



Hardware Simulator Tutorial

This program is part of the software suite
that accompanies the book

The Elements of Computing Systems

by Noam Nisan and Shimon Schocken

MIT Press

www.nand2tetris.org

This software was developed by students at the
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Chief Software Architect: Yaron Ukrainitz

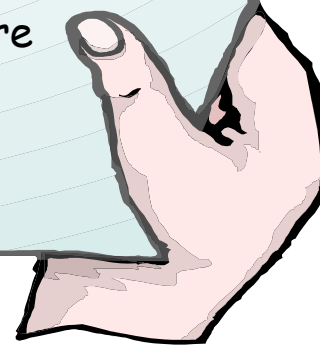
Background

The Elements of Computing Systems evolves around the construction of a complete computer system, done in the framework of a 1- or 2-semester course.

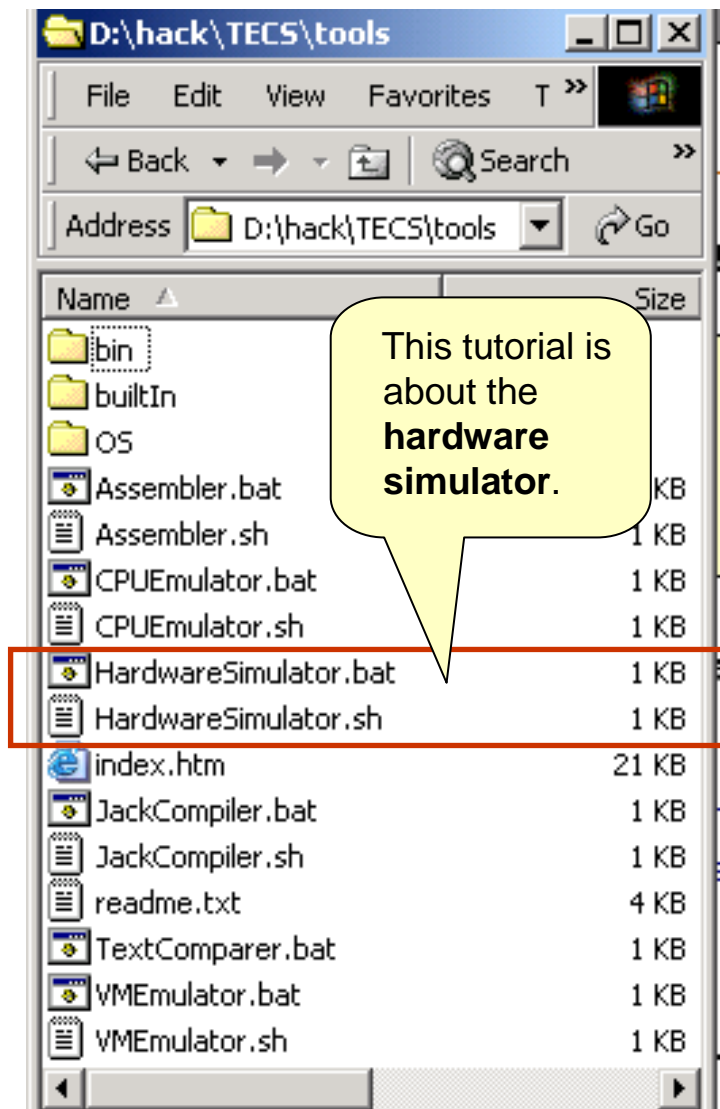
In the first part of the book/course, we build the hardware platform of a simple yet powerful computer, called Hack. In the second part, we build the computer's software hierarchy, consisting of an assembler, a virtual machine, a simple Java-like language called Jack, a compiler for it, and a mini operating system, written in Jack.

The book/course is completely self-contained, requiring only programming as a pre-requisite.

The book's web site includes some 200 test programs, test scripts, and all the software tools necessary for doing all the projects.



The book's software suite



(All the supplied tools are dual-platform: **xxx.bat** starts **xxx** in Windows, and **xxx.sh** starts it in Unix)

Simulators

(HardwareSimulator, CPUEmulator, VMEulator):

- Used to build hardware platforms and execute programs;
- Supplied by us.

Translators (Assembler, JackCompiler):

- Used to translate from high-level to low-level;
- Developed by the students, using the book's specs; Executable solutions supplied by us.

Other

- **bin**: simulators and translators software;
- **builtIn**: executable versions of all the logic gates and chips mentioned in the book;
- **os**: executable version of the Jack OS;
- **TextComparer**: a text comparison utility.

The Hack computer

The **hardware simulator** described in this tutorial can be used to build and test many different hardware platforms. In this book, we focus on one particular computer, called Hack.

Hack -- a 16-bit computer equipped with a screen and a keyboard -- resembles hand-held computers like game machines, PDA's, and cellular telephones.

The first 5 chapters of the book specify the elementary gates, combinational chips, sequential chips, and hardware architecture of the Hack computer.

All these modules can be built and tested using the **hardware simulator** described in this tutorial.

That is how hardware engineers build chips for real: first, the hardware is designed, tested, and optimized on a software simulator. Only then, the resulting gate logic is committed to silicon.



Hardware Simulation Tutorial

- I. [Getting started](#)
- II. [Test scripts](#)
- III. [Built-in chips](#)
- IV. [Clocked chips](#)
- V. [GUI-empowered chips](#)
- VI. [Debugging tools](#)
- VII. [The Hack Platform](#)

Relevant reading (from “*The Elements of Computing Systems*”):

- Chapter 1: *Boolean Logic*
- Appendix A: *Hardware Description Language*
- Appendix B: *Test Scripting Language*

Hardware Simulation Tutorial



Chip Definition (.hdl file)

chip
interface

```
/** Exclusive-or gate. out = a xor b */  
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    // Implementation missing.  
}
```

- Chip interface:
 - ❑ Name of the chip
 - ❑ Names of its input and output pins
 - ❑ Documentation of the intended chip operation
- Typically supplied by the chip architect; similar to an API, or a contract.

Chip Definition (.hdl file)

