the simulation time when v(1) reaches a value of 0.75±0.02 and hit2.75 is the simulation time when v(1) reaches a value of 0.75 ± 0.08 on its second rise.

Measured results are reported to the output and log file. Additionally, for TRAN measures, the results are stored in files called circuitFileName.mt#, where the suffixed number (#) starts at 0 and increases for multiple iterations (.STEP iterations) of a given simulation. Each line of this file will contain the measurement name, followed by its value for that run and/or step iteration. For DC measures, the results are stored in the files circuitFileName.ms#.

**Xyce** also supports an ability to re-measure results from a prior run of **Xyce**. In this mode, one can modify .MEASURE statements and have **Xyce** recalculate the results based on existing simulation data. This can be useful if the original simulation takes some time to complete. (Note: remeasure works for both transient and dc analyses. However, it may be most useful for transient analyses.) The syntax in the netlist is the same and the only thing that changes is how one invokes **Xyce**. For example, if the netlist is called myNetlist.cir and the existing output file is called myNetlist.cir.prn, then remeasure is accomplished with:

```
Xyce -remeasure myNetlist.cir.prn myNetlist.cir
```

There are some important limitations to remeasure. First, the data used by the .MEASURE commands must be present in the output file because, in this mode, **Xyce** is not recalculating the full solution. Second, device lead currents and power are not supported when re-reading the existing simulation data; thus, remeasure should be used only with voltage node data. Third, .prn, .csv and .csd files are supported, but remeasure may only work for .csv and .csd files generated by **Xyce**.

### 9.2.2 .FOUR

Fourier analysis can be performed as a part of the transient analysis using the .FOUR command.

**General Format:**

```
.FOUR freq ov1 <ovn>*
```

freq is the fundamental frequency used for Fourier analysis. The ov1 parameter is the desired solution variable to be analyzed, specifically:

- V(<node name>)
- V(<node name>,<node name>) (the voltage difference between the first and second nodes)
- I(<two-terminal device>)
- Ik(<three-or-more-terminal device>) (see the .PRINT section, [9.1.1](#) for more detail)
- N(device variable) (see the .PRINT section, [9.1.1](#) for more detail)
The pseudo-variables given in Table 9.4 for complex output handling

At least one solution variable must be specified, but Fourier analysis can be performed on several solution variables for each fundamental frequency, \( f_{\text{freq}} \). Multiple .FOUR lines may be used in a netlist. All results from Fourier analysis will be returned to the user in a file with the same name as the netlist file suffixed with .four.

Fourier analysis is performed over the last period \((1/f_{\text{freq}})\) of the transient simulation. The dc component and the first nine harmonics are calculated. The number of harmonics computed by .FOUR is static. So, the main difference between .FOUR and the Fourier analysis in .MEASURE is that the latter allows the user to select the number of harmonics. The default options for the Fourier analysis in .MEASURE is the same as .FOUR. For instance, these two lines will result in the same Fourier analysis:

```
.FOUR 20MEG V(2)
.MEASURE TRAN FOURV2 FOUR V(2) AT=20MEG
```

The Fourier analysis in .MEASURE will allow for more harmonics to be computed using the NUMFREQ option and more interpolation points to be used in the Fourier analysis with GRIDSIZE. For instance, to compute twenty harmonics (including the dc component), the previous .MEASURE line can be amended to:

```
.MEASURE TRAN FOURV2 FOUR V(2) AT=20MEG NUMFREQ=20
```

To increase the number of interpolation points from 200, which is the default, to 500, the line can be amended to:

```
.MEASURE TRAN FOURV2 FOUR V(2) AT=20MEG NUMFREQ=20 GRIDSIZE=500
```

For maximum accuracy of the Fourier analysis, it is recommended that the time integration option DELMAX should be set to period/100. This is the preferred approach to improving the accuracy of the Fourier analysis versus increasing the number of interpolation points.

### 9.3 Graphical Display of Solution Results

Although Xyce does not provide integrated graphical display options, it produces output in a form that may readily be used with commonly available graphical tools, including TecPlot, gnuplot, and MS Excel (see figure 9.1 for an example plot using TecPlot, http://www.amtec.com). The standard Xyce print format (FORMAT=STD or FORMAT=NOINDEX) is well suited for use with gnuplot. However, FORMAT=GNUPLOT may be useful when plotting .STEP data in gnuplot, as it automatically inserts two blank lines between the blocks of step-data that are otherwise in standard format. Comma separated variable (FORMAT=CSV) is the best choice for import into Excel. FORMAT=TECPLOT
produces output specifically targeted at the TecPlot tool. The `FORMAT=PROBE` option to the `.PRINT` command produces output `.csd` files that can be read by the PSpice Probe utility. See the PSpice Users Guide [4] for instructions on using the Probe tool, and the Xyce Reference Guide [3] for more details on the `.PRINT` command options.

![Figure 9.1. TecPlot plot of diode clipper circuit transient response from Xyce .prn file.](image)
10. Guidance for Running Xyce in Parallel

Chapter Overview

This chapter provides guidance for running a parallel version of Xyce, and includes the following sections:

- Section 10.1 Introduction
- Section 10.2 Processor Affinity on Linux systems
- Section 10.3 Problem Size
- Section 10.4 Linear Solver Options
- Section 10.5 Transformation Options
- Section 10.6 Device Distribution Options
10.1 Introduction

**Xyce** is designed from the ground up to be distributed-memory parallel, supported by the message-passing interface (MPI) standard. Although many of the issues pertinent to running in parallel are still being researched, **Xyce** is mature enough that some general principles have emerged for efficiently running problems in a parallel environment. In addition to the information in this chapter, reference [19] provides supplemental information about **Xyce** parallel performance.

Parallel simulations must be run from the command line. Section 2.2.1 provides information about the parallel execution syntax for **Xyce**.

10.2 Processor Affinity on Linux systems

Beginning with release 1.8 of OpenMPI, the default behavior on Linux systems is for OpenMPI to apply “processor affinity” to runs invoked with mpirun. This is intended to improve performance of parallel runs by preventing the processes from moving around the system, possibly degrading memory access efficiency. Since most users of OpenMPI are trying to maximize the performance of their systems, this is generally a good change.

Prior to that release, the default behavior was to allow MPI processes to be moved from processor to processor by the Linux system as needed.

If you are the only person running MPI jobs on a system, and you are only running one job, this change will have no impact on you, but if you are running more than one MPI job at a time, or more than one user on your system is running MPI jobs and the system is not using a resource manager such as slurm, then this change has a profound impact that must be understood and adapted to with mpirun options.

10.2.1 Default OpenMPI Behavior with Processor Affinity Support

At the time of this writing, OpenMPI’s mpirun will, by default, bind processes to a core if the number of processors requested is 2 or less. If the number of processes requested is greater than 2, it will bind processes to a socket.

What this means is that once your run starts, each process of your parallel job will be locked onto the processor (core or socket) on which it started.

10.2.2 Why You Have to Know About This

Unfortunately, OpenMPI by default allocates processors to processes in a round-robin fashion starting from the lowest numbered processor on the system, and each mpirun makes this determination without any access to what other mpirun invocations have done.
The effect of this is that if you start five identical 2-processor parallel runs of Xyce simultaneously on a 16-core system and don’t add extra mpirun options, each of these five jobs will be locked to the same two processors (processors 0 and 1) on the system.

Rather than getting five jobs run in the time it takes to run one, each will only get 20% of the two processors and take at least five times longer to run than a single job would have.

The same thing would be true if five different users each ran one 2-processor Xyce job. All jobs would be running on processors 0 and 1 of this 16-processor system.

Therefore, unless you are the only person on your system and you are only running one job, you must be aware if OpenMPI is using processor affinity on your system, and take appropriate steps to avoid oversubscribing cores.

10.2.3 Affected Systems

At the time of this writing, OpenMPI supports processor affinity only on Linux systems, and so the issues of this section apply only to Linux. The OS X kernel does not support jobs setting their own processor affinity. Some other systems have processor affinity support in their kernels, but it is not yet supported by OpenMPI on those systems.

Systems that are running a resource manager such as slurm (which includes all of Sandia’s high performance computing systems) are not impacted by this issue, because slurm will allocate a specific set of CPUs to be exclusive to your job, and no other jobs of yours or other users can run on these CPUs.

10.2.4 mpirun Command Line Options to Change Default Behavior

If squeezing maximum performance out of the hardware is not important, then the simplest way to avoid the oversubscription issue described above is to use the --bind-to none option to mpirun. This was the default behavior of mpirun prior to release 1.8 of OpenMPI and the default behavior of OpenMPI on every system other than Linux. While the --bind-to none option will potentially allow your mpi processes to move around the system and have degraded memory performance, it will NOT accidentally stack multiple jobs onto the same small set of processors. Any number of mpirun jobs may be run with this option, and they will not compete for resources unless the Linux task scheduler makes them do so.

If you do not want to do without the benefits that processor affinity can bring, you can manually specify the set of CPUs that OpenMPI will use for your job by using the -cpu-set option to mpirun, choosing as your CPU set some numbered processors that you know are not being used by other MPI jobs. For example, mpirun -np 2 -cpu-set 2-3 will run your 2 processor job with the jobs locked to processors 2 and 3 instead of to processors 0 and 1. You will have to make sure to use a different CPU set for each job, and make sure that you are not using the same CPU set as some other user on the system.
There are other options for modifying OpenMPI’s processor binding behavior, so consult OpenMPI documentation if you wish to understand them better.

Finally, if you really want to solve the problem correctly, reaping both the benefits of processor affinity and the simplicity of using mpirun’s defaults, you can install and configure a resource manager on your system. This is a topic that is far outside the scope of Xyce documentation. See http://slurm.schedmd.com/ for documentation on one such resource manager.

10.3 Problem Size

Running Xyce in parallel is often useful for circuits with thousands of devices or more. However, due to the overhead of interprocessor communication, there is an optimal number of processors that will achieve the best performance. This number is dependent upon many factors, including the number and type of devices, the topology of the circuit, and the characteristics of the computing architecture. It is difficult to know a priori what this optimal number of processors is. However, it is apparent when that optimal number is exceeded because, as the number of processors is increased, the total simulation time will also increase. This is due to the increasing amount of required communication and decreasing amount of work per processor. In other words, the benefit of distributing the problem is outweighed by the communication overhead, so increasing the processor count beyond this optimal point is counterproductive.

10.3.1 Ideal Problem Size

In general, a circuit needs to be relatively large to take full advantage of the parallel capability of Xyce. However, parallelism is achieved in two distinct phases of the code: the device evaluation and the linear solve. The device evaluation is, as the name implies, the evaluation of all the device equations in order to compute the residual vector and Jacobian entries for Newton’s method. Xyce distributes the number of devices over the number of processors in parallel, so their evaluation enables speedups in the total simulation time even for thousands of devices.

The linear solve phase is more computationally complex. The Jacobian matrix generated by most circuits is sparse and has heterogeneous structure, in that there is not a regular sparsity pattern in the matrix nonzeros. Sparse, direct linear solvers have proven to be efficient on these types of linear systems up into the tens to hundreds of thousands of unknowns. They become less efficient for linear systems in the hundreds of thousands of unknowns. This is where iterative linear solvers can provide scalable performance because of their inherent parallelism. Unfortunately, the effectiveness of iterative linear solvers is dependent upon preconditioning the linear system (see Section 10.4.6). The benefit of direct over iterative linear solvers is that they rarely fail to compute a solution, so direct linear solvers are the more robust option for enabling simulations to complete.

In general, there are three modes in which Xyce can be executed: “Serial load, serial solve”, “Parallel load, serial solve”, and “Parallel load, parallel solve”. Each of these modes optimizes the amount of available parallelism for a given linear system size, as summarized in Table 10.1. The “load” refers to the device evaluation phase combined with the assembly of the Jacobian matrix and residual vector, while the “solve” refers to the linear solve phase. “Serial load, serial solve” is the only mode of computation that a serial version of Xyce will perform, but it can also
be obtained in a parallel version of Xyce by using only one MPI processor. Both of the “Parallel load” simulation modes require a parallel build of Xyce, where the linear solver method can be a direct method (“serial solve”) or an iterative method (“parallel solve”) using the options discussed in Section 10.4. Hybrid linear solvers, which combine the best attributes of both direct and iterative methods, provide a robust and scalable option. They are not reflected in Table 10.1 but more information about these types of linear solvers will be discussed in Section 10.4.7.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Linear System Size</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Serial load, serial solve”</td>
<td>$10^9$ - $10^{10}$</td>
<td>MPI overhead cannot speed up device evaluation or linear solve.</td>
</tr>
<tr>
<td>“Parallel load, serial solve”</td>
<td>$10^3$ - $10^5$</td>
<td>Distributed device evaluations can speed up the simulation, but iterative linear solvers are not more efficient than direct methods.</td>
</tr>
<tr>
<td>“Parallel load, parallel solve”</td>
<td>$10^5$ or more</td>
<td>Distributed device evaluations can speed up the simulation and so can iterative linear solvers, if an efficient preconditioner is available.</td>
</tr>
</tbody>
</table>

10.3.2 Smallest Possible Problem Size

Circuits consist of a discrete set of components (voltage nodes, devices, etc.). For parallel simulation, it is preferable that Xyce be able to put at least one discrete component of the problem on each processor. In practice, this means the circuit should be distributed across fewer processors than the number of nodes and devices it contains.

