

Chapter 1

Boolean Logic

These slides support chapter 1 of the book

The Elements of Computing Systems

(1st and 2nd editions)

By Noam Nisan and Shimon Schocken

MIT Press

Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

Practice

- Logic gates
- HDL
- Hardware simulation
- Multi-bit buses

Project 1

- Introduction
- Chips
- Guidelines

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Boolean values



off no false 0



on yes true 1



George Boole
1815 - 1864

- Boolean / binary *values*: 0, 1
- Boolean / binary *variable*: holds a 0, or a 1

Boolean values

$b_1 \quad b_0$



1 binary variable: 2 possible states

Boolean values

$b_1 \quad b_0$



1 binary variable: 2 possible states



2 binary variables: 4 possible states



Boolean values

... $b_2 \ b_1 \ b_0$



1 binary variable: 2 possible states



2 binary variables: 4 possible states



3 binary variables: 8 possible states

...



Boolean values

... $b_2 \ b_1 \ b_0$



1 binary variable: 2 possible states



2 binary variables: 4 possible states



3 binary variables: 8 possible states

...



Question: How many different states can be represented by N binary variables?



Answer: 2^N



Boolean functions

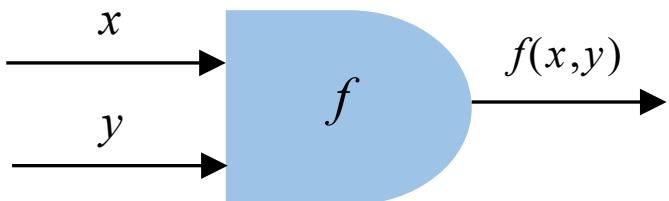
x	y	f

Boolean functions

x	y	f
0	0	0
0	1	0
1	0	0
1	1	1

Boolean functions

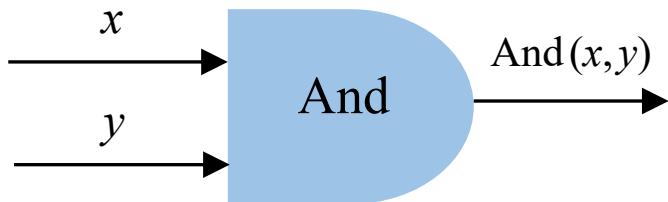
x	y	f
0	0	0
0	1	0
1	0	0
1	1	1



$$f(x,y) = \begin{cases} 1 & \text{when } x == 1 \text{ and } y == 1 \\ 0 & \text{otherwise} \end{cases}$$

Boolean functions

x	y	And
0	0	0
0	1	0
1	0	0
1	1	1



$$\text{And}(x,y) = \begin{cases} 1 & \text{when } x == 1 \text{ and } y == 1 \\ 0 & \text{otherwise} \end{cases}$$

Boolean function (like $\text{And}(x,y)$):

A function that operates on boolean variables, and returns a boolean value.

Boolean operator (like $x \text{ And } y$):

A simple boolean function that operates on a few boolean variables, called *operands*.

Boolean functions

x And y

x	y	And
0	0	0
0	1	0
1	0	0
1	1	1

x Or y

x	y	Or
0	0	0
0	1	1
1	0	1
1	1	1

Question:

How many Boolean functions
 $x \text{ } f \text{ } y$ exist over two binary
(2-valued) variables?

Answer: 16

N binary variables span 2^{2^N}
Boolean functions.

x Nand y

x	y	Nand
0	0	1
0	1	1
1	0	1
1	1	0

x Xor y

x	y	Xor
0	0	0
0	1	1
1	0	1
1	1	0

• • •

$x \text{ } f \text{ } y$

x	y	f
0	0	v_1
0	1	v_2
1	0	v_3
1	1	v_4

Boolean functions

x And y

x	y	And
0	0	0
0	1	0
1	0	0
1	1	1

x Or y

x	y	Or
0	0	0
0	1	1
1	0	1
1	1	1

Not(x)

y	Not
0	1
1	0

Boolean function evaluation (example):

$$\text{Not}(x \text{ Or } (y \text{ And } z))$$

Evaluate this function for, say,
 $x = 0, y = 1, z = 1$

$$\text{Not}(0 \text{ Or } (1 \text{ And } 1)) =$$

$$\text{Not}(0 \text{ Or } 1) =$$

$$\text{Not}(1) =$$

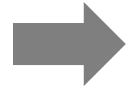
$$0$$

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Basic concepts



Boolean algebra

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Some Boolean identities

Commutative: $x \text{ And } y = y \text{ And } x$
 $x \text{ Or } y = y \text{ Or } x$

Associative: $x \text{ And } (y \text{ And } z) = (x \text{ And } y) \text{ And } z$
 $x \text{ Or } (y \text{ Or } z) = (x \text{ Or } y) \text{ Or } z$

Distributive: $x \text{ And } (y \text{ Or } z) = (x \text{ And } y) \text{ Or } (x \text{ And } z)$
 $x \text{ Or } (y \text{ And } z) = (x \text{ Or } y) \text{ And } (x \text{ Or } z)$

De Morgan: $\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$
 $\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)$

Idempotent: $x \text{ And } x = x$
 $x \text{ Or } x = x$

Double negation: $\text{Not}(\text{Not}(x)) = x$

Some Boolean identities

Commutative: $x \text{ And } y = y \text{ And } x$
 $x \text{ Or } y = y \text{ Or } x$

Associative: $x \text{ And } (y \text{ And } z) = (x \text{ And } y) \text{ And } z$
 $x \text{ Or } (y \text{ Or } z) = (x \text{ Or } y) \text{ Or } z$