chip
interface

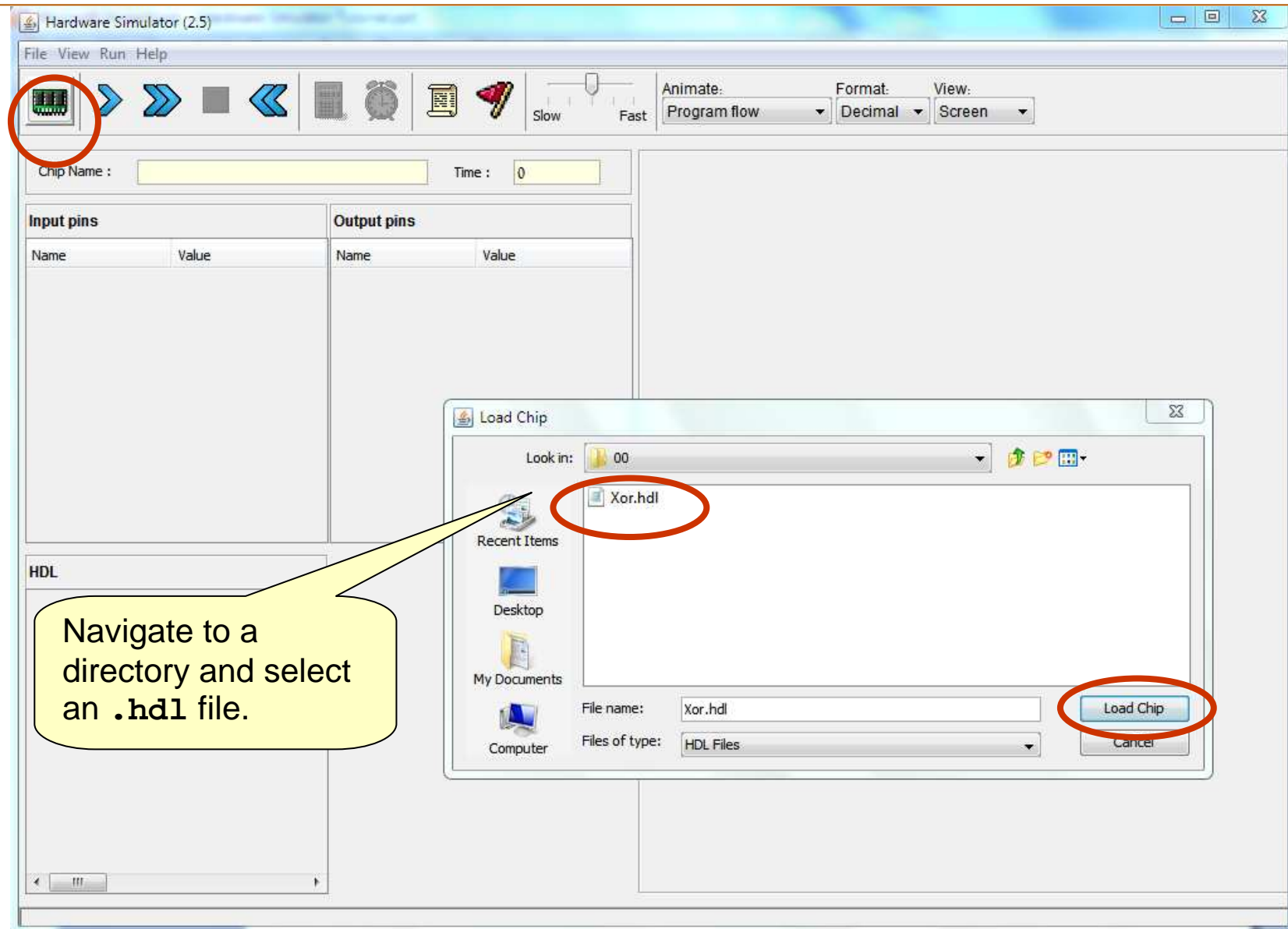
chip
implementation

```
/** Exclusive-or gate. out = a xor b */
CHIP Xor {
    IN a, b;
    OUT out;

    PARTS:
    Not(in=a, out=nota);
    Not(in=b, out=notb);
    And(a=a, b=notb, out=w1);
    And(a=nota, b=b, out=w2);
    Or(a=w1, b=w2, out=out);
}
```

- Any given chip can be implemented in several different ways. This particular implementation is based on: $Xor(a,b) = Or(And(a,Not(b)), And(b,Not(a)))$
- **Not**, **And**, **Or**: *Internal parts* (previously built chips), invoked by the HDL programmer
- **nota**, **notb**, **w1**, **w2**: *internal pins*, created and named by the HDL programmer; used to connect internal parts.

Loading a Chip



Loading a Chip

Hardware Simulator (1.4b1) - G:\TECS\projects\01\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins

Name	Value
a	0
b	0

- Names and current values of the chip's input pins;
- To change their values, enter the new values here.

Output pins

Name	Value
out	0

- Names and current values of the chip's output pins;
- Calculated by the simulator; read-only.

HDL

```
/**
 * Exclusive-or gate. out = a xor b.
 */
CHIP Xor {
  IN a, b;
  OUT out;
  PARTS:
    Not(in=a, out=nota);
    Not(in=b, out=notb);
    And(a=a, b=notb, out=w1);
    And(a=nota, b=b, out=w2);
    Or(a=w1, b=w2, out=out);
}
```

- Read-only view of the loaded .hdl file;
- Defines the chip logic;
- To edit it, use an external text editor.

Internal pins

Name	Value
nota	0
notb	0
w1	0
w2	0

- Names and current values of the chip's internal pins (used to connect the chip's parts, forming the chip's logic);
- Calculated by the simulator; read-only.

Exploring the Chip Logic

The screenshot shows the Hardware Simulator (1.4b1) interface. The title bar indicates the file path is G:\TECS\projects\01\Xor.hdl. The menu bar includes File, View, Run, and Help. The toolbar contains icons for running the simulation (play, fast play, stop, step back, step forward, calculator, clock, and a red arrow) and a slider for speed (Slow to Fast). The 'Animate' dropdown is set to 'Program flow', 'Format' is 'Decimal', and 'View' is 'Screen'. Below the toolbar, the 'Chip Name' is 'Xor' and 'Time' is '0'. The 'Input pins' table has two rows: 'a' with value '0' and 'b' with value '0'. The 'Output pins' table has one row: 'out' with value '0'. The 'HDL' editor shows the following code:

```
/**
 * Exclusive-or gate. out = a XOR b.
 */

CHIP Xor {
  IN a, b;
  OUT out;
  PARTS:
  Not(in=a, out=nota);
  Not(in=b, out=noth);
  And(a=a, b=noth, out=w1);
  And(a=nota, b=b, out=w2);
  Or(a=w1, b=w2, out=out);
}
```

The 'Internal Parts' table is displayed below the HDL editor:

Chip Name	Type	Clocked
Not	Composite	<input type="checkbox"/>
Not	Composite	<input type="checkbox"/>
And	Composite	<input type="checkbox"/>
And	Composite	<input type="checkbox"/>
Or	Composite	<input type="checkbox"/>

Two yellow callout boxes provide instructions:

1. Click the **PARTS** keyword
2. A table pops up, showing the chip's internal parts (lower-level chips) and whether they are:
 - Primitive ("given") or composite (user-defined)
 - Clocked (sequential) or unclocked (combinational)

Exploring the Chip Logic

Hardware Simulator (1.4b1) - G:\TECS\projects\01\Xor.hdl

File View Run Help

Animate: Program flow Format: Decimal View: Screen

Chip Name: Xor Time: 0

Input pins		Output pins	
Name	Value	Name	Value
a	0	out	0
b	0		

1. Click any one of the chip **PARTS**

```
HDL
/**
 * Exclusive-or gate. out = a XOR b.
 */
CHIP Xor {
  IN a, b;
  OUT out;
  PARTS:
  Not(in=a, out=nota);
  Not(in=b, out=noth);
  And(a=a, b=noth, out=w1);
  And(a=nota, b=b, out=w2);
  Or(a=w1, b=w2, out=out);
}
```

Part pins		
Part pin	Gate pin	Value
in	a	0
out	nota	0

2. A table pops up, showing the input/output pins of the selected part (actually, its API), and their current values;

A convenient debugging tool.