10.4 Linear Solver Options

The different linear solvers available in Xyce are:

- KLU
- KSparse
- SuperLU and SuperLU DIST (optional)
- The AztecOO iterative solver library
- The Belos iterative solver library
- The ShyLU hybrid solver library (optional)
AztecOO and Belos are the parallel iterative solvers and KLU, KSparse, and SuperLU (optional) are the serial direct solvers that are available for both serial and parallel builds of Xyce. If KLU, KSparse, or SuperLU is used with a parallel version of Xyce, the devices are evaluated and linear problem is assembled in parallel, but the linear system is solved in serial on one processor. This can be quite effective for circuits with tens of thousands of devices or fewer (see Table 10.1). The ShyLU hybrid linear solver, which combines the robustness of a direct solver with the scalability of an iterative solver, will be discussed in Section 10.4.7.

The user can specify the solver through the .OPTIONS LINSOL control line in the netlist. The default linear solver used by Xyce is described in Table 10.2. By default, a parallel version of Xyce uses AztecOO as the linear solver when the linear system is larger than a thousand unknowns. For any linear system smaller than a thousand unknowns, Xyce uses KLU as the linear solver. A serial version of Xyce uses KLU as its default linear solver. To use a solver other than the default the user needs to add the option "TYPE=<solver>" to the .OPTIONS LINSOL control line in the netlist, where <solver> is 'KLU,' 'KSPARSE,' 'SUPERLU,' 'SUPERLUDIST,' 'AZTECOO,' 'BELOS,' or 'SHYLU.'

Table 10.2. Xyce default linear solver.

<table>
<thead>
<tr>
<th>Solver</th>
<th>Version</th>
<th>Linear System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLU</td>
<td>Serial</td>
<td>all</td>
</tr>
<tr>
<td>KLU</td>
<td>Parallel</td>
<td>1 − 1000 unknowns</td>
</tr>
<tr>
<td>AztecOO</td>
<td>Parallel</td>
<td>1001+ unknowns</td>
</tr>
</tbody>
</table>

10.4.1 KLU

KLU is a serial, sparse direct solver native to the Amesos package in Trilinos [20] and is the default solver for serial builds of Xyce. KLU is the default solver for small circuits in parallel builds of Xyce as well, but this requires the linear system to be solved on one processor and the solution communicated back to all processors. As long as the linear system can fit on one processor, KLU is often a superior approach to using an iterative linear solver. So, if a parallel build of Xyce is run in serial on a circuit that generates a linear system larger than one thousand unknowns and the simulation fails to converge, then specifying KLU as the linear solver may fix that problem.

Some of the solver parameters for KLU can be altered through the .OPTIONS LINSOL control line in the netlist. Table 10.3 lists solver parameters and their default values for KLU.

10.4.2 KSparse

KSparse is a serial, sparse direct solver based on Ken Kundert’s sparse solver, Sparse 1.3. Kundert’s sparse solver was developed as part of the SPICE circuit simulation code. KSparse is built, by default, in Xyce. Similar to KLU, KSparse can be used in a parallel version of Xyce, but the linear system is solved on one processor.
Table 10.3. KLU linear solver options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLU_REPIVOT</td>
<td>Recompute pivot order each solve</td>
<td>1 (true)</td>
</tr>
<tr>
<td>OUTPUT_LS</td>
<td>Write out linear systems solved by KLU to file every # solves</td>
<td>0 (false)</td>
</tr>
<tr>
<td>OUTPUT_BASE_LS</td>
<td>Write out linear systems before any transformations to file every # solves</td>
<td>0 (false)</td>
</tr>
<tr>
<td>OUTPUT_FAILED_LS</td>
<td>Write out linear systems KLU failed to solve to file</td>
<td>0 (false)</td>
</tr>
</tbody>
</table>

10.4.3 SuperLU and SuperLU DIST

SuperLU is a serial, sparse direct solver and SuperLU DIST is a parallel, sparse direct solver with an interface in the Amesos package. SuperLU and SuperLU DIST support are optionally built in Xyce, so they are not available by default in any Xyce build or provided binary. Furthermore, to enable SuperLU and SuperLU DIST support in Xyce, it is necessary to build SuperLU and SuperLU DIST support in Amesos/Trilinos. Similar to KLU, SuperLU can be used in a parallel version of Xyce, but the linear system is solved on one processor. SuperLU DIST can only be used in a parallel version of Xyce, the Amesos interface handles the redistribution of the matrix into the format required by SuperLU DIST. Xyce does not allow modifications to SuperLU and SuperLU DIST solver parameters.

10.4.4 AztecOO

AztecOO is a package in Trilinos [20] that offers an assortment of iterative linear solver algorithms. Xyce uses the Generalized Minimal Residual (GMRES) method [21] from this suite of iterative solvers. Some of the solver parameters for GMRES can be altered through the '.OPTIONS LINSOL' control line in the netlist. Table 10.4 provides a list of solver parameters for AztecOO and their default values.

Table 10.4. AztecOO linear solver options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ_max_iter</td>
<td>Maximum allowed iterations</td>
<td>500</td>
</tr>
<tr>
<td>AZ_tol</td>
<td>Iterative solver (relative residual) tolerance</td>
<td>1.0e-12</td>
</tr>
<tr>
<td>AZ_kspace</td>
<td>Krylov subspace size</td>
<td>500</td>
</tr>
<tr>
<td>OUTPUT_LS</td>
<td>Write out linear systems solved by AztecOO to file every # solves</td>
<td>0 (false)</td>
</tr>
<tr>
<td>OUTPUT_BASE_LS</td>
<td>Write out linear systems before any transformations to file every # solves</td>
<td>0 (false)</td>
</tr>
</tbody>
</table>

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Common AztecOO Warnings

If Xyce is built with the verbosity enabled for the linear algebra package, it is not uncommon to see warnings from AztecOO usually indicating the solver returned unconverged due to a numerical issue.

**NOTE:** AztecOO warnings *do not* indicate the entire simulation has failed, Xyce uses a hierarchy of solvers so if the iterative linear solver fails, the nonlinear solver or time integrator will usually make adjustments and attempt the step again; so the warnings can often be ignored. If the entire simulation eventually fails (i.e., gets a “time-step-too-small” error), then the AztecOO warnings might contain clues as to what went wrong.

The simplest reason for AztecOO to return unconverged would be when the maximum number of iterations is reached, resulting in the following warning:

***************************************************************
Warning: maximum number of iterations exceeded without convergence
***************************************************************

Another reason AztecOO may return unconverged is when the GMRES Hessenberg matrix is ill-conditioned, which is usually a sign that the matrix and/or preconditioner is nearly singular, resulting in the following warning:

***************************************************************
Warning: the GMRES Hessenberg matrix is ill-conditioned. This may indicate that the application matrix is singular. In this case, GMRES may have a least-squares solution.
***************************************************************

It is also common to lose accuracy when either the matrix or preconditioner, or both, are nearly singular. GMRES relies on an estimate of the residual norm, called the recursive residual, to determine convergence. Xyce uses the recursive residual instead of the actual residual for computational efficiency. However, numerical issues can cause the recursive residual to differ from the actual residual. When AztecOO detects but cannot rectify this situation, it outputs the following warning:

***************************************************************
Warning: recursive residual indicates convergence though the true residual is too large.
***************************************************************

Sometimes this occurs when storage is overwritten (e.g. the solution vector was not dimensioned large enough to hold external variables). Other times, this is due to roundoff. In this case, the solution has either converged to the accuracy
of the machine or intermediate roundoff errors occurred preventing full convergence. In the latter case, try solving again using the new solution as an initial guess.

#### 10.4.5 Belos

Belos is a package in Trilinos [20] that offers an assortment of iterative linear solver algorithms. Many of the algorithms available in Belos can also be found in AztecOO. However, Belos offers a few computational advantages because its solvers are implemented using templated C++. In particular, AztecOO can solve linear systems only in double-precision arithmetic, while Belos can solve linear systems that are complex-valued or in extended-precision arithmetic. At this time, Xyce is using a subset of Belos capabilities, the default method is GMRES, and the interface to Belos will recognize most of the AztecOO linear solver options, as shown in Table 10.5.

**Table 10.5.** Belos linear solver options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ_max_iter</td>
<td>Maximum allowed iterations</td>
<td>500</td>
</tr>
<tr>
<td>AZ_tol</td>
<td>Iterative solver (relative residual) tolerance</td>
<td>1.0e-12</td>
</tr>
<tr>
<td>AZ_kspace</td>
<td>Krylov subspace size</td>
<td>500</td>
</tr>
<tr>
<td>OUTPUT_LS</td>
<td>Write out linear systems solved by Belos to file every # solves</td>
<td>0 (false)</td>
</tr>
<tr>
<td>OUTPUT_BASE_LS</td>
<td>Write out linear systems before any transformations to file every # solves</td>
<td>0 (false)</td>
</tr>
</tbody>
</table>

#### 10.4.6 Preconditioning Options

Iterative linear solvers often require the assistance of a preconditioner to efficiently compute a solution of the linear system

$$Ax = b$$

(10.1)

to the requested accuracy. A preconditioner, $M$, is an approximation to the original matrix $A$ that is inexpensive to solve. Then (10.1) can be rewritten to include this (right) preconditioner as

$$AM^{-1}y = b,$$

(10.2)

where $x = M^{-1}y$ is the solution to the original linear system. If $M = A$, then the solution to the linear system is found in one iteration. In practice, $M$ is a good approximation to $A$, then it will take few iterations to compute the solution of the linear system to the requested accuracy. By default, Xyce uses a non-overlapped additive Schwartz preconditioner with an incomplete LU
factorization on each subdomain [22]. The parameters of the incomplete LU factorization are found in Table 10.6. This is a simple preconditioner that always works, but is not always the most effective, so other preconditioning options will be presented in this section.

**Xyce** provides access to preconditioning packages in Trilinos [20], such as Ifpack and ML (optional), through an expanded preconditioning interface. If modifications to the preconditioner are necessary, the user may specify the preconditioner through the '.OPTIONS LINSOL' control line in the netlist. Table 10.6 provides a list of preconditioner parameters and their default values.

### Table 10.6. Preconditioner options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>prec_type</td>
<td>Preconditioner</td>
<td>Ifpack</td>
</tr>
<tr>
<td>AZ_ilut_fill</td>
<td>ILU fill level</td>
<td>2.0</td>
</tr>
<tr>
<td>AZ_drop</td>
<td>ILU drop tolerance</td>
<td>1.0e-3</td>
</tr>
<tr>
<td>AZ_overlap</td>
<td>ILU subdomain overlap</td>
<td>0</td>
</tr>
<tr>
<td>AZ_atthresh</td>
<td>ILU absolute threshold</td>
<td>0.0001</td>
</tr>
<tr>
<td>AZ_rthresh</td>
<td>ILU relative threshold</td>
<td>1.0001</td>
</tr>
<tr>
<td>ML_MAX_LEVEL</td>
<td>ML maximum allowable levels</td>
<td>5</td>
</tr>
<tr>
<td>USE_IFPACK_FACTORY</td>
<td>Additive Schwarz w/ KLU subdomain solve</td>
<td>0 (false)</td>
</tr>
<tr>
<td>USE_AZTEC_PRECOND</td>
<td>Use native ILU from AztecOO package</td>
<td>0 (false)</td>
</tr>
</tbody>
</table>

In practice, the choice of an effective preconditioner is highly problem dependent. By default, **Xyce** provides a preconditioner that works for most circuits, but is not the best preconditioner for all circuits. One simple modification to the default preconditioner that often makes it more effective is the use of a sparse direct solver on each subdomain, instead of an inexact factorization:

`.OPTIONS LINSOL USE_IFPACK_FACTORY=1`

This preconditioner will fail if there is a singular subdomain matrix because the KLU solver on that subdomain will fail. If numerical difficulties are not encountered during the simulation, this preconditioner is superior to inexact factorizations. A more advanced preconditioner that has been effective for certain types of circuits uses the block triangular form (BTF) permutation of the original matrix before generating the additive Schwartz preconditioner. This preconditioner, which is published in [23], will be presented in Section 10.5.4.

### 10.4.7 ShyLU

ShyLU is a package in Trilinos [20] that provides a hybrid linear solver designed to be a black-box algebraic solver [24]. ShyLU support is optionally built in **Xyce**, so it is not available by default in any **Xyce** build or provided binary. Furthermore, to enable ShyLU support in **Xyce**, it is necessary to build the ShyLU package in Trilinos.