Distributive: $x \text{ And } (y \text{ Or } z) = (x \text{ And } y) \text{ Or } (x \text{ And } z)$
 $x \text{ Or } (y \text{ And } z) = (x \text{ Or } y) \text{ And } (x \text{ Or } z)$

De Morgan: $\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$
 $\boxed{\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)}$

Idempotent: $x \text{ And } x = x$
 $x \text{ Or } x = x$

Double negation: $\text{Not}(\text{Not}(x)) = x$

All these identities can be
easily proved from the
function definitions of
And, Or, Not

For example, let's
prove this identity

Boolean algebra

Prove

$$\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$$

Boolean algebra

Prove

$$\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$$

$$f(x,y) = \text{Not}(x \text{ And } y)$$

x	y	f
0	0	1
0	1	1
1	0	1
1	1	0

$$g(x,y) = \text{Not}(x) \text{ Or } \text{Not}(y)$$

x	y	g
0	0	1
0	1	1
1	0	1
1	1	0

Proof: Fill in the right column in both truth tables.

If $f = g$, the identity is proved.

Boolean algebra

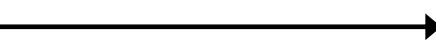
Commutative: $x \text{ And } y = y \text{ And } x$
 $x \text{ Or } y = y \text{ Or } x$

Associative: $x \text{ And } (y \text{ And } z) = (x \text{ And } y) \text{ And } z$
 $x \text{ Or } (y \text{ Or } z) = (x \text{ Or } y) \text{ Or } z$

Distributive: $x \text{ And } (y \text{ Or } z) = (x \text{ And } y) \text{ Or } (x \text{ And } z)$
 $x \text{ Or } (y \text{ And } z) = (x \text{ Or } y) \text{ And } (x \text{ Or } z)$

De Morgan: $\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$
 $\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)$

Idempotent: $x \text{ And } x = x$
 $x \text{ Or } x = x$

Double negation: $\text{Not}(\text{Not}(x)) = x$ 

Substitution:

In any such identity, x and y can be substituted with any boolean function

Substitution examples:

$$\text{Not}(\text{Not}(a)) = a$$

$$\text{Not}(\text{Not}(u \text{ Or } v)) = u \text{ Or } v$$

Etc.

Boolean algebra

Commutative: $x \text{ And } y = y \text{ And } x$
 $x \text{ Or } y = y \text{ Or } x$

Associative: $x \text{ And } (y \text{ And } z) = (x \text{ And } y) \text{ And } z$
 $x \text{ Or } (y \text{ Or } z) = (x \text{ Or } y) \text{ Or } z$

Distributive: $x \text{ And } (y \text{ Or } z) = (x \text{ And } y) \text{ Or } (x \text{ And } z)$
 $x \text{ Or } (y \text{ And } z) = (x \text{ Or } y) \text{ And } (x \text{ Or } z)$

De Morgan: $\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$
 $\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)$

Idempotent: $x \text{ And } x = x$
 $x \text{ Or } x = x$

Double negation: $\text{Not}(\text{Not}(x)) = x$

Task: Simplify this function (example):

Not(Not(x) And Not(x Or y)) =

By De Morgan's rule:

$\text{Not}(\text{Not}(x) \text{ And } (\text{Not}(x) \text{ And } \text{Not}(y))) =$

By the associative rule:

$\text{Not}((\text{Not}(x) \text{ And } \text{Not}(x)) \text{ And } \text{Not}(y)) =$

By the idempotent rule:

$\text{Not}(\text{Not}(x) \text{ And } \text{Not}(y)) =$

By De Morgan's rule:

$\text{Not}(\text{Not}(x \text{ Or } y)) =$

By double negation:

$x \text{ Or } y$

Boolean algebra

Observations about simplifying Boolean functions:

- Can lead to significant optimization
- Based on intuition, experience, and luck
- Can be assisted by some tools
- But, in general: *NP*-hard.

Task: Simplify this function (example):

$$\mathbf{Not(Not(x) \ And \ Not(x \ Or \ y))} =$$

By De Morgan's rule:

$$\mathbf{Not(Not(x) \ And \ (Not(x) \ And \ Not(y)))} =$$

By the associative rule:

$$\mathbf{Not((Not(x) \ And \ Not(x)) \ And \ Not(y))} =$$

By the idempotent rule:

$$\mathbf{Not(Not(x) \ And \ Not(y))} =$$

By De Morgan's rule:

$$\mathbf{Not(Not(x \ Or \ y))} =$$

By double negation:

$$\mathbf{x \ Or \ y}$$

Boolean algebra

Commutative: $(x \text{ And } y) = (y \text{ And } x)$
 $(x \text{ Or } y) = (y \text{ Or } x)$

Associative: $(x \text{ And } (y \text{ And } z)) = ((x \text{ And } y) \text{ And } z)$
 $(x \text{ Or } (y \text{ Or } z)) = ((x \text{ Or } y) \text{ Or } z)$

Distributive: $(x \text{ And } (y \text{ Or } z)) = (x \text{ And } y) \text{ Or } (x \text{ And } z)$
 $(x \text{ Or } (y \text{ And } z)) = (x \text{ Or } y) \text{ And } (x \text{ Or } z)$

De Morgan: $\text{Not}(x \text{ And } y) = \text{Not}(x) \text{ Or } \text{Not}(y)$
 $\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)$

Idempotent: $(x \text{ And } x) = x$
 $(x \text{ Or } x) = x$

Double negation: $\text{Not}(\text{Not}(x)) = x$

Another example: Prove that

$$x \text{ Or } y = \text{Not}(\text{Not}(x) \text{ And } \text{Not}(y))$$

De Morgan:

$$\text{Not}(x \text{ Or } y) = \text{Not}(x) \text{ And } \text{Not}(y)$$

Negate both sides:

$$\text{Not}(\text{Not}(x \text{ Or } y)) = \text{Not}(\text{Not}(x) \text{ And } \text{Not}(y))$$

By double negation:

$$x \text{ Or } y = \text{Not}(\text{Not}(x) \text{ And } \text{Not}(y))$$

Implication

- We don't really "need" Or
- We will soon revisit this reduction

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Boolean function

Formula (example)

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$

Truth table

x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

A Boolean function can be expressed using a *formula*, or a *truth table*

The two representations are equivalent

Question: Can we construct each representation from the other one?