Interactive Chip Testing

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins		Output pins	
Name	Value	Name	Value
a	0	out	0
b	1		

Internal pins	
Name	Value
nota	1
notb	1
w1	0
w2	0

```
// Xor (exclusive or) gate
// if a<=b out=1 else out=0
CHIP Xor {
  IN a,b;
  OUT out;
  PARTS:
    Not (in=a,out=nota);
    Not (in=b,out=notb);
    And (a=a,b=notb,out=w1);
    And (a=nota,b=b,out=w2);
    Or (a=w1,b=w2,out=out);
}
```

1. User: changes the values of some input pins

2. Simulator: responds by:

- Darkening the output and internal pins, to indicate that the displayed values are no longer valid
- Enabling the *eval* (calculator-shaped) button.

Interactive Chip Testing

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins		Output pins	
Name	Value	Name	Value
a	0	out	1
b	1		

Re-calc

Internal pins	
Name	Value
nota	1
notb	0
w1	0
w2	1

```
// Xor (exclusive or) gate
// if a<>b out=1 else out=0
CHIP Xor {
  IN a,b;
  OUT out;
  PARTS:
    Not (in=a,out=nota);
    Not (in=b,out=notb);
    And (a=a,b=notb,out=w1);
    And (a=nota,b=b,out=w2);
    Or (a=w1,b=w2,out=out);
}
```

1. User: changes the values of some input pins
2. Simulator: responds by:
 - Darkening the output and internal pins, to indicate that the displayed values are no longer valid
 - Enabling the *eval* (calculator-shaped) button.
3. User: Clicked the *eval* button
4. Simulator: re-calculates the values of the chip's internal and output pins (i.e. applies the chip logic to the new input values)
5. To continue interactive testing, enter new values into the input pins and click the *eval* button.

Hardware Simulation Tutorial



Test Scripts

```
load Xor.hdl,  
output-file Xor.out,  
compare-to Xor.cmp,  
output-list a%B3.1.3  
           b%B3.1.3  
           out%B3.1.3;  
  
set a 0,  
set b 0,  
eval,  
output;  
  
set a 0,  
set b 1,  
eval,  
output;  
Etc.
```

Generated
output file
(Xor.out)

	a	b	out
	0	0	0
	0	1	1
	1	0	1
	1	1	0

Test scripts:

- Are used for specifying, automating and replicating chip testing
- Are supplied for every chip mentioned in the book (so you don't have to write them)
- Can effect, batch-style, any operation that can be done interactively
- Are written in a simple language described in Appendix B of the book
- Can create an output file that records the results of the chip test
- If the script specifies a compare file, the simulator will compare the `.out` file to the `.cmp` file, line by line.

Loading a Script

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name : Xor Time : 0

Input pins		Output pins	
Name	Value	Name	Value
a	0	a	0
b	0	b	0

To load a new script (.tst file), click this button;

Interactive loading of the chip itself (.hdl file) may not be necessary, since the test script typically contains a "load chip" command.

```
//Xor
//if
CHI
IN
OU
PA
Not
Not (in=b,out=notb),
And (a=a,b=notb,out=w1);
And (a=nota,b=b,out=w2);
Or (a=w1,b=w2,out=out);
}
```

The screenshot shows the Hardware Simulator (1.1b) interface. The top menu bar includes File, View, Run, and Help. Below the menu is a toolbar with icons for running the simulation: a single step, a multi-step execution (highlighted with a callout), a pause (highlighted with a callout), a reset (highlighted with a callout), and a speed control slider (highlighted with a callout). The main window is divided into several panes. The 'Chip Name' field is empty. The 'Input pins' and 'Output pins' tables are visible. The 'HDL' pane shows the script being executed, with lines of code like 'load Xor.hdl', 'output-file Xor.out', 'compare-to Xor.cmp', 'output-list a%B3.1.3 b%B3.1.3 out%B3.1.3;', 'set a 0, set b 0, eval, output;', 'set a 0, set b 1, eval, output;', 'set a 1, set b 0, eval, output;', and 'set a 1, set b 1, eval, output;'. A callout points to the multi-step execution icon, stating 'Multi-step execution, until a pause'. Another callout points to the pause icon, stating 'Pauses the script execution'. A third callout points to the reset icon, stating 'Resets the script'. A fourth callout points to the speed control slider, stating 'Controls the script execution speed'. A large callout on the right side of the screen explains the script format: 'Script = series of simulation steps, each ending with a semicolon.' The status bar at the bottom indicates 'New script loaded: E:\project 1\Xor.tst'.

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Time: 0

Input pins

Name	Value
a	0
b	0

Output pins

Name	Value
out	0

HDL

```
// Xor (exclusive or) gate
// if a<b then out=1 else out=0
CHIP Xor
IN a,b;
OUT out;
PARTS:
Not (in a) ta;
Not (in b) tb;
And (ta, tb) and1;
And (a, b) and2;
Xor (and1, and2) out;
```

Controls the script execution speed

Resets the script

Pauses the script execution

Multi-step execution, until a pause

Executes the next simulation step

Script = series of simulation steps, each ending with a semicolon.

load Xor.hdl,
output-file Xor.out,
compare-to Xor.cmp,
output-list a%B3.1.3 b%B3.1.3 out%B3.1.3;

set a 0,
set b 0,
eval,
output;

set a 0,
set b 1,
eval,
output;

set a 1,
set b 0,
eval,
output;

set a 1,
set b 1,
eval,
output;

New script loaded: E:\project 1\Xor.tst

Running a Script

The screenshot shows the Hardware Simulator (1.1b) interface. The title bar reads "Hardware Simulator (1.1b) - E:\project 1\Xor.hdl". The menu bar includes "File", "View", "Run", and "Help". The toolbar contains various icons, with the "Run" icon (a blue double arrow) circled in red. Below the toolbar, there are fields for "Chip Name:" and "Time: 0". To the left, there are tables for "Input pins" and "Output pins". The "Input pins" table has columns "Name" and "Value", with rows for "a" and "b", both with a value of 0. The "Output pins" table has columns "Name" and "Value", with a row for "out" with a value of 0. The main area on the right displays a script. The first line, "load Xor.hdl,", is highlighted in yellow and circled in red. Below it, the script continues with "output-file Xor.out,", "compare-to Xor.cmp,", "output-list a%B3.1.3 b%B3.1.3 out%B3.1.3;", and several "set", "eval", and "output" commands. A large orange arrow points downwards from the circled script line, with the text "Script execution flow" written inside it. A yellow callout box on the left contains the text "Typical 'init' code:" followed by a numbered list: 1. Loads a chip definition (.hdl) file, 2. Initializes an output (.out) file, 3. Specifies a compare (.cmp) file, 4. Declares an output line format. The status bar at the bottom reads "New script loaded: E:\project 1\Xor.tst".