ShyLU is hybrid in both the parallel programming sense - using MPI and threads - and in the mathematical sense - using features from direct and iterative methods. **Xyce** uses ShyLU as a global Schur complement solver [22]. This solver can be expensive, but also has proven to be a robust and scalable approach for some circuit matrices [25].
ShyLU is under active development and testing in Xyce, so a minimum number of options are provided to the user for controlling this solver. The solution approach is static, the diagonal blocks of the partitioned matrix are solved using KLU, while the Schur complement is solved using an iterative method (AztecOO's GMRES specifically). The matrix partitioning is generated using a wide separator, which is a conventional vertex separator where all the vertices that are adjacent to the separator in one of the subgraphs are added in. The only options that can be modified are shown in Table 10.7. This includes the maximum number of iterations and solver tolerance used by GMRES and the dropping threshold that ShyLU uses to generate a preconditioner for GMRES.

Table 10.7. ShyLU linear solver options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ_max_iter</td>
<td>Maximum allowed iterations</td>
<td>30</td>
</tr>
<tr>
<td>AZ_tol</td>
<td>Iterative solver (relative residual) tolerance</td>
<td>1.0e-12</td>
</tr>
<tr>
<td>ShyLU_rthresh</td>
<td>Relative dropping threshold for Schur complement preconditioner</td>
<td>1.0e-3</td>
</tr>
<tr>
<td>OUTPUT_LS</td>
<td>Write out linear systems solved by ShyLU to file every # solves</td>
<td>0 (false)</td>
</tr>
<tr>
<td>OUTPUT_BASE_LS</td>
<td>Write out linear systems before any transformations to file every # solves</td>
<td>0 (false)</td>
</tr>
</tbody>
</table>

10.5 Transformation Options

Transformations are often used to permute the original linear system to one that is easier or more efficient for direct or iterative linear solvers. Xyce has many different permutations that can be applied to remove dense rows and columns from a matrix, reduce fill-in, find a block triangular form, or partition the linear system for improved parallel performance.

10.5.1 Removing Dense Rows and Columns

The transformation that reduces the linear system through removal of all rows and columns with single non-zero entries in the matrix is called singleton filtering. The values associated with these removed entries can be resolved in a pre- or post-processing phase with the linear solve. A byproduct of this transformation is a more tractable and sparse linear system for the load balancing and linear solver algorithms. This functionality can be turned on by adding ‘TR_SINGLETON_FILTER=1’ to the ‘.OPTIONS LINSOL’ control line in the netlist. This option is enabled by default whenever iterative solvers are used in Xyce.

10.5.2 Reordering the Linear System

Approximate Minimum Degree (AMD) ordering is a symmetric permutation that reduces the fill-in for direct factorizations. If given a nonsymmetric matrix $A$, the transformation computes the AMD
ordering of $A + A^T$. This functionality may be turned on by adding `TR_AMD=1` to the `.OPTIONS LINSOL` control line in the netlist. For parallel builds of Xyce, AMD ordering is enabled by default whenever iterative solvers are used. In parallel, the AMD ordering is performed only on the local graph for each processor, not the global graph. This is to reduce the fill-in for the incomplete LU factorization used by the additive Schwartz preconditioner, see Section 10.4.6.

### 10.5.3 Partitioning the Linear System

Partitioning subdivides the linear system and then distributes it to the available processors. A good partition can have a dramatic effect on the parallel performance of a circuit simulation tool. There are two key components to a good partition:

- Effective load balance
- Minimizing communication overhead.

An effective load balance ensures the computational load of the calculation is equally distributed among available processors. Minimizing communication overhead seeks to distribute the problem in a way to reduce impacts of underlying message passing during the simulation run. For runs with a small number of devices per processor the communication overhead becomes the critical issue, while for runs with larger numbers of devices per processor the load balancing becomes more important.

Xyce provides hypergraph partitioning via the Zoltan library of parallel partitioning heuristics integrated into Xyce. The Isorropia package in Trilinos provides access to Zoltan and can be controlled through the `.OPTIONS LINSOL` control line in the netlist. Table 10.8 provides the partitioning options and their default parameters. For parallel builds of Xyce, when iterative solvers are used, Isorropia is enabled by default to use hypergraph partitioning. The linear system is statically load balanced at the beginning of the simulation based on the graph of the Jacobian matrix.

**Table 10.8. Partitioning options.**

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR_PARTITION</td>
<td>Partitioning package</td>
<td>0 (none), serial, 1 (Isorropia), parallel</td>
</tr>
<tr>
<td>TR_PARTITION_TYPE</td>
<td>Isorropia partitioner type</td>
<td>HYPERGRAPH</td>
</tr>
</tbody>
</table>

Xyce includes an expanded partitioning interface to allow the user to access multiple partitioners through Isorropia. Users may change the partitioner provided by adding `TR_PARTITION_TYPE` to the `.OPTIONS LINSOL` control line in the netlist. There are two options for partitioning: hypergraph (`TR_PARTITION_TYPE=HYPERGRAPH`) and, optionally, graph (`TR_PARTITION_TYPE=GRAPH`) partitioning through ParMETIS. Occasionally it is desirable to turn off the partitioning option, even for parallel simulations. To do so, users can add the `TR_PARTITION=0` to the `.OPTIONS LINSOL` control line.
These techniques can be very effective for improving the efficiency of the iterative linear solvers. See the \textit{Zoltan User Guide} \cite{Zoltan} for more details.

\section*{10.5.4 Permuting the Linear System to Block Triangular Form}

The block triangular form (BTF) permutation is often useful for direct and iterative solvers, enabling a more efficient computation of the linear system solution. In particular, the BTF permutation has shown promise when it is combined with an additive Schwartz preconditioner (see Section 10.4.6) in the simulation of circuits with unidirectional flow.

The global BTF transformation computes the permutation of the linear system to block triangular form, and uses the block structure to partition the linear system. The partitioning can be a simple linear distribution of block rows, \texttt{TR\_GLOBAL\_BTF=1}, or a hypergraph partitioning of block rows, \texttt{TR\_GLOBAL\_BTF=2}. As the global BTF transformation includes elements of other transformations, it is imperative to turn off other linear solver options. To use the global BTF, the linear solver control line in the netlist should contain:

\begin{verbatim}
.OPTIONS LINSOL TR\_GLOBAL\_BTF=<1,2> TR\_SINGLETON\_FILTER=1 + TR\_AMD=0 TR\_PARTITION=0
\end{verbatim}

This transformation is only useful in parallel when using a preconditioned iterative solver. It is often more effective when combined with the exact factorization of each subdomain, given by the \texttt{USE\_IFPACK\_FACTORY=1} option. In practice, the structure that this transformation takes advantage of is found in CMOS memory circuits \cite{CMOS_memory}.

\section*{10.6 Device Distribution Options}

\texttt{Xyce} uses different parallel distributions for the objects that evaluate the device models and the linear system. As discussed in Section 10.5.3, a good parallel partition of the linear system can improve load balance and minimize communication. The same is true for the parallel distribution of devices, since they have widely varying computational cost and the circuit connectivity graph is often irregular. Furthermore, a more efficient device distribution strategy can overlap netlist processing with the simulation setup, enabling scalable parsing for larger netlists.

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRATEGY</td>
<td>Distribution strategy</td>
<td>0</td>
</tr>
</tbody>
</table>

\texttt{Xyce} provides three different device distribution strategies that can be controlled through the \texttt{.OPTIONS DIST} control line in the netlist, see Table 10.9. The default strategy (\texttt{STRATEGY=}0) that \texttt{Xyce} uses for parallel device distribution is a first-come-first-served approach, in that the total number of devices in a circuit is divided evenly over the number of parallel processors in the order
of parsing. This is the simplest distribution strategy, but it does not take into account the connectivity of a circuit or balance device model computation. Therefore, this strategy can exhibit parallel imbalance for post-layout circuits that have a substantial portion of parasitic devices.

_Xyce_ provides two other distribution strategies that enable scalable parsing for flattened circuits or distribute devices in a more balanced manner. The "flat round robin" strategy (STRATEGY=1) will generate the same device distribution as the default strategy, but every parallel processor will participate in reading their portion of the netlist. In that way, this strategy provides a more scalable setup than the default strategy, but can only be applied to flattened (non-hierarchical) netlists. The "device balanced" strategy (STRATEGY=2) will evenly divide each of the device types over the number of parallel processors, so each processor will have a balanced number of each model type. This alleviates the parallel imbalance in the device model computation that can be experienced with post-layout circuits. However, it does not take into account the circuit connectivity, so the communication will not be minimized by this strategy.
11. Handling Power Node Parasitics

Chapter Overview

This chapter includes the following sections:

- Section 11.1 Power Node Parasitics
- Section 11.2 Two Level Algorithms Overview
- Section 11.3 Examples
- Section 11.4 Restart
11.1 Power Node Parasitics

Parasitic elements (R, L, C) are frequently required for circuit simulations to capture important circuit behavior. Most parasitic elements (interconnects, etc.) can be added to netlists without causing any difficulties for the Xyce solvers. Small circuits in particular are very robust to the addition of parasitic elements. Larger circuits, however, that must be simulated in parallel will in general tend to have more solver difficulties with the addition of parasitic devices. Of particular note are parasitic elements attached to the power and/or ground nodes of large digital circuits. An example of this is shown in figure 11.1. As these nodes tend to be highly connected, they can potentially have a very high impact on solver difficulties.

One of the parallel algorithms used by Xyce is called singleton removal [23], which is applied at the linear solver level and is crucial for getting many large circuits to run in parallel. This algorithm takes advantage of the fact that, in circuit simulation, some solution values are available explicitly, rather than being a quantity that needs to be calculated as the solution to a particular equation. In circuit simulation, such quantities are usually the values of independent sources. For instance, the presence of an independent voltage source at a particular node in a circuit fixes the voltage at that node to be the value of the independent source; therefore, equations reflecting the value of the voltage at that particular node do not have to be added to the set of linear equations used (in part) to determine the voltages at all the nodes in the circuit. The technique of fixing such node voltages without including them in the rest of the linear solve can be handled in a preprocessing phase referred to as the singleton removal phase.

When simulating in parallel, singleton removal is crucial as some voltage sources (especially power supplies in digital circuits) are connected to hundreds or thousands of circuit nodes. This presents a big problem in parallel because having numerous connections can often mean a communication bottleneck during the linear solve. Using singleton removal eliminates that bottleneck.

While singleton removal can result in a great improvement for circuits with ideal power supplies, for circuits with nonideal power supplies, the communication bottleneck remains. Once parasitic elements are placed between the power supply and the rest of the circuit, it is only the voltage at the circuit node directly connected to the independent source that can be removed via singleton removal. Other nodes connected to this independent source through parasitic elements have

![Figure 11.1. Power node parasitics example. NOTE: An RLC network sits between the VDD, VSS sources and the main circuit, so these highly connected nodes cannot be removed with a singleton filter.](image)
voltagesthat must now be solved for directly.

11.2 Two Level Algorithms Overview

Fortunately, Xyce [19] provides a workaround that allows power node parasitics to be included in large circuits without breaking singleton removal. The workaround requires the use of a two-level Newton solve, in which the problem is divided into two very separate pieces, each for the most part treated as an entirely separate circuit with minimal coupling terms linking the pieces together.

For power-node problems, two-level users will typically split the netlist into "top" and "inner" netlists. The top netlist contains the power node parasitics and the ideal voltage sources, and very little else. The inner circuit should contain the rest of the circuit. Xyce couples the two circuits through an "EXT" (external) device in the top circuit, and two or more independent voltage sources on the inner circuit. The values on the inner voltages are imposed from the top circuit, and the currents and conductances of the EXT device come from the inner circuit. An example is given below.

Xyce will construct a different linear system for each circuit. As such, the inner circuit will appear to have independent sources, allowing the singleton removal algorithm to work.

Since at least the 1980s, literature has included the two-level Newton algorithm, although mostly as it applied to circuit-device simulation. [27] and [28] provide a mathematical description, while [19] provides more information about the Xyce implementation.

11.3 Examples

11.3.1 Explanation and Guidance

Figures 11.2 and 11.3 provide an example of a circuit that uses the two level algorithm. The top circuit (compTop.cir) invokes the inner circuit (compInner.cir) with the extern device, y1. To run this circuit, the user will only specify the top circuit on the command line:

Xyce compTop.cir <return>

The extern device (YEXT y1 sits between the contents of compTop.cir and compInner.cir and is connected to two nodes in the top-level circuit, DD1 and SS1. From the perspective of compTop.cir, the YEXT y1 device looks like a nonlinear two-terminal resistor, which is the equivalent of the entire inner circuit.

In the inner circuit, Xyce applies nodes DD1 and SS1 though the independent sources Vconnect0000 and Vconnect0001. By convention, the inner circuit must contain an independent voltage source for each node to which the EXT device is connected. The default naming convention requires that these sources be named vconnectxxxx, with xxxx being a four-digit integer starting at 0000.