Formula \rightarrow truth table

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$



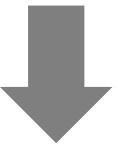
Truth table

x	y	z	f
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

Formula \rightarrow truth table

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$



Truth table

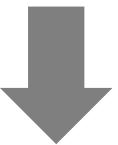
x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	
0	1	1	
1	0	0	0
1	0	1	0
1	1	0	
1	1	1	

When $y = 0, f$ must be 0

Formula \rightarrow truth table

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$



Truth table

x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	
1	1	1	

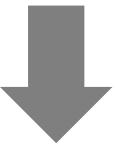
When $y = 0, f$ must be 0

When $x = 0, f$ must be 0

Formula \rightarrow truth table

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$



Truth table

x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

When $y = 0, f$ must be 0

When $x = 0, f$ must be 0

$(1 \text{ And} (\text{Not}(1) \text{ Or } 0)) \text{ And } 1 = 1$

$(1 \text{ And} (\text{Not}(1) \text{ Or } 1)) \text{ And } 1 = 1$

Formula \rightarrow truth table

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$

Truth table



x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

Lemma

Given a Boolean function expressed as a formula, we can always construct from it its truth table.

Proof: Evaluate the function over all the possible values of its variables (which is *the* definition of a truth table)

Boolean function synthesis: Truth table \rightarrow formula

Formula

$$f(x, y, z) = (x \text{ And} (\text{Not}(y) \text{ Or } z)) \text{ And } y$$

Truth table



x	y	z	f
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

Can we also go the other way around,
for any given truth table?

Boolean function synthesis: Truth table \rightarrow formula

x	y	z	f
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

Goal: Synthesize a formula which is equivalent to this truth table

Boolean function synthesis

x	y	z	f	f ₁	f ₃	f ₅
0	0	0	1	1	0	0
0	0	1	0	0	0	0
0	1	0	1	0	1	0
0	1	1	0	0	0	0
1	0	0	1	0	0	1
1	0	1	0	0	0	0
1	1	0	0	0	0	0
1	1	1	0	0	0	0

→ $(\text{Not}(x) \text{ And Not}(y) \text{ And Not}(z)) \text{ Or}$

→ $(\text{Not}(x) \text{ And } y \text{ And Not}(z))$ Or

→ $(x \text{ And Not}(y) \text{ And Not}(z))$

1. Focus on the rows where $f = 1$
2. For each such row i , define a function f_i which equals 1 in row i and 0 elsewhere.
Define f_i to be a conjunction of all of f 's variables or their negations, as the variable is 1 or 0 in the i 'th row
3. Define f to be the disjunction of all these conjunctions

Boolean function synthesis

x	y	z	f
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

$$\begin{aligned} & (\text{Not}(x) \text{ And Not}(y) \text{ And Not}(z)) \text{ Or} \\ & (\text{Not}(x) \text{ And } y \text{ And Not}(z)) \quad \text{Or} \\ & (x \text{ And Not}(y) \text{ And Not}(z)) \\ \hline & \text{Not}(z) \text{ And } (\text{Not}(x) \text{ Or Not}(y)) \end{aligned} \quad \left. \begin{array}{l} \text{Disjunctive} \\ \text{Normal} \\ \text{Form (DNF)} \end{array} \right\} \quad \begin{array}{l} \text{(following} \\ \text{simplification)} \end{array}$$

1. Focus on the rows where $f = 1$
2. For each such row i , define a function f_i which equals 1 in row i and 0 elsewhere.
Define f_i to be a conjunction of all of f 's variables or their negations, as the variable is 1 or 0 in the i 'th row
3. Define f to be the disjunction of all these conjunctions

Boolean function synthesis

x	y	z	f
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

Lemma

Given a boolean function expressed as a truth table, we can always synthesize a formula that expresses that function

Proof: Use the truth table to construct the DNF (which is a formula)

Theorem

Any boolean function can be represented as a formula containing only the operators And, Or, Not

Proof: Construct the function's truth table, then use the truth table to construct the DNF (which, by definition, uses only And, Or, Not).

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The expressive power of Nand

x Nand y		
x	y	Nand
0	0	1
0	1	1
1	0	1
1	1	0

x And y		
x	y	And
0	0	0
0	1	0
1	0	0
1	1	1

x Or y		
x	y	Or
0	0	0
0	1	1
1	0	1
1	1	1

Not(x)	
x	Not
0	1
1	0

Observations

- $\text{Not}(x) = x \text{ Nand } x$
- $x \text{ And } y = \text{Not}(x \text{ Nand } y)$
- $x \text{ Or } y = \text{Not}(\text{Not}(x) \text{ And } \text{Not}(y))$
(De Morgan)

In other words:

- Not can be realized using Nand
- And can be realized using Nand
- Or can be realized using Nand

Theorem: Any Boolean function can be realized using only Nand.

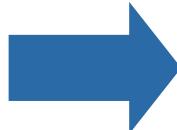
Proof : Any Boolean function can be expressed using Not, And, and Or (DNF). Combined with the above observations, we get the theorem.

The expressive power of Nand

Theorem: Any Boolean function can be realized using only Nand.