File View Run Help

Chip Name: Time: 0

Name	Value
a	0
b	0

Name	Value
out	0

load Xor.hdl,
output-file Xor.out,
compare-to Xor.cmp,
output-list a%B3.1.3 b%B3.1.3 out%B3.1.3;

set a 0,
set b 0,
eval,
output;

set a 0,
set b 1,
eval,
output;

set a 1,
set b 0,
eval,
output;

set a 1,
set b 1,
eval,
output;

Script execution flow

Typical "init" code:

1. Loads a chip definition (.hdl) file
2. Initializes an output (.out) file
3. Specifies a compare (.cmp) file
4. Declares an output line format.

New script loaded: E:\project 1\Xor.tst

Running a Script

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins		Output pins	
Name	Value	Name	Value
a	1	out	0
b	1		

Comparison of the output lines to the lines of the .cmp file are reported.

HDL

```
// Xor (exclusive or) gate
// if a<=b out=1 else out=0
CHIP Xor {
  IN a,b;
  OUT out;
  PARTS:
    Not (in=a,out=nota);
    Not (in=b,out=notb);
    And (a=a,b=notb,out=w1);
    And (a=nota,b=b,out=w2);
    Or (a=w1,b=w2,out=out);
}
```

```
load Xor.hdl,
output-file Xor.out,
compare-to Xor.cmp,
output-list a%B3.1.3 b%B3.1.3 out%B3.1.3;

set a 0,
set b 0,
eval,
output;

set a 0,
set b 1,
eval,
output;

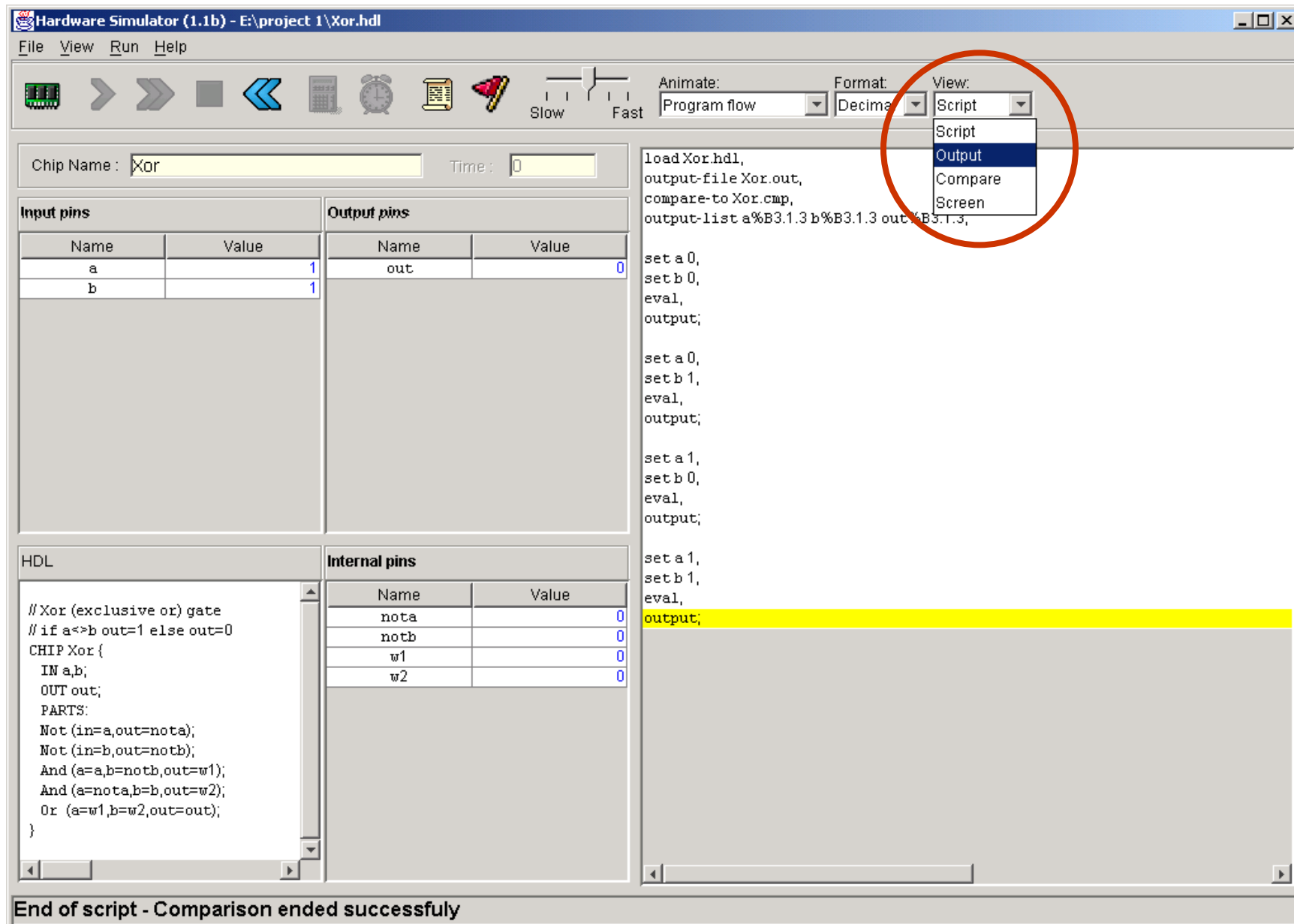
set a 1,
set b 0,
eval,
output;

set a 1,
set b 1,
eval,
output;
```

Script execution ends

End of script - Comparison ended successfully

Viewing Output and Compare Files



The screenshot shows the Hardware Simulator (1.1b) interface. The title bar reads "Hardware Simulator (1.1b) - E:\project 1\Xor.hdl". The menu bar includes File, View, Run, and Help. The toolbar contains various icons for simulation control, including a chip, step buttons, a calculator, a clock, a document, and a speaker, along with "Slow" and "Fast" speed indicators. The "Animate:" dropdown is set to "Program flow", and the "Format:" dropdown is set to "Decima". The "View:" dropdown menu is open, with "Output" selected and highlighted in blue. The "Script" option is also visible. The main window is divided into several sections: "Chip Name:" (Xor) and "Time:" (0) at the top; "Input pins" and "Output pins" tables; "HDL" code; "Internal pins" table; and a script editor on the right. The "Input pins" table has columns "Name" and "Value" with rows for "a" (1) and "b" (1). The "Output pins" table has columns "Name" and "Value" with a row for "out" (0). The "HDL" section contains Verilog code for an XOR gate. The "Internal pins" table has columns "Name" and "Value" with rows for "nota" (0), "notb" (0), "w1" (0), and "w2" (0). The script editor on the right shows a sequence of commands: "load Xor.hdl", "output-file Xor.out", "compare-to Xor.cmp", "output-list a%B3.1.3 b%B3.1.3 out%B3.1.3", "set a 0", "set b 0", "eval", "output;", "set a 0", "set b 1", "eval", "output;", "set a 1", "set b 0", "eval", "output;", "set a 1", "set b 1", "eval", "output;". The "output;" command is highlighted in yellow. The status bar at the bottom reads "End of script - Comparison ended successfully".