NOTE: The .tran statement on the inner circuit must match the .tran statement on the top circuit. The same is true for the .DC analysis statements. Also, as both circuit files have their own .print
**Figure 11.2.** Two-level top netlist example.

statements, both will produce *.prn output files.

The coupling between the top and inner layers requires extra linear solves, so when using this algorithm the code will run more slowly. In general, one can expect a factor-of-two slowdown, for circuits that can be run either as conventional or two-level simulations. So, in practice this algorithm should only be applied when it is really needed (i.e., when conventional simulations fail).

Finally, when using this two-level method, one must take particular care with file names. In practice, a Xyce user may frequently change netlist file names to reflect new details about the run. When this happens, the name of the netlist invoked on the `YEXT y1` line must be changed. Failure to do so may result in using the wrong file for the inner simulation.

## 11.4 Restart

Restart works with the two-level algorithm. However, as the two-level algorithm involves two separate netlist input files, a two-level restart requires a separate restart file for each phase of the problem. So, the two files (e.g., `compTop.cir` and `compInner.cir`) require `.options restart` statements, and the statements in the two files must be consistent with each other. *The user must enforce this*, because the Xyce code does not check consistency between the top and inner file `.options restart` statements.
THIS CIRCUIT IS THE INNER PART OF A TWO LEVEL EXAMPLE.

* compInner.cir - BSIM3 Transient Analysis

M1 Anot A DD1 DD1 PMOS w=3.6u l=1.2u
M2 Anot A SS1 SS1 NMOS w=1.8u l=1.2u
M3 Bnot B DD1 DD1 PMOS w=3.6u l=1.2u
M4 Bnot B SS1 SS1 NMOS w=1.8u l=1.2u
M5 AorBnot SS1 DD1 DD1 PMOS w=1.8u l=3.6u
M6 AorBnot B 1 SS1 NMOS w=1.8u l=1.2u
M7 1 Anot SS1 SS1 NMOS w=1.8u l=1.2u
M8 Lnot SS1 DD1 DD1 PMOS w=1.8u l=3.6u
M9 Lnot Bnot 2 SS1 NMOS w=1.8u l=1.2u
M10 2 A SS1 SS1 NMOS w=1.8u l=1.2u
M11 Qnot SS1 DD1 DD1 PMOS w=3.6u l=3.6u
M12 Qnot AorBnot 3 SS1 NMOS w=1.8u l=1.2u
M13 3 Lnot SS1 SS1 NMOS w=1.8u l=1.2u
MQL0 8 Qnot DD1 DD1 PMOS w=3.6u l=1.2u
MQL1 8 Qnot SS1 SS1 NMOS w=1.8u l=1.2u
MLT0 9 Lnot DD1 DD1 PMOS w=3.6u l=1.2u
MLT1 9 Lnot SS1 SS1 NMOS w=1.8u l=1.2u
CQ Qnot 0 30f
CL Lnot 0 10f

Vconnect0000 DD1 0 0
Vconnect0001 SS1 0 0

Va A 0 pulse(0 5 10ns .ins .ins 15ns 30ns)
Vb B 0 0

.model nmos nmos (level=9)
.model pmos pmos (level=9)
.options linsol type=klu
.options timeint abstol=1.0e-6 reltol=1.0e-3
.tran 0.01ns 60ns
.print tran v(a) v(b) 1.0+v(9) 1.0+v(8)

.END

Figure 11.3. Two-level inner netlist example.
12. Specifying Initial Conditions

Chapter Overview

This chapter includes the following sections:

- Section 12.1 Initial Conditions Overview
- Section 12.2 Device Level IC= Specification
- Section 12.3 .IC and .DCVOLT Initial Condition Statements
- Section 12.4 .NODESET Initial Condition Statements
- Section 12.5 .SAVE Statements
- Section 12.6 UIC and NOOP
12.1 Initial Conditions Overview

*Xyce* provides several different options for users to set an initial condition. Reasons for setting initial conditions include, but are not limited to:

- Improving the robustness of the DCOP solution
- Optimizing performance by reusing a DCOP solution of a previous run to start new transient runs
- Setting an initial state for a digital circuit
- Initiating an oscillator circuit.

As noted, setting initial conditions can be particularly useful for multistate digital circuits. Figure [12.1](#) provides an example result demonstrating how initial conditions can be used to set the state of a digital circuit. In this case, obtaining the state purely through transient simulation can be time-consuming and often is not practical.

![Figure 12.1](#)

*Figure 12.1*. Example result with (left) and without (right) an IC on the output. NOTE: The preset example, with an IC, starts in the initial state directly out of the DCOP calculation, while the non-preset example requires a long transient to equilibrate.
12.2 Device Level IC= Specification

Many devices in Xyce support setting initial junction voltage conditions on the device instance line with the IC= keyword. This is frequently used to set the state of digital circuits. Figure 12.2 presents a simple inverter example demonstrating the use of IC= on a BSIMSOI device. In this example, the two initial conditions are specified as a vector, which is the preferred syntax. The initial conditions can also be specified separately (e.g., IC1=2 IC2=0).

While many circuit simulators have a similar IC= capability, Xyce implementation differs in some important respects. For any device with an IC= statement, Xyce enforces the junction drop in parallel with the device junction as a voltage source in parallel with the device. Xyce then applies the parallel voltage source through the DCOP calculation, and then removes it prior to the beginning of the transient. This strongly enforces the requested junction drop, meaning that if the DCOP converges, the requested voltage drop will be in the solution. In many other circuit codes, Xyce applies IC= as a weaker constraint, with the intent of improving DCOP calculation robustness.

IC= can be applied to the following devices: BSIM3, BSIM4, BSIMSOI, Capacitor, Inductor and Digital Behavioral Devices (U and Y).

```
MOS LEVEL=10 INVERTER WITH IC=

.subckt INV IN OUT VDD GND
MN1 OUT IN GND GND GND NMOS w=4u  l=0.15u IC=2,0
MP1 OUT IN VDD GND VDD PMOS w=10u  l=0.15u
.ends

.tran 20ns 30us
.print tran v(vout) v(in)+1.0 v(1)

VDDdev VDD 0 2V
RIN IN 1 1K
VIN1 1 0 2V PULSE (2V 0V 1.5us 5ns 5ns 1.5us 3.01us)
R1 VOUT 0 10K
C2 VOUT 0 0.1p
XINV1 IN VOUT VDD 0 INV
.MODEL NMOS NMOS ( LEVEL = 10 )
.MODEL PMOS PMOS ( LEVEL = 10 )

.END
```

**Figure 12.2.** Example netlist with device-level IC=.
12.3  .IC and .DCVOLT Initial Condition Statements

.IC and .DCVOLT are equivalent methods for specifying initial conditions. How Xyce applies them, however, depends on whether the UIC parameter, discussed in a following subsection, is present on the .TRAN line. If UIC is not specified, then Xyce applies the conditions specified by .IC and .DCVOLT statements throughout the DCOP phase, ensuring the specified values will be the solved values at the end of the DCOP calculation. Xyce allows unspecified variables to find their computed values, consistent with the imposed voltages.

```
RC circuit
  .ic v(1)=1.0
  c1 1 0 1uF
  R1 1 2 1K
  v1 2 0 0V
  .print tran v(1)
  .tran 0 5ms
  .options timeint reltol=1e-6 abstol=1e-6
  .end
```

Figure 12.3. Example netlist with .IC. NOTE: Without the .IC statement, the capacitor is not given an initial charge, and the transient signals are flat. With the .IC statement, it has an initial charge, which then decays in transient. Without the .IC statement, the capacitor is not given an initial charge, and the signals in transient are all flat. With the .IC statement, it has an initial change which then decays in transient.

If UIC is specified on the .TRAN line, then Xyce skips the DCOP calculation altogether, and uses the values specified on .IC and .DCVOLT lines as the initial values for the transient calculation. Unspecified values are set to zero.

For the UIC and non-UIC cases, Xyce ignores specified values that do not correspond to existing circuit variables. Finally, the .IC capability can only set voltage values, not current values.

12.3.1 Syntax

```
  .IC V(node1) = val1 <V(node2) = val2> ...
  .DCVOLT V(node1) = val1 <V(node2) = val2> ...
```

where: val1, val2, ... specify nodal voltages and node1, node2, ... specify node numbers.
12.3.2 Example

.IC V(1) = 2.0 V(A) = 4.5
.DCVOLT 1 2.0 A 4.5

Fig. 12.3 provides a more complete example (showing a full netlist).
12.4 .NODESET Initial Condition Statements

.NODESET is similar to .IC, except that Xyce enforces the specified conditions less strongly. For .NODESET simulations, Xyce performs two nonlinear solves for the DCOP condition. For the first solve, Xyce enforces the .NODESET values throughout the solve, similar to .IC. For the second solve, Xyce uses the result of the first solve as an initial guess, and allows all the values to float and eventually obtain their unconstrained, self-consistent values. As such, the computed values will not necessarily match the specified values.

If used with UIC or NOOP [12.6], .NODESET behaves the same as .IC and .DCVOLT.

12.4.1 Syntax

.NODESET V(node1) = val1 <V(node2) = val2> ...
.NODESET node1 val1 <node2 val2>

where: val1, val2, ... specify nodal voltages and node1, node2, ... specify node numbers.

12.4.2 Example

.NODESET V(1) = 2.0 V(A) = 4.5
.NODESET 1 2.0 A 4.5
12.5 .SAVE Statements

_Xyce_ stores operating point information using `.SAVE` statements, and can then reuse that information to start subsequent transient simulations. Using `.SAVE` results in solution data being stored in a text file, comprised of `.NODESET` or `.IC` statements. This file can be applied to other simulations using `.INCLUDE`.

The `.SAVE` syntax is as follows:

```
.SAVE [TYPE=<IC|NODESET>] [FILE=<filename>] [LEVEL=<all|none>] + [TIME=<save_time>]
```

where:

The `TYPE` can be set to `NODESET` or `IC`. By default, it will be `NODESET`.

The `FILE` is the user-specified output file name for the output file. If this is not specified, _Xyce_ uses `netlist.cir.ic`.

The `LEVEL` is an HSPICE compatibility parameter. _Xyce_ supports `ALL` and `NONE`. If `NONE` is specified, then no save file is created. The default `LEVEL` is `ALL`.

`TIME` is an HSPICE compatibility parameter. This is unsupported in _Xyce_. _Xyce_ outputs the save file only at time=0.0.
12.6 UIC and NOOP

As noted earlier, the **UIC** key word on the **TRAN** line will disable the DCOP calculation, and result in **Xyce** immediately going to transient. If the user specifies **.IC**, **.NODESET**, or **.DCOP input**, then the transient calculation will use the specified initial values as the initial starting point. The **NOOP** keyword works exactly the same way as **UIC**.

```
pierce oscillator
 c1 1 0 100e-12
 c2 3 0 100e-12
 c3 2 3 99.5e-15
 c4 1 3 25e-12
 l1 2 4 2.55e-3
 r1 1 3 1e5
 r2 3 5 2.2e3
 r3 1 4 6.4
 v1 5 0 12
 Q1 3 1 0 NBJT
 .MODEL NBJT NPN (BF=100)
 .print tran v(2) v(3)
 .tran 1ns 1us UIC
 .ic v(2)=-10000.0 v(5)=12.0
```

**Figure 12.4.** Example netlist with UIC.

NOTE: This circuit is a pierce oscillator, which only oscillates if the operating point calculation is skipped. If the **.IC** statement is not included, the oscillator will take a long time to achieve its steady-state amplitude. By including the **.IC** statement, the amplitude of node 2 is preset to a value close to its final steady-state amplitude. The transient in this example only runs for 10 cycles as a demonstration. In general, the time scales for this oscillator are much longer and require millions of cycles.

12.6.1 Example

```
.tran 1ns 1us UIC
.tran 1ns 1us NOOP
```

Some circuits, particularly oscillator circuits, will only function properly if the operating point calculation is skipped, as they need an inconsistent initial state to oscillate. Figure 12.4 presents a Pierce oscillator example.
Chapter Overview

This chapter includes the following sections:

- Section 13.1 Introduction
- Section 13.2 Ground Synonym Replacement
- Section 13.3 Removal of Unused Components
- Section 13.4 Adding Resistors to Dangling Nodes
13.1 Introduction

In an effort to make Xyce more compatible with other commercial circuit simulators (e.g., HSPICE), some optional tools have been added to increase the netlist processing capabilities of Xyce. These options, which occur toward the beginning of a simulation, have been incorporated not only to make Xyce more compatible with different (i.e. non-Xyce) netlist syntaxes, but also to help detect and remove certain singular netlist configurations that can often cause a Xyce simulation to fail. Because all of the commands described in this section occur as a precursory step to setting up a Xyce simulation, they are all invoked in a netlist file via the keyword .PREPROCESS. This chapter describes each of the different functionalities that can be invoked via a .PREPROCESS statement in detail and provides examples to illustrate their use.