Conclusion: Any computer can be built from Nand gates only:

x Nand y		
x	y	Nand
0	0	1
0	1	1
1	0	1
1	1	0



Computers:
Machines that realize
Boolean functions:
 $f(\text{input bits}) = \text{output bits}$

OK, so we *can* build a computer from Nand gates only.

But how can we *actually* do it?

That's what the Nand to Tetris course is all about!

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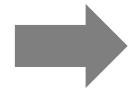


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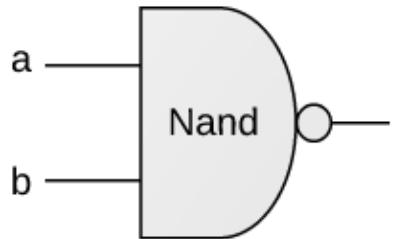
Logic gates



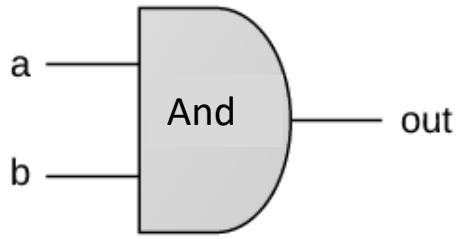
Elementary gates (Nand, And, Or, Not, ...)

- Composite gates (Mux, Adder, ...)

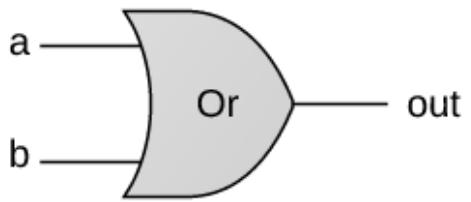
Elementary gates



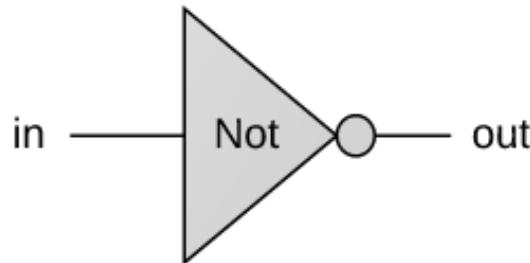
if (a==1 and b==1)
then out=0 else out=1



if (a==1 and b==1)
then out=1 else out=0



if (a==1 or b==1)
then out=1 else out=0

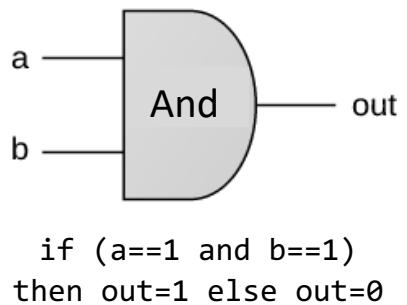


if (in==0)
then out=1 else out=0

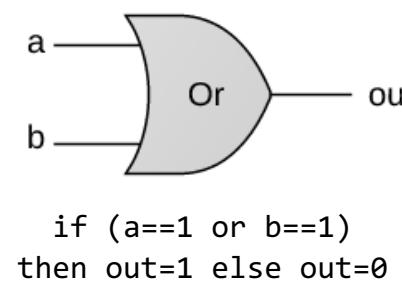
Why focus on these particular gates?

- Because either {Nand} or {And, Or, Not} (as well as other subsets) can be used to span any given Boolean function
- Because they have efficient hardware implementations.

Elementary gates

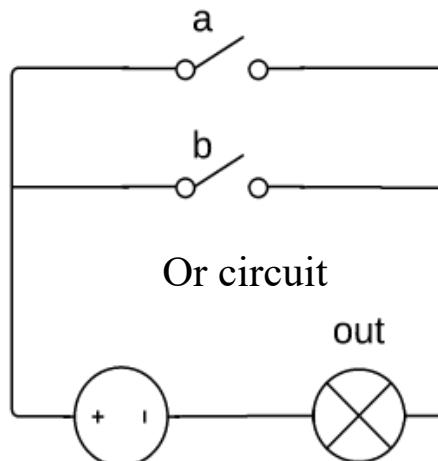
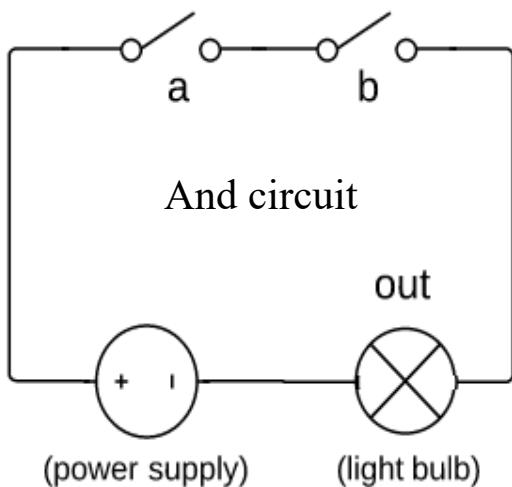


x	y	And
0	0	0
0	1	0
1	0	0
1	1	1

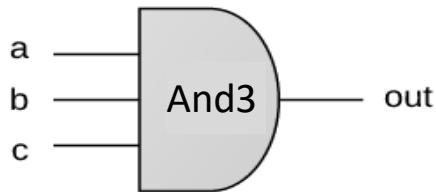


x	y	Or
0	0	0
0	1	1
1	0	1
1	1	1

Circuit implementations:

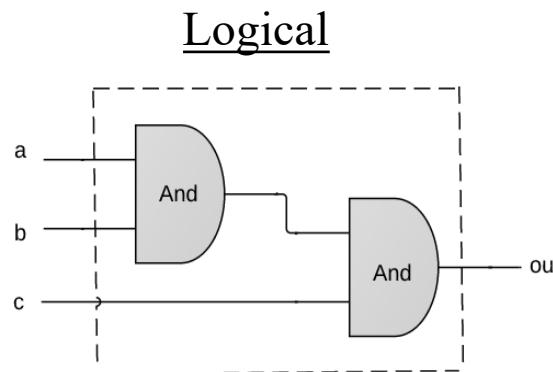
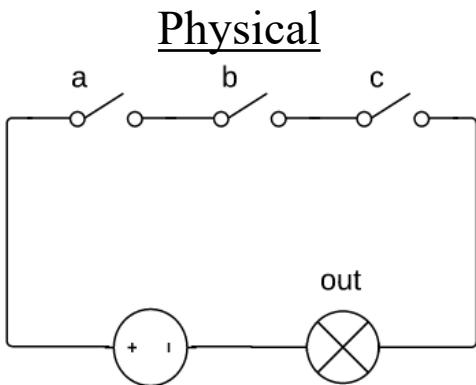


Composite gates



```
if (a==1 and b==1 and c==1)  
then out=1 else out=0
```

Possible implementations:



- This course does not deal with physical implementations
(circuits, transistors, relays... that's EE, not CS)
- We focus only on logical implementations

Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

Practice



Logic gates



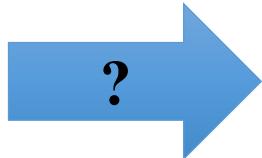
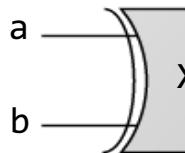
HDL

- Hardware simulation
- Multi-bit buses

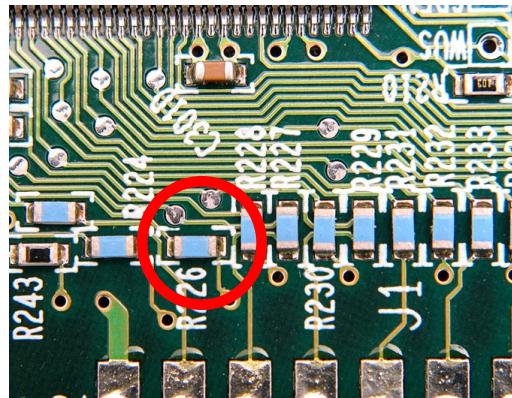
Project 1

- Introduction
- Chips
- Guidelines

Building a chip



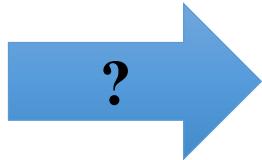
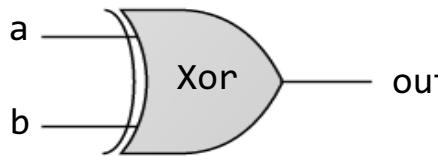
```
if ((a == 0 and b == 1) or (a == 1 and b == 0))  
    sets out = 1  
else  
    sets out = 0
```



The process

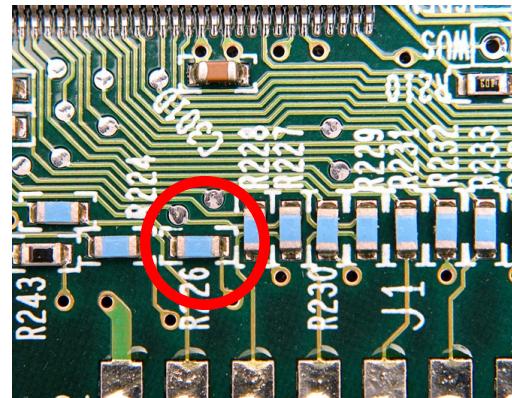
- Design the chip architecture
- Specify the architecture in HDL
- Test the chip in a hardware simulator
- Optimize the design
- Realize the optimized design in silicon.

Building a chip



?

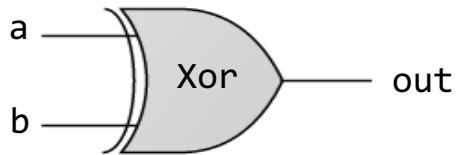
```
if ((a == 0 and b == 1) or (a == 1 and b == 0))  
    sets out = 1  
else  
    sets out = 0
```



The process

- ✓ Design the chip architecture
- ✓ Specify the architecture in HDL
- ✓ Test the chip in a hardware simulator
 - Optimize the design
 - Realize the optimized design in silicon.

Design: Requirements



```
if ((a == 0 and b == 1) or (a == 1 and b == 0))  
    sets out = 1  
else  
    sets out = 0
```

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

Requirement

Build a chip that delivers this functionality

```
/** Sets out = (a And Not(b)) Or (Not(a) And b) */  
  
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        // Missing implementation
```