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins

Name	Value
a	1
b	1

Output pins

Name	Value
out	0

HDL

```
// Xor (exclusive or) gate
// if a<>b out=1 else out=0
CHIP Xor{
  IN a,b;
  OUT out;
  PARTS:
    Not (in=a,out=nota);
    Not (in=b,out=notb);
    And (a=a,b=notb,out=w1);
    And (a=nota,b=b,out=w2);
    Or (a=w1,b=w2,out=out);
}
```

Internal pins

Name	Value
nota	0
notb	0
w1	0
w2	0

Script

```
load Xor.hdl,
output-file Xor.out,
compare-to Xor.cmp,
output-list a%B3.1.3 b%B3.1.3 out%B3.1.3,

set a 0,
set b 0,
eval,
output;

set a 0,
set b 1,
eval,
output;

set a 1,
set b 0,
eval,
output;

set a 1,
set b 1,
eval,
output;
```

End of script - Comparison ended successfully

Viewing Output and Compare Files

Hardware Simulator (1.1b) - E:\project 1\Xor.hdl

File View Run Help

Chip Name: Xor Time: 0

Input pins

Name	Value
a	1
b	1

Output pins

Name	Value
out	0

HDL

```
// Xor (exclusive or) gate
// if a<>b out=1 else out=0
CHIP Xor {
  IN a,b;
  OUT out;
  PARTS:
    Not (in=a,out=nota);
    Not (in=b,out=notb);
    And (a=a,b=notb,out=w1);
    And (a=nota,b=b,out=w2);
    Or (a=w1,b=w2,out=out);
}
```

Internal pins

Name	Value
nota	0
notb	0
w1	0
w2	0

Output table:

a	b	out
0	0	0
0	1	1
1	0	1
1	1	0

Observation:
This output file looks like a **Xor** truth table

Conclusion: the chip logic (**Xor.hdl**) is apparently correct (but not necessarily efficient).

End of script - Comparison ended successfully



Built-In Chips

General

- A built-in chip has an HDL interface and a Java implementation (e.g. here: [Mux16.class](#))
- The name of the Java class is specified following the **BUILTIN** keyword
- Built-In implementations of all the chips that appear in the book are supplied in the [tools/builtIn](#) directory.

```
// Mux16 gate (example)
CHIP Mux16 {
    IN a[16],b[16],sel;
    OUT out[16];
    BUILTIN Mux16;
}
```

Built-in chips are used to:

- Implement primitive gates (in the computer built in this book: [Nand](#) and [DFF](#))
- Implement chips that have peripheral side effects (like I/O devices)
- Implement chips that feature a GUI (for debugging)
- Provide the functionality of chips that the user did not implement for some reason
- Improve simulation speed and save memory (when used as parts in complex chips)
- Facilitate behavioral simulation of a chip before actually building it in HDL
- Built-in chips can be used either *explicitly*, or *implicitly*.

Explicit Use of Built-in Chips

The screenshot shows the Hardware Simulator (1.4b1) interface. The title bar indicates the file path: G:\TECS\tools\builtIn\Mux16.hdl. The menu bar includes File, View, Run, and Help. The toolbar contains various icons, with the first icon (a chip) circled in red. Below the toolbar, the 'Chip Name' field is set to 'Mux16' and the 'Time' field is set to '0'. The 'Input pins' table has three rows: 'a[16]' with value '0', 'b[16]' with value '0', and 'sel' with value '0'. The 'Output pins' table has one row: 'out[16]' with value '0'. The 'HDL' window shows the following code:

```
// MIT Press 2004. Book site: http://www
// File name: tools/builtIn/Mux16.hdl

/**
 * 16-bit multiplexor. If sel=0 then
 */
CHIP Mux16 {
    IN a[16], b[16], sel;
    OUT out[16];

    BUILTIN Mux;
}
```

A 'Load Chip' dialog box is open, showing the 'Look in' field set to 'builtIn'. The file list contains: HalfAdder.hdl, Inc16.hdl, Keyboard.hdl, Mux.hdl, Mux16.hdl (selected), and Mux4Way16.hdl. The 'File name' field is set to 'Mux16.hdl' and the 'Files of type' dropdown is set to 'HDL Files'. The 'Load Chip' button is circled in red.

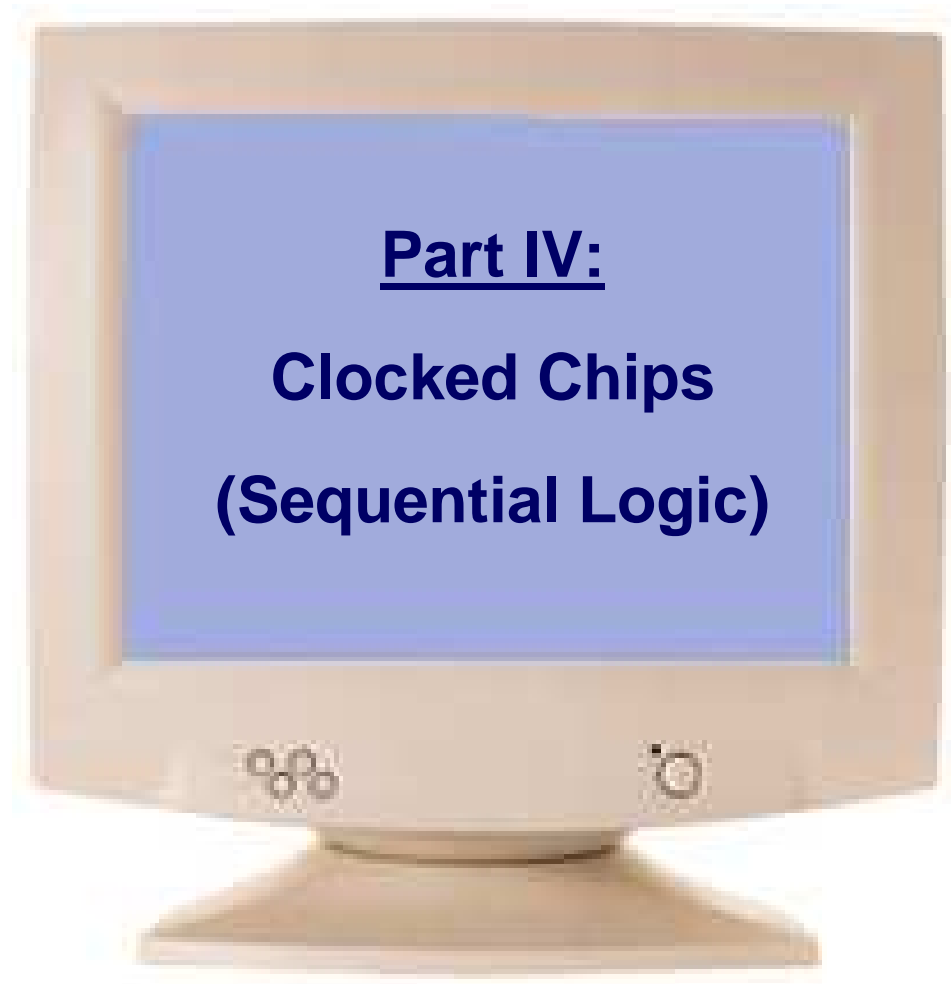
Annotations:

- A yellow speech bubble points to the first toolbar icon: "The chip is loaded from the **tools/builtIn** directory (includes executable versions of all the chips mentioned in the book)."
- A yellow speech bubble points to the 'Standard interface.' text: "Standard interface."
- A yellow speech bubble points to the 'BUILTIN Mux;' line in the HDL code: "Built-in implementation."