13.2 Ground Synonym Replacement

In certain versions of SPICE, keywords such as GROUND, GND, and GND! can be used as node names in a netlist file to represent the ground node of a circuit. Xyce, however, only recognizes node 0 as an official name for ground. Hence, if any of the prior node names is encountered in a netlist file, Xyce will treat these as different nodes from ground. To illustrate this point, consider the netlist of figure 13.1. When the node Gnd is encountered in the definition of resistor R3, Xyce instantiates this as a new node. The schematic diagram corresponding to this netlist (figure 13.2) shows that the resistor R3 is “floating” between node 2 and a node with only a single device connection, node Gnd. When Xyce executes the netlist of figure 13.1, the voltage V(2) will evaluate to 0.5V.

![Circuit with "floating" resistor R3](image)

**Figure 13.1.** Example netlist where Gnd is treated as being different from node 0.

If one would rather treat Gnd the same as node 0 in the above example, use the figure 13.3 netlist instead. When the statement .PREPROCESS REPLACEGROUND TRUE is present in a netlist, Xyce will treat any nodes named GND, GND!, GROUND, or any capital/lowercase variant of these keywords (e.g., gR0unD) as synonyms for node 0. Hence, according to Xyce, the figure 13.3 netlist corresponds to figure 13.4 schematic diagram, and the voltage V(2) will evaluate to 0.33V.

NOTE: Only one .PREPROCESS REPLACEGROUND statement is allowed per netlist file. This constraint...
Figure 13.2. Circuit diagram corresponding to the netlist of figure 13.1 where node Gnd is treated as being different from node 0.

Circuit where resistor R3 does *not* float

V1 1 0 1
R1 1 2 1
R2 2 0 1
R3 2 Gnd 1

.PREPROCESS REPLACEGROUND TRUE

.DC V1 1 1 0.1
.PRINT DC V(2)
.END

Figure 13.3. Example netlist where Gnd is treated as a synonym for node 0.

Figure 13.4. Circuit diagram corresponding to figure 13.3 where node Gnd is treated as a synonym for node 0.
prevents the user from setting REPLACEGROUND to TRUE on one line and then to FALSE on another line. Also, there is no way to differentiate between different keywords. So, for example, it is not possible to treat GROUND as a synonym for node 0 while allowing GND to represent an independent node. If REPLACEGROUND is set to TRUE, **Xyce** will treat both of these keywords as node 0.

### 13.3 Removal of Unused Components

Consider a slight variant of the circuit in figure 13.3 with the netlist given in figure 13.5. Here, the resistor R3 is connected in a peculiar configuration: both terminals of the resistor are tied to the same circuit node, as is illustrated in figure 13.6. Clearly, the presence of this resistor has no effect on the other voltages and currents in the circuit since, by the very nature of its configuration, it has no voltage across it and, hence, does not draw any current. Therefore, in some sense, the component can be considered as “unused.” The presence of a resistor such as R3 is rarely or never introduced by design, rather the presence of such components is the result of either human or automated error during netlist creation.

![Circuit with an unused resistor R3](image)

**Figure 13.5.** Netlist with a resistor R3 whose device terminals are both the same node (node 2).

While the presence of the resistor R3 in figure 13.3 does not change the behavior of the circuit, it adds an additional component to the netlist **Xyce** must include when solving for the voltages and currents in the circuit. If the number of such components in a given netlist is large, it is potentially desirable to remove them from the netlist to ease the burden on **Xyce**’s solver engines. This, in turn, can help to avoid possible convergence issues. For example, even though the netlist in figure 13.5 will run properly in **Xyce**, the netlist of figure 13.7 will abort. The voltage source V2 attempts to place a 1V difference between its two device terminals; however, as both nodes of the voltage source are the same, the voltage source is effectively shorted.

**Xyce** includes the following command to prevent similar situations:

```
.PREPROCESS REMOVEUNUSED <component list>
```

where `<component list>` is a list of device types separated by commas. For each device type specified in the list, **Xyce** checks for instances of that device type for which all of the device’s
Figure 13.6. Circuit of figure 13.5 containing a resistor R3 whose terminals are tied to the same node (node 2).

Figure 13.7. Circuit with improperly connected voltage source V2.

Circuit with improperly connected voltage source V2

V1 1 0 1
R1 1 2 1
R2 2 0 1
V2 2 2 1

.DC V1 1 1 0.1
.PRINT DC V(2)
.END
terminals are connected to the same node. If such a device is found, **Xyce** removes that device from the netlist. For instance, when executing the netlist of figure [13.8], **Xyce** will seek out such devices and remove them from the netlist. This causes the resistor R3 to be removed from the netlist. Figure [13.9] presents the schematic of the resulting **Xyce**-simulated circuit. NOTE: The presence of “C” in the **REMOVEUNUSED** statement does not cause **Xyce** to abort even though there are no capacitors in the netlist. Also, as in the case of a **REPLACEGROUND** statement, only one **PREPROCESS REMOVEUNUSED** line may be present in a netlist, or **Xyce** will abort.

Table [13.1] lists devices that can be removed via a **REMOVEUNUSED** statement. In the case of MOS-FETs and BJTs, three device terminals must be the same (the gate, source, and drain in the case of a MOSFET; the base, collector, and emitter in the case of a BJT) to remove either device from the netlist.

![Circuit with improperly connected voltage source V2](image)

**Figure 13.8.** Circuit with an “unused” resistor R3 removed from the netlist.

![Circuit of figure 13.8 where resistor R3 has been removed via the .PREPROCESS REMOVEUNUSED statement](image)

**Figure 13.9.** Circuit of figure 13.8 where resistor R3 has been removed via the .PREPROCESS REMOVEUNUSED statement.

Table 13.1: List of keywords and device types which can be used in a .PREPROCESS REMOVEUNUSED statement.

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Device Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Capacitor</td>
</tr>
</tbody>
</table>

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Table 13.1: List of keywords and device types which can be used in a .PREPROCESS REMOVEUNUSED statement.

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Device Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Diode</td>
</tr>
<tr>
<td>I</td>
<td>Independent Current Source</td>
</tr>
<tr>
<td>L</td>
<td>Inductor</td>
</tr>
<tr>
<td>M</td>
<td>MOSFET</td>
</tr>
<tr>
<td>Q</td>
<td>BJT</td>
</tr>
<tr>
<td>R</td>
<td>Resistor</td>
</tr>
<tr>
<td>V</td>
<td>Independent Voltage Source</td>
</tr>
</tbody>
</table>

13.4 Adding Resistors to Dangling Nodes

Consider the netlist of figure [13.10] and the corresponding schematic of figure [13.11]. Nodes 3 and 4 of the netlist are what we will henceforth refer to as dangling nodes. We say that node 4 dangles because it is only connected to the terminal of a single device, while we say that node 3 dangles because it has no DC path to ground. The first of these situations—connection to a single device terminal only—can arise, for example, in a netlist which contains nodes representing output pins that are not connected to a load device. For instance, the resistance $R_2$ in figure [13.10] could represent the resistance of an output pin of a package that is meant to drive resistive loads. Hence, an actual physical implementation of the circuit of figure [13.11] would normally include a resistor between node 4 and ground, but, in creating the netlist, the presence of such an output load has been (either intentionally or unintentionally) left out.

The second situation—where a node has no DC path to ground—is sometimes an effect that is purposely incorporated into a design (e.g., the design of switched capacitor integrators (e.g., see [29], chapter 10), but oftentimes it is also the result of some form of error in the process of creating the netlist. For instance, when graphical user interfaces (GUIs) are used to create circuit schematics that are then translated into netlists via software, one very common unintentional error is to fail to connect two nodes that are intended to be connected. To illustrate this point, consider the schematic of figure [13.12]. The schematic seems to indicate that the lower terminal of resistor $R_2$ should be connected to node 3. This is not the case as there is a small gap between node 3 and the line intended to connect node 3 to the resistor. Such an error can often go unnoticed when creating a schematic of the netlist in a GUI. Thus, when the schematic is translated into a netlist file, the resulting netlist would not connect the resistor to node 3 and would instead create a new node at the bottom of the resistor, resulting in the circuit depicted in figure [13.11].

While neither of the previous situations is necessarily threatening (Xyce will run the figure [13.10] netlist successfully to completion), there are times when it is desirable to somehow make a dangling node not dangle. For instance, returning to the example in which the resistor $R_2$ represents the resistance of an output pin, one may want to simulate the circuit when a 1K load is attached between node 4 and ground in figure [13.11]. In the case where a node has no DC path to ground, the situation is slightly more dangerous if, for instance, the node in question is also connected to a high-gain device such as the gate of a MOSFET. As the DC gate bias has a great impact on the DC current traveling through the drain and source of the transistor, not having a well-defined DC gate voltage can greatly degrade the simulated performance of the circuit.
Circuit with two dangling nodes, nodes 3 and 4

V1 1 0 1
R1 1 2 1
C1 2 3 1
C2 3 0 1
R2 2 4 1

.DC V1 0 1 0.1
.PRINT DC V(2)
.END

Figure 13.10. Netlist of circuit with two dangling nodes, nodes 3 and 4.

Figure 13.11. Schematic of netlist in figure 13.10.

In both prior examples, the only true way to “fix” each of these issues is to find all dangling nodes in a particular netlist file and augment the netlist at/near these nodes to obtain the desired behavior. If, however, the number of components in a circuit is very large (say on the order of hundreds of thousands of components), manually augmenting the netlist file for each dangling node becomes a practical impossibility if the number of such nodes is large.

Hence, it is desirable for **Xyce** to be capable of automatically augmenting netlist files so as to help remove dangling nodes from a given netlist. The command `.PREPROCESS ADDRRESISTORS` is designed to do just this. Assuming the netlist of figure 13.13 is stored in the file `filename`, the `.PREPROCESS ADDRRESISTORS` statements will cause **Xyce** to create a new netlist file called `filename_xyce.cir` (depicted in figure 13.14). The line `.PREPROCESS ADDRRESISTORS NODCPATH 1G` instructs **Xyce** to create a copy of the netlist file containing a set of resistors of value 1 GΩ that are connected between ground and the nodes that did not have a DC path to ground. Similarly, the line `.PREPROCESS ADDRRESISTORS ONETERMINAL 1M` instructs **Xyce** to add to the same netlist file a set of resistors of value 1 MΩ that are connected between ground and devices that are connected to only one terminal. The resistor `RNODECPATH1` in figure 13.14 achieves the first of these goals while `RONETERM1` achieves the second. Figure 13.15 shows a schematic of the resulting circuit.
Some general comments regarding the use of .PREPROCESS ADDRESISTORS statements include:

- **Xyce** does not terminate immediately after the netlist file is created. In other words, if **Xyce** is run on the filename of figure 13.13 netlist, it will attempt to execute this netlist as given (i.e., it tries to simulate the circuit of figure 13.11) and generates the file filename_xyce.cir as a byproduct. It is important to point out that the resistors that are added at the bottom of the netlist file filename_xyce.cir do not get added to the original netlist when **Xyce** is running on the file filename. If one wishes to simulate **Xyce** with these resistors in place, one must run **Xyce** on filename_xyce.cir explicitly.

- The naming convention for resistors which connect to ground nodes which do not have a DC path to ground is RNODCPATH<i>, where i is an integer greater than 0; the naming conven-
* Original Netlist Title:

*Circuit with two dangling nodes, nodes 3 and 4.

V1 1 0 1
R1 1 2 1
C1 2 3 1
C2 3 0 1
R2 2 4 1

*.PREPROCESS ADDRISTORS NODCPATH 1G
* Xyce: "*.PREPROCESS ADDRISTORS" statement
* automatically commented out in netlist copy.
*.PREPROCESS ADDRISTORS ONETERMINAL 1M
* Xyce: "*.PREPROCESS ADDRISTORS" statement
* automatically commented out in netlist copy.

.DC V1 0 1 0.1
.PRINT DC V(2)

*XYCE-GENERATED OUTPUT: Adding resistors between ground
* and nodes connected to only 1 device terminal:

RONETERM1 4 0 1M

*XYCE-GENERATED OUTPUT: Adding resistors between ground
* and nodes with no DC path to ground:

RONDCPATH1 3 0 1G

.END

Figure 13.14. Output file filename_xyce.cir which results from
the .PREPROCESS ADDRISTORS statements for the netlist of figure
13.12 (with assumed file name filename).
tion is similar for nodes which are connected to only one device terminal (i.e., of the form \texttt{RONETERM<i>}). \textsc{Xyce} will not change this naming convention if a resistor with one of the above names already exists in the netlist.

Hence, if a resistor named \texttt{RNODCPATH1} exists in netlist file \texttt{filename}, and \textsc{Xyce} detects there is a node in this netlist file that has no DC path to ground, \textsc{Xyce} will add another resistor with name \texttt{RNODCPATH1} to the netlist file \texttt{filename}\_\texttt{xyce.cir} (assuming that either \texttt{.PREPROCESS ADDRESISTORS NODCPATH} or \texttt{.PREPROCESS ADDRESISTORS ONETERMINAL} are present in \texttt{filename}). If \textsc{Xyce} is subsequently run on \texttt{filename}\_\texttt{xyce.cir}, it will exit in error due to the presence of two resistors with the same name.