Gate Interface

Expressed as an HDL *stub file*

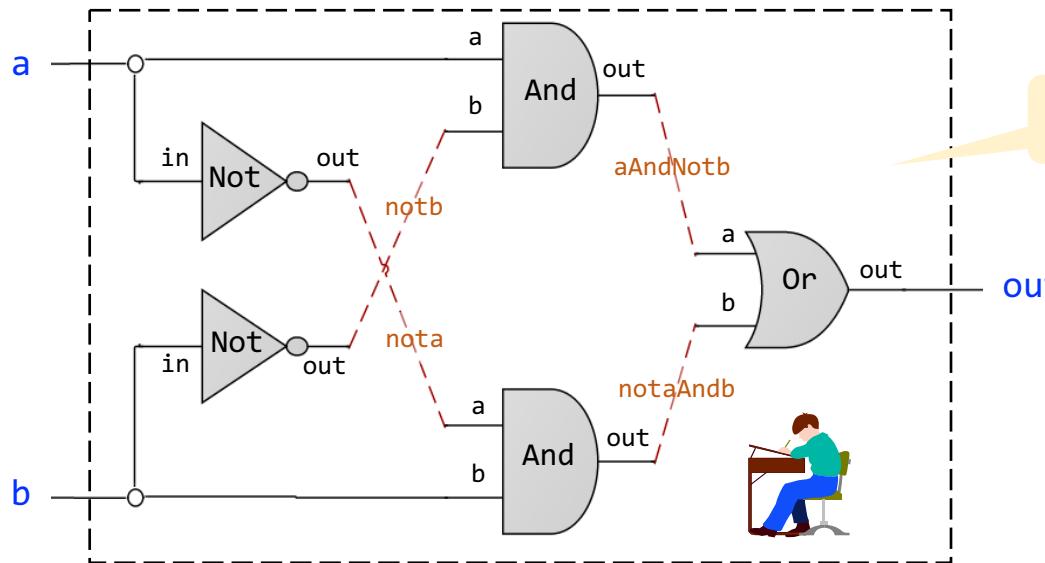
Design: Implementation

```
/** Sets out = (a And Not(b)) Or (Not(a) And b) */
CHIP Xor {
    IN a, b;
    OUT out;
    PARTS:
        // Missing implementation
```

Gate Interface

Expressed as an
HDL *stub file*

Design: Implementation



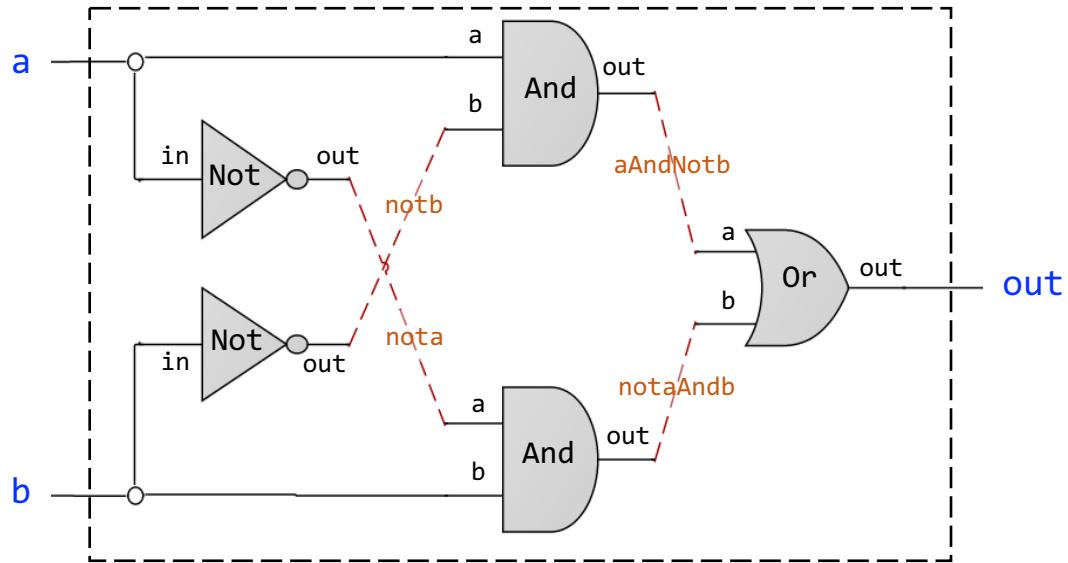
Gate diagram

```
/** Sets out = (a And Not(b)) Or (Not(a) And b) */
CHIP Xor {
    IN a, b;
    OUT out;
    PARTS:
        // Missing implementation
}
```

Gate Interface

Expressed as an
HDL *stub file*

Design: Implementation

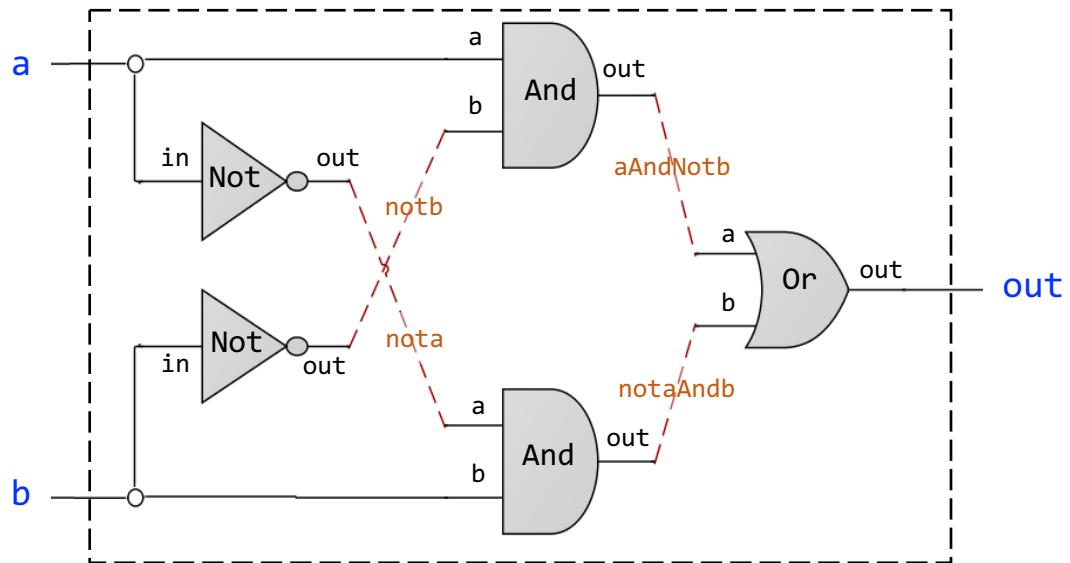


```
/** Sets out = (a And Not(b)) Or (Not(a) And b) */
CHIP Xor {
    IN a, b;
    OUT out;
    PARTS:
        Not (in=a, out=nota);
        Not (in=b, out=notb);
        And (a=a, b=notb, out=aAndNotb);
        And (a=nota, b=b, out=notaAndb);
}
```