Implicit Use of Built-in Chips

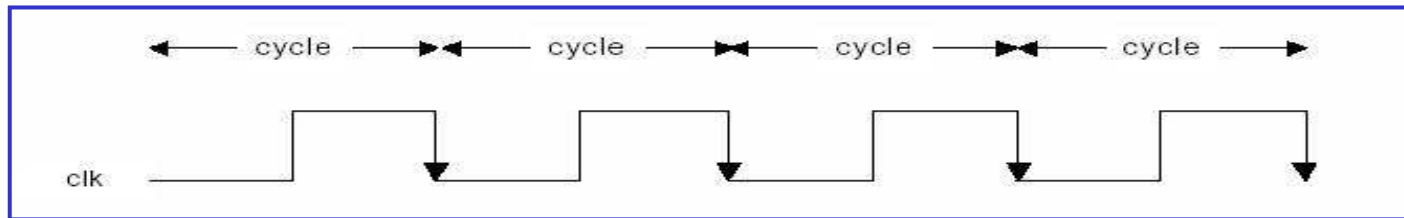
```
/** Exclusive-or gate. out = a xor b */  
CHIP Xor {  
    IN a, b;  
    OUT out;  
    PARTS:  
        Not(in=a,out=Nota);  
        Not(in=b,out=Notb);  
        And(a=a,b=Notb,out=aNotb);  
        And(a=Nota,b=b,out=bNota);  
        Or(a=aNotb,b=bNota,out=out);  
}
```

- When any HDL file is loaded, the simulator parses its definition. For each internal chip `Xxx(...)` mentioned in the PARTS section, the simulator looks for an `Xxx.hdl` file in the same directory (e.g. `Not.hdl`, `And.hdl`, and `Or.hdl` in this example).
- If `Xxx.hdl` is found in the current directory (e.g. if it was also written by the user), the simulator uses its HDL logic in the evaluation of the overall chip.
- If `Xxx.hdl` is not found in the current directory, the simulator attempts to invoke the file `tools/builtIn/Xxx.hdl` instead.
- And since `tools/builtIn` includes executable versions of all the chips mentioned in the book, it is possible to build and test any of these chips before first building their lower-level parts.



Clocked (Sequential) Chips

- The implementation of clocked chips is based on *sequential logic*
- The operation of clocked chips is regulated by a master clock signal:



- In our jargon, a clock cycle = *tick*-phase (low), followed by a *tock*-phase (high)
- During a *tick-tock*, the internal states of all the clocked chips are allowed to change, but their outputs are “latched”
- At the beginning of the next *tick*, the outputs of all the clocked chips in the architecture commit to the new values
- In a real computer, the clock is implemented by an oscillator; in simulators, clock cycles can be simulated either manually by the user, or repeatedly by a test script.

The D-Flip-Flop (DFF) Gate

```
/** Data Flip-flop:
 *  out(t)=in(t-1)
 *  where t is the time unit.
 */
CHIP DFF {
    IN in;
    OUT out;

    BUILTIN DFF;
    CLOCKED in, out;
}
```

DFF:

- A primitive memory gate that can “remember” a state over clock cycles
- Can serve as the basic building block of all the clocked chips in a computer.

Clocked chips

- Clocked chips include registers, RAM devices, counters, and the CPU
- The simulator knows that the loaded chip is clocked when one or more of its pins is declared “clocked”, or one or more of its parts (or sub-parts, recursively) is a clocked chip
- In the hardware platform built in the book, all the clocked chips are based, directly or indirectly, on (many instances of) built-in DFF gates.

Simulating Clocked Chips

Hardware Simulator (1.4b1) - G:\TECS\tools\builtIn\RAM8.hdl

File View Run Help

Chip Name: RAM8 (Clocked)

Input pins

Name	Value
in[16]	
load	
address[3]	

HDL

```
* In words: the chip always outputs  
* location specified by address. If  
* into the memory location specifi  
* available through the out output  
*/  
  
CHIP RAM8 {  
  
    IN in[16], load, address[3];  
    OUT out[16];  
  
    BUILTIN RAM8;  
    CLOCKED in, load;  
}
```

Clocked (sequential) chips are clock-regulated.

Therefore, the standard way to test a clocked chip is to set its input pins to some values (as with combinational chips), simulate the progression of the clock, and watch how the chip logic responds to the ticks and the tocks.

For example, consider the simulation of an 8-word random-access memory chip (RAM8).

A built-in, clocked chip (RAM8) is loaded

happens to be GUI-empowered, the simulator displays its GUI (More about GUI-empowered chips, soon)

Simulating Clocked Chips

Hardware Simulator (1.4b1) - G:\TECS\tools\builtIn\RAM8.hdl

File View Run Help

Chip Name: Time: 0

Input pins

Name	Value
in[16]	112
load	1
address[3]	5

Output pins

Name	Value
out[16]	0

RAM 8:

0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0

HDL

```
* In words: the chip always outputs  
* location specified by address. If  
* into the memory location specifi  
* available through the out output  
*/  
  
CHIP RAM8 {  
    IN in[16], load, address[3];  
    OUT out[16];  
  
    BUILTIN RAM8;  
    CLOCKED in, load;  
}
```

1. User: enters some input values and clicks the clock icon once (*tick*)

A built-in, clocked chip (**RAM8**) is loaded

Simulating Clocked Chips

Hardware Simulator (1.4b1) - G:\TECS\tools\builtIn\RAM8.hdl

File View Run Help

Chip Name: Time: 0+

Input pins

Name	Value
in[16]	112
load	1
address[3]	5

Output pins

Name	Value
out[16]	0

HDL

```
* In words: the chip always outputs  
* location specified by address. If  
* into the memory location specifi  
* available through the out output  
*/  
  
CHIP RAM8 {  
  
    IN in[16], load, address[3];  
    OUT out[16];  
  
    BUILTIN RAM8;  
    CLOCKED in, load;  
}
```

RAM 8:

Address	Value
0	0
1	0
2	0
3	0
4	0
5	112
6	0
7	0

1. User: enters some input values and clicks the clock icon once (*tick*)

2. Simulator: changes the internal state of the chip, but note that the chip's output pin is not yet effected.

A built-in, clocked chip (**RAM8**) is loaded

Simulating Clocked Chips

Hardware Simulator (1.3b1) - D:\hack\tools\BuiltIn\RAM8.hdl

File View Run Help

Chip Name: RAM8 (Clocked) Time: 0+

Input pins

Name	Value
in[16]	112
load	1
address[3]	5

Output pins

Name	Value
out[16]	0

RAM 8:

0	0
1	0
2	0
3	0
4	0
5	112
6	0
7	0

HDL

```
/**
 * Memory of 8 registers, each 16 bit
 * stored at the memory location spe
 * memory location specified by add
 * from the next time step.)
 */

CHIP RAM8 {
    IN in[16], load, address[3];
    OUT out[16];

    BUILTIN RAM8;
}
```

Annotations:

- 1. User: enters some input values and clicks the clock icon once (*tick*)
- 2. Simulator: changes the internal state of the chip, but note that the chip's output pin is not yet effected.
- 3. User: clicks the clock icon again (*tock*)
- A built-in, clocked chip (**RAM8**) is loaded

Simulating Clocked Chips

Hardware Simulator (1.4b1) - G:\TECS\tools\builtIn\RAM8.hdl

File View Run Help

Chip Name: Time: 1

Input pins

Name	Value
in[16]	112
load	1
address[3]	5

Output pins

Name	Value
out[16]	112

RAM 8:

0	0
1	0
2	0
3	0
4	0
5	112
6	0
7	0

HDL

```
* In words: the chip always outputs  
* location specified by address. If  
* into the memory location specifi  
* available through the out output  
*/  
  
CHIP RAM8 {  
  
  IN in[16], load, address[3];  
  OUT out[16];  
  
  BUILTIN RAM8;  
  CLOCKED in, load;  
}
```

1. User: enters some input values and clicks the clock icon once (*tick*)

2. Simulator: changes the internal state of the chip, but note that the chip's output pin is not yet effected.

3. User: clicks the clock icon again (*tock*)

4. Simulator: commits the chip's output pin to the value of the chip's internal state.

A built-in, clocked chip (**RAM8**) is loaded

Simulating Clocked Chips Using a Test Script

The screenshot shows the Hardware Simulator (1.1b) interface. The title bar indicates the file path: D:\hack\tools\BuiltIn\RAM8.hdl. The menu bar includes File, View, Run, and Help. The toolbar contains icons for loading a chip, single-action tick-tock, repeated tick-tocks, and a clock icon. The 'Chip Name' field is set to 'RAM8 (Clocked)' and the 'Time' field is set to '1'. The 'Input pins' table shows values for 'in[16]', 'load', and 'address'. The 'Output pins' table shows values for 'out[16]'. The 'HDL' window displays the chip definition code. The 'Script' window shows the default script: 'Repeat { Tick, Tock; }'. A 'View' dropdown menu is open, showing options: Script, Output, Compare, and Screen. The 'Script' option is selected.

Chip Name: RAM8 (Clocked) Time: 1

Input pins

Name	Value
in[16]	112
load	1
address	5

Output pins

Name	Value
out[16]	112

HDL

```
// 8-registers memory
CHIP RAM8 {
    IN in[16], load, address[3];
    OUT out[16];

    BUILTIN RAM8;

    CLOCKED in, load;
}
```

Script

```
Repeat {
    Tick,
    Tock;
}
```

Controls the script speed, and thus the simulated clock speed, and thus the overall chip execution speed

Single-action tick-tock

Tick-tocks repeatedly and infinitely

Default script: always loaded when the simulator starts running;

The logic of the default script simply runs the clock repeatedly;

Hence, executing the default script has the effect of causing the clock to go through an infinite train of tics and tocks.

This, in turn, causes all the clocked chip parts of the loaded chip to react to clock cycles, repeatedly.



Built-in Chips with GUI Effects

Hardware Simulator (1.1b) - E:\GUIDemo.hdl

File View Run Help

Animate: Program flow Format: Decimal View: Screen

Chip Name: GUIDemo (Clocked) Time: 0

Input pins		Output pins	
Name	Value	Name	Value
in[16]	0	out[16]	0
load	0		
address[15]	0		

HDL

```
// demo GUI-empowered chips
CHIP GUIDemo {
  IN in[16],load,address[15];
  OUT out[16];

  PARTS:
  RAM16K(in=in,load=load,
    address=address[0..13],
    out=a);
  Screen(in=in,load=load,
    address=address[0..12],
    out=b);
  Keyboard(out=c);
}
```

Internal pins

Name	Value
	0
	0
	0

1. A chip whose parts include **built-in chips** was loaded into the simulator (ignore the chip logic for now)

Note: the signature of the internal part does not reveal if the part is implemented by a built-in chip or by another chip built by the user. Thus in this example you have to believe us that all the parts of this loaded chip are built-in chips.

Built-in Chips with GUI Effects

The screenshot shows the Hardware Simulator (1.1b) interface. The title bar reads "Hardware Simulator (1.1b) - E:\GUIDemo.hdl". The menu bar includes "File", "View", "Run", and "Help". The toolbar contains icons for running the simulation (play, fast play, stop, reset, single step, clock, memory, and a speaker for audio). The "Animate" dropdown is set to "Program flow", "Format" is "Decimal", and "View" is "Screen".

The "Chip Name" field shows "GUIDemo (Clocked)" and the "Time" is "0". The "Input pins" table has columns "Name" and "Value":

Name	Value
in[16]	0
load	0
address[15]	0

The "HDL" window shows the following code:

```
// demo GUI-empowered chips
CHIP GUIDemo {
  IN in[16],load,address[15];
  OUT out[16];

  PARTS:
    RAM16K(in=in,load=load,
      address=address[0..13],
      out=a);
    Screen(in=in,load=load,
      address=address[0..12],
      out=b);
    Keyboard(out=c);
}
```

The "Internal pins" window shows a table with columns "Name" and "Value":

Name	Value
a	0
b	0
c	0

The "RAM 16K" window shows a table with columns "Address" and "Value":

Address	Value
0	0
1	0
2	0
3	0
4	0
5	0
6	0

The "Screen" window shows a keyboard icon and a display area. The "Keyboard" window shows a keyboard icon and a display area.

Annotations:

- 2. If the loaded chip or some of its parts have GUI side-effects, the simulator displays the GUI's here.
- 1. A chip whose parts include built-in chips was loaded into the simulator (ignore the chip logic for now)
- GUI of the built-in RAM16K.hdl chip
- GUI of the built-in Keyboard.hdl chip

The Logic of the GUIDemo Chip

```
// Demo of built-in chips with GUI effects
CHIP GUIDemo {
    IN in[16],load,address[15];
    OUT out[16];
    PARTS:
        RAM16K(in=in,load=load,address=address[0..13],out=null);
        Screen(in=in,load=load,address=address[0..12],out=null);
        Keyboard(out=null);
}
```

RAM16K,
Screen, &
Keyboard
are built-in
chips with GUI
side-effects

- **Effect:** When the simulator evaluates this chip, it displays the GUI side-effects of its built-in chip parts
- **Chip logic:** The only purpose of this demo chip is to force the simulator to show the GUI of some built-in chips. Other than that, the chip logic is meaningless: it simultaneously feeds the 16-bit data input (**in**) into the **RAM16K** and the **Screen** chips, and it does nothing with the keyboard.