- Commands \texttt{.PREPROCESS ADDRESISTORS NODCPATH} and \texttt{.PREPROCESS ADDRESISTORS ONETERMINAL} do not have to be simultaneously present in a netlist file. The presence of either command will generate a file \texttt{filename}\_\texttt{xyce.cir}, and the presence of both will not generate two separate files. As with other \texttt{.PREPROCESS} commands, however, a netlist file is allowed to contain only one \texttt{NODCPATH} and one \texttt{ONETERMINAL} command each. If multiple \texttt{NODCPATH} and/or \texttt{ONETERMINAL} lines are found in a single netlist file, \textsc{Xyce} will exit in error.

- It is possible that a single node can have no DC path to ground and be connected to only one device terminal. If a \texttt{NODCPATH} and \texttt{ONETERMINAL} command are present in a given netlist file, only the resistor corresponding to the \texttt{ONETERMINAL} command is added to the netlist file \texttt{filename}\_\texttt{xyce.cir} and the resistor corresponding to the \texttt{NODCPATH} command is omitted. If a \texttt{NODCPATH} command is present but a \texttt{ONETERMINAL} command is not, then \textsc{Xyce} will add a resistor corresponding to the \texttt{NODCPATH} command to the netlist, as usual.

- In generating the file \texttt{filename}\_\texttt{xyce.cir}, the original \texttt{.PREPROCESS ADDRESISTOR} statements are commented out with a warning message. This is to prevent \textsc{Xyce} from creating the file \texttt{filename}\_\texttt{xyce.cir}\_\texttt{xyce.cir} when the file \texttt{filename}\_\texttt{xyce.cir} is run.

NOTE: This feature avoids generating redundant files. While \texttt{filename}\_\texttt{xyce.cir}\_\texttt{xyce.cir} would be slightly different from \texttt{filename}\_\texttt{xyce.cir} (e.g., a different date and time stamp), both files would functionally implement the same netlist.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{xyce.png}
\caption{Schematic corresponding to the \textsc{Xyce}-generated netlist of figure 13.14.}
\end{figure}
Chapter Overview

This chapter provides guidance for using the mesh-based device simulation capability of Xyce. It includes the following sections:

- Section 14.1 Introduction
- Section 14.2 One-Dimensional Example
- Section 14.3 Two-Dimensional Example
- Section 14.4 Doping Profile
- Section 14.5 Electrodes
- Section 14.6 Meshing
- Section 14.8 Mobility Models
- Section 14.9 Bulk Materials
- Section 14.10 Output and Visualization
14.1 Introduction

This chapter describes how to use the mesh-based device simulation functionality of Xyce, which is based on the solution a coupled set of partial differential equations (PDEs), discretized on a mesh. Such devices are often referred to as Technology Computer-Aided Design (TCAD) devices. While the rest of Xyce is intended to be similar to analog circuit simulators such as SPICE, the TCAD device capability is intended to be similar to commercial device simulators, such as PISCES [30] and DaVinci [31].

Xyce offers two different TCAD devices—a one-dimensional device and a two-dimensional device—and enables both to be invoked in the same way as a conventional lumped parameter circuit device. Generally, this capability is intended for very detailed simulation of semiconductor devices, such as diodes, bipolar transistors, and MOSFETs. As the Xyce TCAD devices can be invoked from the netlist, they can be embedded in a circuit as part of a mixed-mode simulation.

14.1.1 Equations

Kramer [32] and Selberherr [33], among others, describe device simulation equations. The most common formulation and the one used in Xyce, is the drift-diffusion (DD) formulation, which consists of three coupled PDEs (a single Poisson equation for electrostatic potential and two continuity equations; one each for electrons and holes).

Poisson equation

The electrostatic potential $\phi$ satisfies Poisson’s equation:

$$-\nabla \cdot (\epsilon \nabla \phi(x)) = \rho(x)$$  \hspace{1cm} (14.1)

where $\rho$ is the charge density and $\epsilon$ is the permittivity of the material. For semiconductor devices, local carrier densities and local doping determine charge density;

$$\rho(x) = q(p(x) - n(x) + C(x))$$  \hspace{1cm} (14.2)

Here, $p(x)$ is the spatially dependent concentration of holes; $n(x)$, the concentration of electrons; and $q$, the magnitude of the charge on an electron. $C(x)$ is the total doping concentration, which can also be represented as $C(x) = N_D^+(x) - N_A^-(x)$, where $N_D^+$ the concentration of positively ionized donors, $N_A^-$ the concentration of negatively ionized acceptors.

Species continuity equations

Continuity equations relate the convective derivative of the species concentrations to the creation and destruction of particles (“recombination/generation”).

$$\frac{\partial n(x)}{\partial t} + \nabla \cdot \Gamma_n = -R(x)$$  \hspace{1cm} (14.3)
\[ \frac{\partial p(x)}{\partial t} + \nabla \cdot \Gamma_p = -R(x) \]  

(14.4)

Here \( n \) is the electron concentration and \( p \) is the hole concentration. \( R \) is the recombination rate for both species. \( \Gamma_n \) and \( \Gamma_p \) are particle fluxes for electrons and holes, respectively. \( R \) is the recombination rate for both species, and the right hand sides are equal since creation and destruction of carriers occurs in pairs. The quantities \( \Gamma_n \) and \( \Gamma_p \) are electron and hole fluxes, and are determined from the following expressions:

\[ \Gamma_n = n(x) \mu_n E(x) + D_n \nabla n(x) \]  

(14.5)

\[ \Gamma_p = p(x) \mu_p E(x) + D_p \nabla p(x) \]  

(14.6)

\( \mu_n, \mu_p \) are mobilities for electrons and holes, and \( D_n, D_p \) are diffusion constants. \( E(x) \) is the electric field, which is given by the gradient of the potential, or \(-\partial \phi / \partial x\).

14.1.2 Discretization

Xyce uses a box-integration discretization, with the Scharfetter-Gummel method, to model the flux of charged species. For a more-detailed description of this method, refer to [32][33][34].

14.2 One Dimensional Example

While one-dimensional device simulation has limits on its usefulness, the simulation much faster than 2D, and it can provide reasonable physical predictions in many situations. Two-terminal diodes are a good candidate for one dimensional simulation, because they allow for assumptions that simplify the specification and shorten the parameter list of the device.

Figure 14.1 provides an example netlist for a simulation of a one-dimensional diode, while figure 14.2 shows its corresponding schematic. This regulator circuit is based on the principle that connecting one or more diodes in series with a resistor and a power supply will produce a relatively constant voltage. The input voltage (node 2) is a sine wave, with a frequency of 50 Hz and an amplitude of 1 V. The expected output (node 3) signal should be (mostly) flat.

14.2.1 Netlist Explanation

The model line for PDE devices serves only to set the level. The default level is 1, for a one-dimensional device. Setting level=2 will invoke two-dimensional devices. In this example, the level is not explicitly set, and so Xyce uses the default value which is 1.

The instance line is where most of the specific parameters are set for a TCAD device. In this example, the line appears as:

YPDE Z1 3 4 DIODE na=1.0e17 nd=1.0e17 graded=1 l=5.0e-4 nx=101

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PDE Diode Regulator Circuit

VP 1 0 PULSE(0 5 0.0 2.0e-2 0.0 1.0e+20 1.2e+20)
VF 2 1 SIN(0 1 50 2.0e-2)
VT1 4 0 0V
R1 2 3 1k

* TCAD/PDE Device
YPDE Z1 3 4 DIODE na=1.0e17 nd=1.0e17 graded=1 + l=5.0e-4 nx=101
.MODEL DIODE ZOD

.TRAN 1.0e-3 12.0e-2
.print TRAN format=tecplot + v(1) v(2) v(3) v(4) I(VF) I(VT1)

$options NONLIN maxstep=100 maxsearchstep=3 + searchmethod=2
$options TIMEINT reltol=1.0e-3 abstol=1.0e-6
.END

Figure 14.1. Voltage regulator circuit, using a one-dimensional TCAD diode. Figure 14.3 illustrates the result of this netlist. The PDE device instance line is in red, and the PDE device model line is in blue.

Figure 14.2. Voltage regulator schematic
The diode, Z1, is the PDE device in this example.
Doping parameters $n_a$ and $n_d$ represent the majority carrier doping levels on the N- and the P-sides of the junction, respectively. $\text{graded}=1$ is also a doping parameter, and specifies that the junction is a graded junction, rather than an abrupt step-function junction. $l=5.0\times10^{-4}$ specifies the length of the device, in cm. $nx=101$ specifies that there are 101 mesh points, including the two endpoints. For the one-dimensional device, the mesh is always uniform, so the size of each mesh cell, $\Delta x$ will be:

$$\Delta x = \frac{l}{nx - 1} = \frac{5.0\times10^{-4} \text{ cm}}{100} = 5.0\times10^{-6} \text{ cm}$$  \hspace{1cm} (14.7)

The mesh points $i = 0 \rightarrow 100$ will have the following locations, $x_i$:

$$x_i = i \Delta x$$
$$x_0 = 0.0 \text{ cm}$$
$$x_1 = 5.0\times10^{-6} \text{ cm}$$
$$x_2 = 10.0\times10^{-6} \text{ cm}$$
$$\vdots$$
$$x_{100} = 5.0\times10^{-4} \text{ cm}$$

### 14.2.2 Boundary Conditions and Doping Profile

The cited netlist example relies mostly on default parameters; therefore, it specifies nothing about electrodes, or boundary conditions, and has a minimal doping specification. A one-dimensional device can have only two electrodes connected to the circuit. The electrodes are at opposite ends of the domain, one at the first mesh point ($x=0.0$ cm, $i=0$) and the other at the opposite end of the domain, at the last mesh point ($x=5.0\times10^{-4}$ cm, $i=101$).

The electrode associated with the first mesh point ($x=0.0$ cm) is connected to the second circuit node on the instance line, while the electrode associated with the last mesh point ($x=l$) is connected to the first circuit node on the instance line. For the doping used in this example, the junction is in the exact center of the device ($x=l/2$), and the n-side is the region defined by $x<l/2$, and the p-side is the region defined by $x>l/2$. This default doping, along with the electrode-circuit connectivity, results in a one-dimensional device that behaves like a traditional SPICE-style diode. For a complete discussion of how to specify a doping profile see section [14.4.1]. For a complete discussion of how to specify electrodes (including boundary conditions), see section [14.5].

### 14.2.3 Results

Figure [14.3] shows the transient behavior of this circuit. The voltage drop across the diode ($V(3)$) is nearly the same for a wide range of currents, and is nearly constant. The voltage drop ($V(2) - V(3)$) across the series resistor, $R_1$, is much more sensitive, and so most of the voltage variation of the input sine wave is accounted for by $R_1$. 

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14.3 Two-Dimensional Example

Figure 14.3. Results for voltage regulator. In the left plot, the transient output is shown, in which the input voltage is blue and the output voltage is red. In the right plot, the initial carrier densities are shown, with the electron density in red and the hole density in blue.

14.3.1 Netlist Explanation

The two-dimensional device can have 2 to 4 electrodes. In this example there are three; nodes 5, 3, and 7, corresponding to the three names on the “node” line, which appears as:

+ node = {name = collector, base, emitter}

This line specifies that node 5 is connected to an electrode named “collector,” node 3 is connected to an electrode named “base,” and node 7 is connected to an electrode named “emitter”. Although this example only contains the electrode names, the “node” specification can contain a lot of information. Section 14.5 provides a full explanation of the electrode parameters.

The next line contains parameters concerned with plotting the results, and appears as follows:

+ tecplotlevel=2 txtdatalevel=1
Two-Dimensional Example

VPOS 1 0 DC 5V
VBB 6 0 DC -2V
RE 1 2 2K
RB 3 4 190K

YPDE BJT 5 3 7 PDEBJT meshfile=internal.msh
+ node = {name = collector, base, emitter}
+ tecplotlevel=2 txtdatalevel=1
+ mobmodel=arora
+ l=2.0e-3 w=1.0e-3
+ nx=30 ny=15
.MODEL PDEBJT ZOD level=2

* Zero-volt sources acting as an ammeter to measure the
* base, collector, and emitter currents, respectively
VMON1 4 6 0
VMON2 5 0 0
VMON3 2 7 0

.DC VPOS 0.0 12.0 0.5 VBB -2.0 -2.0 1.0
.options NONLIN maxstep=70 maxsearchstep=1
+ searchmethod=2
.options TIMEINT reltol=1.0e-3 abstol=1.0e-6
+ firstdcopstep=0 lastdcopstep=1
.PRINT DC V(1) I(VMON1) I(VMON2) I(VMON3)
.END

Figure 14.4. Two-dimensional BJT netlist. Figures 14.6 and 14.7 provide some of the results of this netlist.
Figure 14.5. Two-dimensional BJT circuit schematic. This schematic is for the circuit described by the netlist in figure 14.4. The mesh in the large circle is the mesh used in the example. The other mesh, which contains some mesh refinement, is included in the figure as an example of what is possible with an external mesh generator.
These are not related to the output specified by .PRINT, which outputs circuit data. The tecplotlevel command enables files to be output readable by Tecplot, which can then be used to create contour plots of quantities such as the electron density, electrostatic potential and the doping profile. Figures 14.6 and 14.7 contain examples of Tecplot-generated contour plots, which were generated from the results of this example.