Practice: Complete the missing HDL code

Design: Implementation



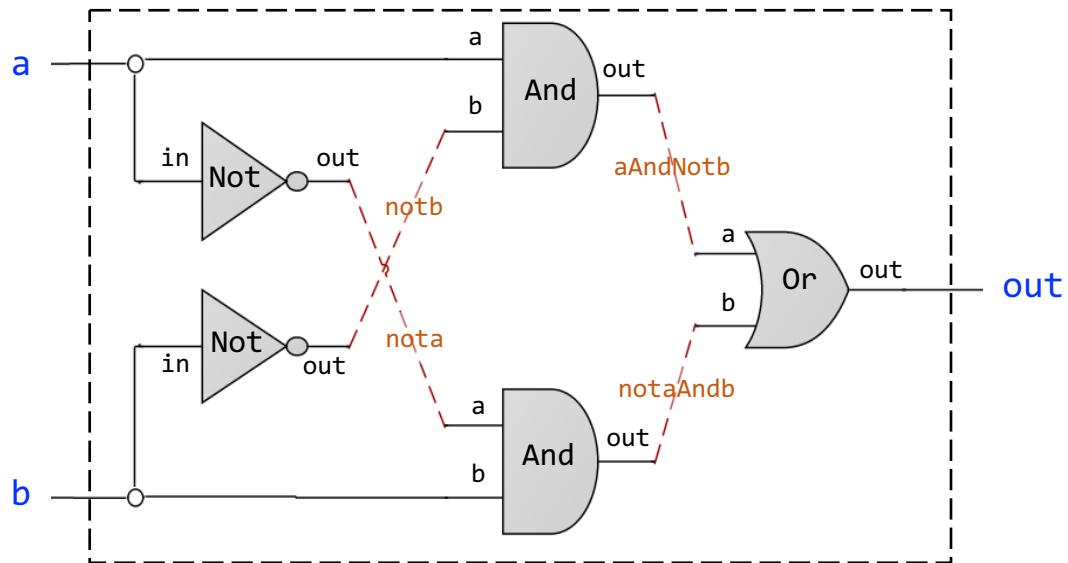
```
/** Sets out = (a And Not(b)) Or (Not(a) And b) */

CHIP Xor {
    IN a, b;
    OUT out;

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



Interface / Implementation



gate interface {
 `/** Sets out = (a And Not(b)) Or (Not(a) And 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=aAndNotb);
 And (a=nota, b=b, out=notaAndb);
 Or (a=aAndNotb, b=notaAndb, out=out);
 }

A logic gate has:

- One interface
- Many possible implementations

Hardware description languages

Observations:

- HDL is a functional / declarative language
- An HDL program can be viewed as a textual specification of a chip diagram
- The order of HDL statements is insignificant.

```
/** Sets out = (a And Not(b)) Or (Not(a) And 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=aAndNotb);
        And (a=nota, b=b, out=notaAndb);
        Or  (a=aAndNotb, b=notaAndb, out=out);
}
```

Hardware description languages

Common HDLs

- VHDL
- Verilog
- ...

Our HDL

- Similar in spirit to other HDLs
- Minimal and simple
- Provides all you need for this course

Our HDL Guide / Documentation:

[The Elements of Computing Systems / Appendix 2: HDL](#)