GUIDemo Chip in Action

Hardware Simulator (1.1b) - E:\GUIDemo.hdl

File View Run Help

Chip Name: GUIDemo (Clocked) Time: 5+

Input pins

Name	Value
in[16]	-1
load	1
address[15]	5012

Output pins

Name	Value
out[16]	0

2. User: runs the clock

3. 16 black pixels are drawn beginning in row = 156 col = 320

1. User enters:

- in = -1 (=16 1's in binary)
- address = 5012
- load = 1

HDL

```
// demo GUI-empowered chips
CHIP GUIDemo {
  IN in[16], load, address[15];
  OUT out[16];

  PARTS:
    RAM16K(in=in, load=load,
      address=address[0..13],
      out=a);
    Screen(in=in, load=load,
      address=address[0..12],
      out=b);
    Keyboard(out=c);
}
```

RAM 16K

Explanation: According to the specification of the computer architecture described in the book, the pixels of the physical screen are continuously refreshed from an 8K RAM-resident memory map implemented by the **Screen.hdl** chip. The exact mapping between this memory chip and the actual pixels is specified in Chapter 5. The refresh process is carried out by the simulator.



System Variables

The simulator recognizes and maintains the following variables:

- Time: the number of time-units (clock-cycles) that elapsed since the script started running is stored in the variable `time`
- Pins: the values of all the input, output, and internal pins of the simulated chip are accessible as variables, using the names of the pins in the HDL code
- GUI elements: the values stored in the states of GUI-empowered built-in chips can be accessed via variables. For example, the value of register 3 of the `RAM8` chip can be accessed via `RAM8[3]`.

All these variables can be used in scripts and *breakpoints*, for debugging.

Breakpoints

Hardware Simulator (1.1b) - D:\hack\tools\BuiltIn\RAM8.hdl

File View Run Help

Chip Name: RAM8 (Clocked) Time: 1

Input pins

Name	Value
in[16]	
load	
address[3]	

Output pins

Name	Value
out[16]	112

Breakpoint Panel

Variable Name	Value
Time	15
In	1024
RAM8[3]	172

RAM 8:

0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0

1. Open the breakpoints panel

2. Previously-declared breakpoints

3. To update an existing breakpoint, double-click it

3. Add, delete, or update breakpoints

HDL

```
// 8-registers memory
CHIP RAM8 {
```

The breakpoints logic:

- Breakpoint = (variable, value)
- When the specified variable in some breakpoint reaches its specified value, the script pauses and a message is displayed
- A powerful debugging tool.

Scripts for Testing the Topmost Computer chip

```
load Computer.hdl
ROM32K load Max.hack,
output-file ComputerMax.out,
compare-to ComputerMax.cmp,
output-list time%S1.4.1
    reset%B2.1.2
    ARegister[]%D1.7.1
    DRegister[]%D1.7.1
    PC[]%D0.4.0
    RAM16K[0]%D1.7.1
    RAM16K[1]%D1.7.1
    RAM16K[2]%D1.7.1;
breakpoint PC 10;
// First run: compute max(3,5)
set RAM16K[0] 3,
set RAM16K[1] 5,
output;
repeat 14 {
    tick, tock, output;
}
// Reset the PC (preparing for
// second run)
set reset 1,
tick, tock, output;
// Etc.
clear-breakpoints;
```

- Scripts that test the CPU chip or the Computer chip described in the book usually start by loading a machine-language program (.asm or .hack file) into the ROM32K chip
- The rest of the script typically uses various features like:
 - Output files
 - Loops
 - Breakpoints
 - Variables manipulation
 - tick, tock
 - Etc.
- All these features are described in Appendix B of the book (*Test Scripting Language*).

Visual Options

The screenshot shows the Hardware Simulator (1.1b) window. The title bar reads "Hardware Simulator (1.1b) - D:\hack\tools\BuiltIn\RAM8.hdl". The menu bar includes "File", "View", "Run", and "Help". The toolbar contains icons for loading a chip, running, pausing, and stepping through the simulation, along with a speed slider between "Slow" and "Fast". The "Animate:" dropdown is set to "Program flow", "Format:" is set to "Decimal", and "View:" is set to "Screen". Below the toolbar, the "Chip Name:" field is "RAM8 (Clocked)" and the "Time:" field is "1". The "Input pins" table shows "in[16]" with value "112" and "load address" with value "112". The "Output pins" table is empty. The "HDL" window shows code for an 8-register chip. Three callout boxes provide details on the visual options.

Chip Name: RAM8 (Clocked) Time: 1

Input pins

Name	Value
in[16]	112
load address	112

Output pins

Name	Value

Format of displayed pin values:

- **Decimal** (default)
- **Hexadecimal**
- **Binary**

Visual Options:

- **Program flow:** animates the flow of the currently loaded program
- **Program & data flow:** animates the flow of the current program and the data flow throughout the GUI elements displayed on the screen
- **No animation** (default): program and data flow are not animated.
- **Tip:** When running *programs* on the **CPU** or **Computer** chip, any animation effects slow down the simulation considerably.

Script Options:

- **Script:** displays the current test script
- **Output:** displays the generated output file
- **Compare:** displays the supplied comparison file
- **Screen:** displays the GUI effects of built-in chips, if any.



The Hack Chip-Set and Hardware Platform

Elementary logic gates

(Project 1):

- **Nand** (primitive)
- **Not**
- **And**
- **Or**
- **Xor**
- **Mux**
- **Dmux**
- **Not16**
- **And16**
- **Or16**
- **Mux16**
- **Or8Way**
- **Mux4Way16**
- **Mux8Way16**
- **DMux4Way**
- **DMux8Way**

Combinational chips

(Project 2):

- **HalfAdder**
- **FullAdder**
- **Add16**
- **Inc16**
- **ALU**

Sequential chips

(Project 3):

- **DFF** (primitive)
- **Bit**
- **Register**
- **RAM8**
- **RAM64**
- **RAM512**
- **RAM4K**
- **RAM16K**
- **PC**

Computer Architecture

(Project 5):

- **Memory**
- **CPU**
- **Computer**

Most of these chips are generic, meaning that they can be used in the construction of many different computers.

The Hack chip-set and hardware platform can be built using the hardware simulator, starting with primitive **Nand.hdl** and **DFF.hdl** gates and culminating in the **Computer.hdl** chip.

This construction is described in chapters 1,2,3,5 of the book, and carried out in the respective projects.

Aside: H.D. Thoreau about chips, bugs, and close observation:

I was surprised to find that the chips were covered with such combatants, that it was not a duellum, but a bellum, a war between two races of ants, the red always pitted against the black, and frequently two red ones to one black. The legions of these Myrmidons covered all the hills and vales in my wood-yard, and the ground was already strewn with the dead and dying, both red and black.



It was the only battle which I have ever witnessed, the only battlefield I ever trod while the battle was raging; internecine war; the red republicans on the one hand, and the black imperialists on the other. On every side they were engaged in deadly combat, yet without any noise that I could hear, and human soldiers never fought so resolutely.... The more you think of it, the less the difference. And certainly there is not the fight recorded in Concord history, at least, if in the history of America, that will bear a moment's comparison with this, whether for the numbers engaged in it, or for the patriotism and heroism displayed.

From "Brute Neighbors," Walden (1854).