The txtdatalevel command enables a text file with volume averaged information to be output to a file. *Xyce* will update both of these output files at each time step or DC sweep step.

The next line, *mobmodel=arora*, specifies which mobility model to use. Section 14.8 provides for more detail on available mobility models.

The last two lines, specify the mesh of the device, and are given by:

+ l=2.0e-3 w=1.0e-3
+ nx=30 ny=15

This numbers are used in nearly the same way as the one-dimensional case used the \( l \) and \( nx \) parameters. The mesh is Cartesian, and the spacing is uniform.

### 14.3.2 Doping Profile

As in the one-dimensional example, the two-dimensional example in figure 14.4 specifies nothing about the doping profile, and thus relies on default settings. In this case there are three specified electrodes, which by default results in the doping profile of the bipolar junction transistor (BJT). Section 14.4 provides a complete description of how to specify a doping profile, and describes the various default impurity profiles.

### 14.3.3 Boundary Conditions and Electrode Configuration

As in the one-dimensional example, the two-dimensional example in figure 14.4 specifies nothing about the electrode configuration or the boundary conditions, and relies on default settings. To be consistent with the default three-terminal doping, the device has terminals that correspond to that of a BJT. All three electrodes (collector, base, emitter) are along the top of the device.

By default all electrodes are considered to be neutral contacts. The boundary conditions applied to the electron density, hole density, and electrostatic potential are all Dirichlet conditions.

Section 14.5 discusses how to specify electrodes in detail (including boundary conditions).

### 14.3.4 Results

Figures 14.6, 14.7 and 14.8 provide results for the two-dimensional example. The first two figures are contour plots of the electrostatic potential. The first corresponds to the first DC sweep step, where \( V_{POS} \) is set to 0.0 Volts. The second corresponds to the final DC sweep step, in which
VPOS has a value of 12.0 volts. The voltage source, VPOS, applies a voltage to the emitter load resistor, RE, so some of the 12.0V is dropped across RE, an the rest is applied to the BJT.

The third figure is an I-V curve of the dependence of the three terminal currents on the applied emitter voltage. For the entire sweep, $-2.0$ V has been applied to the base load resistor and, as this transistor is a PNP transistor, this results in the transistor being in an “on” state. The emitter-collector current varies nearly linearly with the applied emitter voltage. Also, as can be expected because of current conservation, the three currents sum to nearly zero.

Note that the mesh used to generate these results is visible in figure 14.6 and was generated using the internal “uniform mesh”. This mesh will not produce a very accurate result, as it does not resolve the depletion regions very well. Accuracy can often be improved using mesh refinement near the depletion regions. However, such meshes must be read in from an external mesh generator, which currently has limited support as a alpha-level capability.

### 14.4 Doping Profile

*Xyce* used default doping profiles in the two examples from the previous section, so no doping parameters were specified. Default profiles are uniquely specified by the number of electrodes. In practice, especially for two-dimensional simulations, the user will generally need to specify the doping profile manually.

#### 14.4.1 Manually Specifying the Doping

Figure 14.9 shows a circuit netlist for a one-dimensional device with a detailed, manual specification of the doping profile. Figure 14.12 illustrates a similar, two-dimensional version of this
Figure 14.7. Final two-dimensional BJT result. A Tecplot-generated contour plot of the electrostatic potential at the last DC sweep step of the netlist in figure 14.4.

Figure 14.8. I-V two-dimensional BJT result for the netlist in figure 14.4. The three plotted currents are through the three BJT electrodes, and as expected they add (if corrected for sign) to zero. I(VMON1) is the base current, I(VMON2) the collector current, and I(VMON3) the emitter current. V(1) is the voltage applied to the emitter load resistor, RE.
Doping and Electrode specification example
vscope 0 1 0.0
rscope 2 1 50.0
cid 3 0 1.0u
r1 4 3 1515.0
vid 4 0 5.00
YPDE Z1DIODE 2 3 PDEDIODE nx=301 l=26.0e-4
* DOPING REGIONS: region 1, region 2, region 3
+ region= {name = reg1, reg2, reg3
+ function = uniform, gaussian, gaussian
+ type = ntype, ptype, ntype
+ nmax = 4.0e+12, 1.0e+19, 1.0e+18
+ nmin = 0.0e+00, 4.0e+12, 4.0e+12
+ xloc = 0.0, 24.5e-04, 9.0e-04
+ xwidth = 0.0, 4.5e-04, 8.0e-04
+ flatx = 0, 0, -1
} *--------end of Diode PDE device ----------------

.MODEL PDEDIODE ZOD level=1
.options NONLIN maxsearchstep=1 searchmethod=2
.options TIMEINT reltol=1.0e-3 abstol=1.0e-6
.DC vscope 0 0 1
.print DC v(1) v(2) v(3) v(4) I(vscope) I(vid)
.END

Figure 14.9. One-dimensional example, with detailed doping

problem. For this discussion, the one-dimensional example will be referred to, but the information conveyed is equally applicable to the two-dimensional case.

In both examples, the parameters associated with doping are in red text. The doping is specified with one or more regions, which are summed together to obtain the total profile. Doping regions are specified in a tabular format, with each column representing a different region.

In the one-dimensional example, there are three regions, which are illustrated in figure 14.10. Region 1 is a uniform n-type doping, with a constant magnitude of 4.0e+12 donors per cubic cm. This magnitude is set by the parameter nmax. As the doping in this region is spatially uniform, the only meaningful parameters are function (which in this case specifies a spatially uniform distribution), type (ntype or ptype) and nmax. The other parameters, nmin through flatx (1D) or flaty (2D), are ignored for a spatially uniform region.

Region 2 is a more complicated region, in that the doping profile varies spatially. This region is doped with p-type impurities, and the doping profile has a Gaussian shape. Semiconductor processing often consists of an implant followed by an anneal, which results in a diffusive profile. The Gaussian function is a solution to the diffusion problem, when it is assumed that the impurity exists in a fixed quantity.
The peak of the Region 2 doping profile is given by the parameter $n_{\text{max}}$, and is 1.0e+19 acceptors per cubic cm. This peak has a location in the device specified by $x_{\text{loc}}$=24.5e-04 cm. The parameters $n_{\text{min}}$ and $x_{\text{width}}$ are fitting parameters.

Region 3 is also based on a Gaussian function, but unlike Region 2, it is flat on one side of the peak. This is set by the $\text{flatx}$ parameter. Table 14.1 lists conventions for “flat” parameters.

<table>
<thead>
<tr>
<th>$\text{flatx or flaty value}$</th>
<th>Description</th>
<th>$1\text{D Cross Section}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Gaussian on both sides of the peak ($x_{\text{loc}}$) location.</td>
<td>[\text{Gaussian on both sides of the peak (xloc) location.} ]</td>
</tr>
<tr>
<td>+1</td>
<td>Gaussian if $x&gt;x_{\text{loc}}$, flat (constant at the peak value) if $x&lt;x_{\text{loc}}$.</td>
<td>[\text{Gaussian if x&gt;loc, flat (constant at the peak value) if x&lt;loc.} ]</td>
</tr>
<tr>
<td>-1</td>
<td>Gaussian if $x&lt;x_{\text{loc}}$, flat (constant at the peak value) if $x&gt;x_{\text{loc}}$.</td>
<td>[\text{Gaussian if x&lt;loc, flat (constant at the peak value) if x&gt;loc.} ]</td>
</tr>
</tbody>
</table>
Expression doping example
.param xs=1.0e+4; distance scalar
.param A_B=19.574867;boron params
.param x0_B=-0.228
.param w_B=0.152
.param A_SB=18.61832;antimony params
.param x0_SB=3.694
.param w_SB=0.542
.param A_AS=20.11501;arsenic params
.param x0_AS=0.061
.param w_AS=0.038
.Func ifmax (a,b) {if(a>b, a, b)}
.Func FB(X){(10**A_B)*exp(-(((X*xs)-x0_B)/(2*w_B))**2))}
.Func FSB(X){(10**A_SB)*exp(-(((X*xs)-x0_SB)/(2*w_SB))**2))}
.Func FAS(X){(10**A_AS)
+ *exp(-(((ifmax((X*xs)-x0_AS,0))/(2*w_AS))**2))}

\section{Specifying doping profiles using expressions}

The \texttt{Xyce} expression library can be used to specify doping profiles. An example of this is given in figures 14.11. In the example, the same \texttt{region} specification is used to specify doping regions. However, unlike the previous example, each species is assigned an user-defined expression to define the profile as a function of depth. This capability is only available for one dimensional devices.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example_image.png}
\caption{One-dimensional example, with expression-based doping. Each of the functions (FB, FAS and FSB) correspond to a different dopant, and are functions of depth. The red text shows where these three functions are used to specify doping profiles.}
\end{figure}
14.4.2 Default Doping Profiles

Xyce has a few default doping profiles that are invoked when the user doesn’t specify detailed doping information. The default doping profiles are an artifact of early TCAD device development in Xyce, but are sometimes still useful. In particular, the simple step-junction diode is often a useful canonical problem. It is convenient to invoke a step-junction doping without having to use the tabular specification for more complex regions.

Most real devices will have doping profiles that do not exactly match the default profiles. When attempting to simulate a realistic device, it will be necessary to skip the defaults and use the region tables described in the previous section.

One-Dimensional Case

For the one-dimensional case, Xyce assumes that the doping profile is a simple junction diode, with the junction location exactly in the middle. The acceptor and donor concentrations are given by the parameters $N_a$ and $N_d$, respectively.

The use of $N_a$ and $N_d$, implicitly specifies a step junction doping profile, and is mutually exclusive with the more complex “doping region” table specification, described in section 14.4.1. If a netlist is input to Xyce with a “doping region” table and $N_a$ (or $N_d$), the code will immediately exit with an error.

Two-Dimensional Case

Doping level defaults in the two-dimensional case are somewhat more complicated than in the one-dimensional case, because having two-dimensions allows for more configurations, and an arbitrary number (2 to 4) of electrodes. During Xyce development, it was decided that the default doping profiles would be determined uniquely by the number of electrodes present. Table 14.2 provides the three available default dopings. In the case of the BJT and MOSFET dopings, it is possible to specify either n-type or p-type using the $\text{type}$ instance parameter. If the detailed, manual doping is used, then the $\text{type}$ parameter is ignored.

For a two-electrode device, the default doping is that of a simple diode. Xyce uses the acceptor and donor doping parameters, $N_a$ and $N_d$, in the same manner as in the one-dimensional device—the junction is assumed to be exactly in the middle of the domain.

For a three-electrode device (as shown in the example), the default doping is that of a bipolar junction transistor (BJT). By default the transistor is a PNP, but by setting the instance parameter $\text{type}=\text{NPN}$, an NPN transistor can be specified instead. The two-dimensional example in section 14.3 relies on this default.

For a four-terminal device, the default doping is that of a metal-oxide-semiconductor (MOSFET). The maximum number of electrodes is four, and no default profiles are available for more than four electrodes. By default this transistor is assumed to be NMOS, rather than PMOS.
<table>
<thead>
<tr>
<th>Number of Electrodes</th>
<th>Doping Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Step Function Diode</td>
</tr>
<tr>
<td>3</td>
<td>Bipolar Junction Transistor (BJT)</td>
</tr>
<tr>
<td>4</td>
<td>Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET)</td>
</tr>
</tbody>
</table>
14.5 Electrodes

Because minimal electrodes were specified in the two examples given above, Xyce used the defaults. In practice, especially for two-dimensional simulations, the user must specify the electrodes in more detail.

14.5.1 Electrode Specification

A detailed electrode specification is specified in blue text in figure [14.12]. As with the doping parameters, the electrode parameters are specified in a tabular format, in which each table column specifies the different electrode parameters. The name parameter is the only required parameter.

The number of specified electrodes must match the number of connected circuit nodes, and the order of the electrode columns, from left to right, is in the same order as the circuit nodes, also from left to right. In the figure [14.12] example, the first electrode column, which specifies an electrode named “anode,” is connected to the circuit through circuit node 2. Respectively, the second column, for the “cathode” electrode, is connected to the circuit via circuit node 3.

Boundary Conditions

In the example, the default $bc$ parameter has been set to “Dirichlet” on all the electrodes. The $bc$ parameter sets the type of boundary condition applied to the density variables, the electron density and the hole density. Dirichlet and Neumann are two possible settings for the $bc$ parameter. If Dirichlet is specified, the electron and hole densities are set to a specific value at the contact, and the applied values enforce charge neutrality. (Note: The Xyce Reference Guide [3] provides the charge-neutral equation.) If Neumann is specified, Xyce applies a zero-flux condition, which enforces that the current through the electrode will be zero.

This parameter does not affect the electrostatic potential boundary condition. The boundary condition applied to the potential is always Dirichlet, and is (in part) determined from the connected nodal voltage. To apply a specific voltage to an electrode contact, a voltage source should be attached to it, such as $VBB$ in figure [14.5].

Electrode Material

Table [14.3] lists several different electrode materials that can be specified. The main effect of any metal (nonneutral) material is that Xyce imposes a Schottky barrier at the contact, generally making numerical solutions more difficult, so materials should be applied with caution.

The Xyce Reference Guide [3] provides a detailed description of Schottky barriers and how they are imposed on contacts in Xyce. The guide also provides values for electron affinities of various bulk materials and workfunction values for the various metal contacts.
Doping and electrode specification example

vscope 1 0 0.0
rscope 2 1 50.0
cid 3 0 1.0u
r1 4 3 1515.0
vid 4 0 1.00

*------------- Diode PDE device ------------------
YPDE Z1DIODE 2 3 PDEDIODE
+ tecplotlevel=1 txtdatalevel=1 cyl=1
+ meshfile=internal.msh
+ nx=25  l=70.0e-4 ny=40  w=26.0e-4
* ELECTRODES: ckt node 2, ckt node 3
+ node = {name = anode, cathode
+  bc = dirichlet, dirichlet
+  start = 0.002, 0.002
+  end = 0.005, 0.005
+  side = top, bottom
+  material = neutral, neutral
+  oxideBndryFlag = 0, 0 }
* DOPING REGIONS: region 1, region 2, region 3
+ region= {name = reg1, reg2, reg3
+  function = uniform, gaussian, gaussian
+  type = ntype, ptype, ntype
+  nmax = 4.0e+12, 1.0e+19, 1.0e+18
+  nmin = 0.0e+00, 4.0e+12, 4.0e+12
+  xloc = 0.0, 60.0e-04, 100.0
+  xwidth = 0.0, 4.0e-04, 1.0
+  yloc = 0.0, 24.5e-04, 9.0e-04
+  ywidth = 0.0, 4.5e-04, 8.0e-04
+  flatx = 0, -1, -1
+  flaty = 0, 0, -1 }
*--------end of Diode PDE device ----------------

.MODEL PDEDIODE ZOD level=2
.options NONLIN maxsearchstep=1 searchmethod=2
.options TIMEINT reltol=1.0e-3 abstol=1.0e-6
.DC vscope 0 0 1
.print DC v(1) v(2) v(3) v(4) I(vscope) I(vid)
.END

Figure 14.12. Two-dimensional example, with detailed doping and detailed electrodes.
Table 14.3: Electrode Material Options. NOTE: Neutral contacts are the default, and pose the least problem to the solvers.

<table>
<thead>
<tr>
<th>Material</th>
<th>Symbol</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutral</td>
<td>neutral</td>
<td>Default</td>
</tr>
<tr>
<td>aluminum</td>
<td>al</td>
<td></td>
</tr>
<tr>
<td>p+-polysilicon</td>
<td>ppoly</td>
<td></td>
</tr>
<tr>
<td>n+-polysilicon</td>
<td>npoly</td>
<td></td>
</tr>
<tr>
<td>molybdenum</td>
<td>mo</td>
<td></td>
</tr>
<tr>
<td>tungsten</td>
<td>w</td>
<td></td>
</tr>
<tr>
<td>molybdenum disilicide</td>
<td>modi</td>
<td></td>
</tr>
<tr>
<td>tungsten disilicide</td>
<td>wdi</td>
<td></td>
</tr>
<tr>
<td>copper</td>
<td>cu</td>
<td></td>
</tr>
<tr>
<td>platinum</td>
<td>pt</td>
<td></td>
</tr>
<tr>
<td>gold</td>
<td>au</td>
<td></td>
</tr>
</tbody>
</table>

There is also an oxideBndryFlag parameter, which if set to true (1), will model the contact as having an oxide layer in between the metal contact and the bulk semiconductor. By default, oxideBndryFlag is false (0).

Location Parameters

Each electrode has three location parameters: start, end, and side.

Xyce assumes the internal mesh to be rectangular, and the electrodes can be on any of the sides. The four side possibilities are: top, bottom, right and left. These four sides are parallel to the mesh directions. The start and end parameters are floating-point numbers that specify the starting and ending location of an electrode, in centimeters.

The lower left hand corner of the mesh rectangle is located at the origin. A side=bottom electrode with start=0.0 and end=1.0e-4 will originate at the lower left hand corner of the mesh (x=0.0, y=0.0) and end at (x=1.0e-4, y=0.0).

Xyce will attempt to match the specified electrode to the specified mesh. However, if the user specifies a mesh that is not consistent with the electrode locations then the electrodes will not be able to have the exact length specified. For example, if the mesh spacing is $\Delta x = 1.0e-5$, then the electrodes can only have a length that is a multiple of 1.0e-5.

14.5.2 Electrode Defaults

Defaults exist for each electrode parameter other than names. In practice, the electrode locations are usually explicitly specified using the electrode table. Default electrode locations were created to correspond with the default dopings; they should only be used in that context.
Location Parameters

In practice, the electrode locations will usually be explicitly specified, but they have defaults to correspond with the default dopings. The default electrode locations in one-dimensional devices are for a diode. One electrode is located at \( x=x_{\text{min}} \), while the other is located at \( x=x_{\text{max}} \).

The default electrode locations in two-dimensional devices depend on the number of electrodes, similar to the default dopings. Table 14.2 can be used to determine such configurations. For the two-terminal diode, the two electrodes are along the y-axis, at the \( x=x_{\text{min}} \) and \( x=x_{\text{max}} \) extrema. For the three-terminal BJT, all three electrodes are parallel to the x-axis, along the top, at \( y=y_{\text{max}} \). For the four-terminal MOSFET, the drain, gate, and source electrodes are also along the top, but the bulk electrode spans the entire length of the bottom of the mesh, at \( y=y_{\text{min}} \).

14.6 Meshes

One- and two-dimensional devices can create Cartesian meshes. For two-dimensional devices, users must specify `meshfile=internal.msh` to invoke the Cartesian meshing capability (this is necessary for historical reasons). Meshes generated in this manner are very simple as there are only two parameters per dimension, and the resulting mesh is uniform. Figure 14.6 provides an example of such a mesh. Mesh spacing is determined from the following expressions:

\[
\Delta x = \frac{l}{nx - 1} \tag{14.8}
\]
\[
\Delta y = \frac{w}{ny - 1} \tag{14.9}
\]

This mesh specification assumes the domain is a rectangle. Nonrectangular domains can only be described using an external mesh program.

Externally generated meshes for 1D devices can be including using `meshfile=<filename>` in the PDE device instance line. The file specified by `<filename>` must consist of two space-delimited columns of numbers. The first column specifies the location of the mesh points. The second column is not currently used, but it must exist, so it is suggested to make it a column of zeros.

14.7 Cylindrical meshes

For two-dimensional devices, the simulation area may be a cylinder slice. This capability is turned on by the instance parameter `cyl=1`. It is assumed that the axis of the cylinder corresponds to the minimum radius (or x-axis value) of the mesh, while the circumference corresponds to the maximum radius (or maximum x-axis value).
14.8 Mobility Models

There are several mobility models available to the one- and two-dimensional devices, and they are listed in Table 14.4. These models are fairly common, and can be found in most device simulators. The Xyce Reference Guide describes these models in more detail.

<table>
<thead>
<tr>
<th>Mobility Name</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>arora</td>
<td>Basic mobility model</td>
<td>Arora, et al. [35]</td>
</tr>
<tr>
<td>analytic or caughey-thomas</td>
<td>Basic mobility model</td>
<td>Caughey and Thomas [36]</td>
</tr>
<tr>
<td>carr</td>
<td>Includes carrier-carrier interactions</td>
<td>Dorkel and Leturq [37]</td>
</tr>
<tr>
<td>philips</td>
<td>Philips model</td>
<td>Klassen [38] [39]</td>
</tr>
</tbody>
</table>

Setting the mobmodel parameter to the name of the model (as provided in the first column of table 14.4) specifies the mobility model from the netlist. The mobility model is specified as an instance parameter on the device instance line, as (typically) mobmodel=arora. Figure 14.4 provides a more detailed example.

The default mobility is “arora”, which is a basic model lacking carrier or field dependence. Because it lacks these dependencies, it generally is more numerically robust. The “carr” model includes carrier-carrier dependence, as does the “philips” model. For all of these models, field dependence can be optionally turned on from the netlist, using the fielddep=true parameter.

14.9 Bulk Materials

The bulk material is specified using the bulkmaterial instance parameter. Xyce supports Silicon (si) as a default bulk material. It can also simulate several III-V materials, including Gallium Arsenide (gaas), Germanium (ge), Indium Aluminum Arsenide (inalas or alinas), Indium Gallium Arsenide (ingaas or gainas), Indium Phosphide (inp), and Indium Gallium Phosphide (ingap); but these materials have not been extensively tested. The mobility models described in the previous section each support most of these materials.

14.10 Output and Visualization

14.10.1 Using the .PRINT Command

For simple plots (such as I-V curves), output results for Xyce can be generated with the .PRINT statement, which is described in detail in section 9.1.1. Figures 14.3 and 14.8 are examples of the kind of data that is produced with .PRINT statement netlist commands. These particular
14.10.2 Multidimensional Plots

Device simulation has visualization needs which go beyond that of conventional circuit simulation. Multidimensional perspective and/or contour plots are often desirable. **Xyce** is capable of outputting multi-dimensional plot data in several formats, including Tecplot (available for purchase from http://www.tecplot.com), gnuplot (available free from http://www.gnuplot.info), and SG PLOT. Currently, the options for each of these formats can only enable or disable the output of files, and when enabled, a new file (or a new append to an existing file) will happen at every time step or DC sweep step.

For long simulations, this may produce a prohibitive number of files. There is no equivalent to the `.OPTIONS OUTPUT INITIAL_INTERVAL` command, nor does the output of plot data use this command. Plot files are either output at every step or not at all.

For each type of plot file, the file is placed in the execution directory. Each individual device instance is given a unique file, or files, and the file names are derived from the name of the PDE device instance. The instance names provides the prefix, and the file type (Tecplot, gnuplot, Sgplot) determines the suffix.

**Tecplot Data**

Tecplot is a commercial plotting program from Amtec Engineering, Inc., and is a good choice for creating contour plots of spatially dependent data. All of the graphical examples in this chapter were created with Tecplot. (See figures [14.6](#) and [14.7](#) for examples.) The output of Tecplot files is enabled using the instance parameter, `tecplotlevel=1`. If set to zero, no Tecplot files are output. If set to one, **Xyce** outputs a separate Tecplot file for each nonlinear solve. If set to two, **Xyce** creates a single Tecplot file containing data for every nonlinear solve and appends the file at the end of each solve.

By default `tecplotlevel` is set to one, meaning the code will produce a separate Tecplot file for each time step or DC sweep step. The suffix for a Tecplot (ASCII text) data file is `*.dat`.

**Gnuplot Data**

Gnuplot is an open source plotting program available on most Linux/Unix platforms. The parameter for this type of output is `gnuplotlevel=1`. This type of output file is off (zero) by default, meaning no gnuplot files will be output. The suffix for gnuplot files is `*gnu.dat`. Like Tecplot files, gnuplot files are also in ASCII text format.

14.10.3 Additional Text Data

**Xyce** can also output additional information for each PDE device by setting the instance parameter, `txtdatalevel=1`. It is on (1) by default, so this output will happen unless specifically disabled by
Global data for DC step 1:
Current Time = 0.0000e+00
Vmin = -8.6931e-06
Vmax = 5.4030e-01
NnMin = 0.0000e+00
NnMax = 1.0000e+16
NpMin = 3.9240e+03
NpMax = 1.0000e+19

Information for electrode: COLLECTOR
potential: 2.9795e-01
current: 8.5365e-06
charge: -6.6211e-15
dIdVckt: 3.7993e-02
dQdVckt: 0.0000e+00

Information for electrode: BASE
potential: 5.4030e-01
current: -8.5408e-06
charge: 1.5958e-14
dIdVckt: 1.0463e+01
dQdVckt: 0.0000e+00

Information for electrode: EMITTER
potential: -8.6931e-06
current: 4.3465e-09
charge: -2.3232e-13
dIdVckt: 7.2130e+01
dQdVckt: 0.0000e+00

Figure 14.13. Text output, from the circuit given in figure 14.4.

setting the parameter to zero. A typical output file (associated with the netlist given in figure 14.4) is shown in figure 14.13.
References


[5] *gEDA Project Home Page.*
   http://www.geda.seul.org/ .

[6] *Qucs-S: Quacs with SPICE.*


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#
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```

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