```
/** Sets out = (a And Not(b)) Or (Not(a) And 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=aAndNotb);
        And (a=nota, b=b, out=notaAndb);
        Or  (a=aAndNotb, b=notaAndb, out=out);
}
```

Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

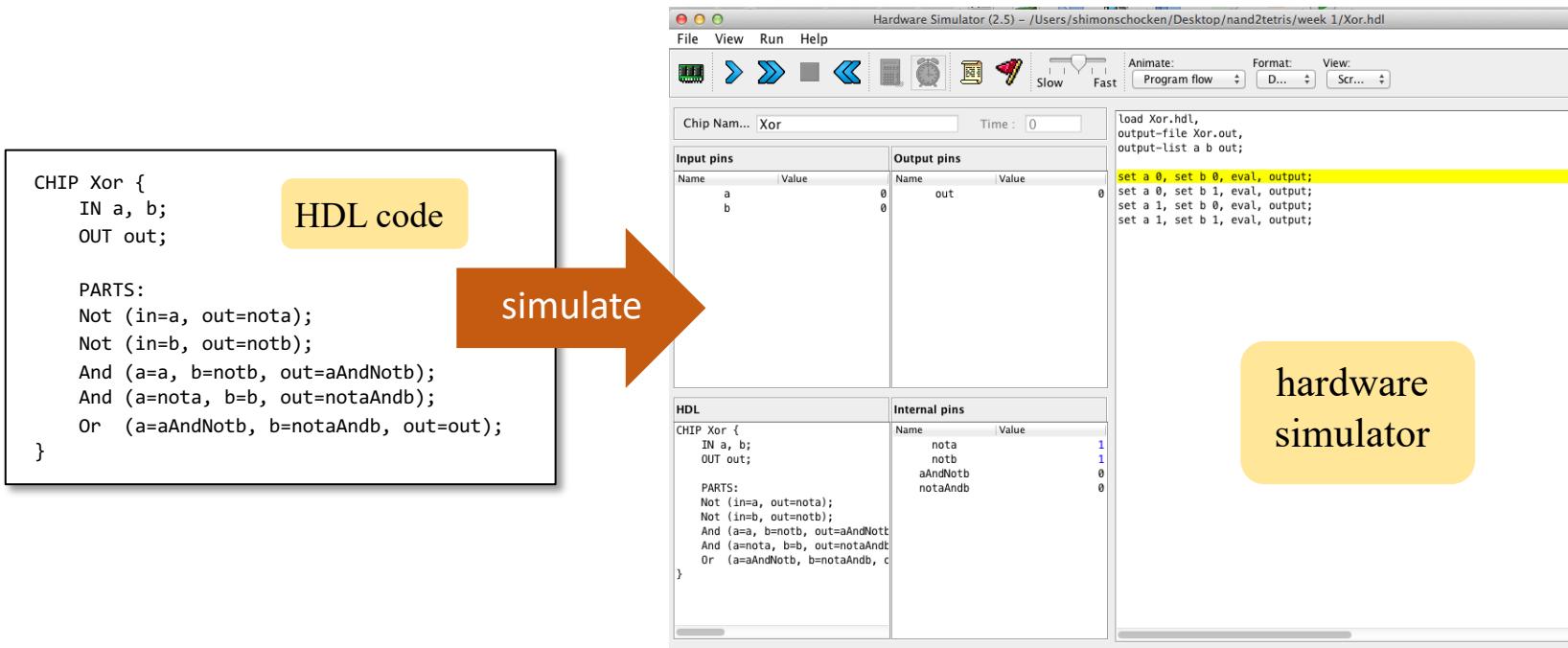
Practice

- ✓ Logic gates
- ✓ HDL
- Hardware simulation
- Multi-bit buses

Project 1

- Introduction
- Chips
- Guidelines

Hardware simulation in a nutshell

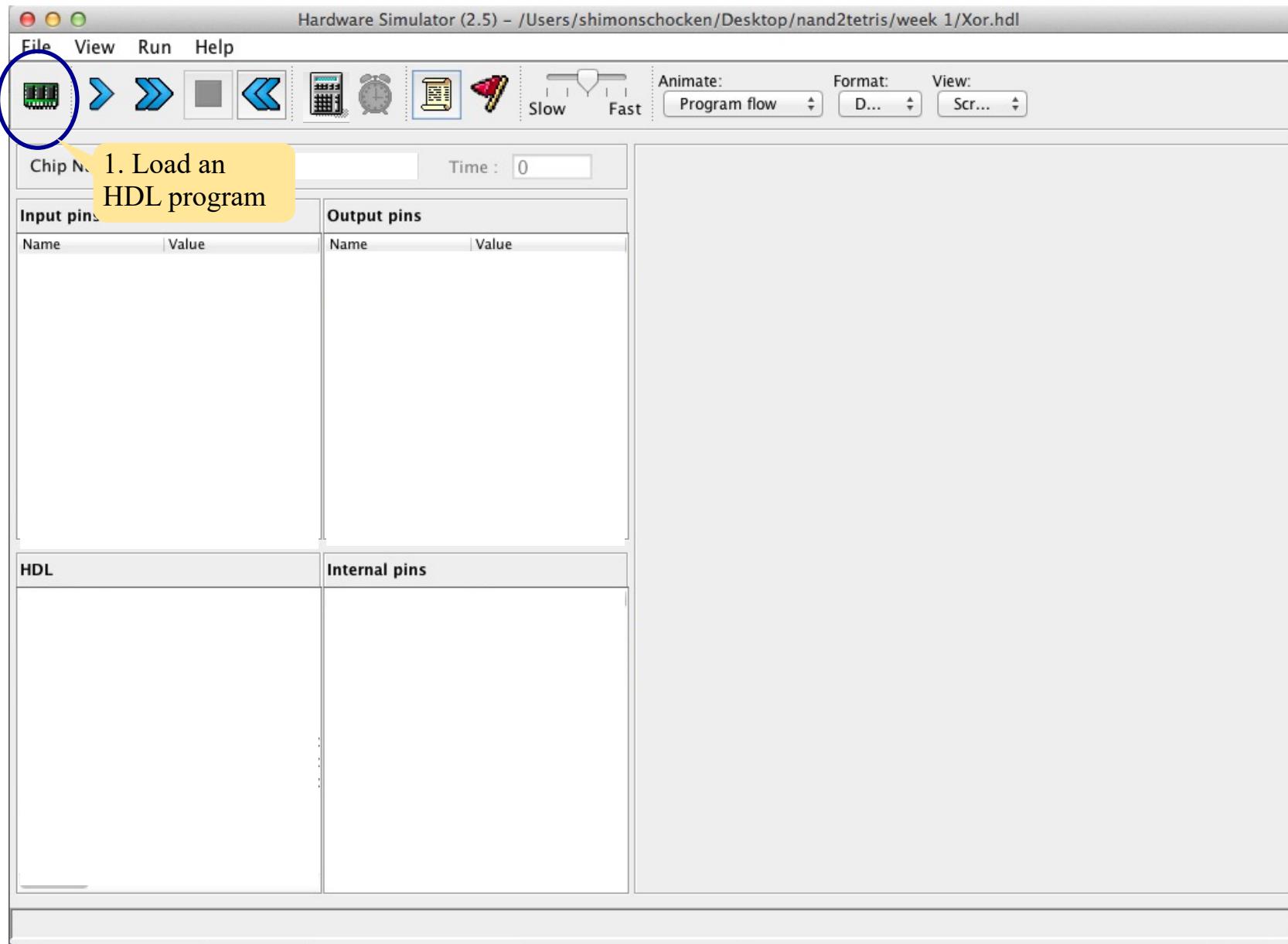


Simulation options

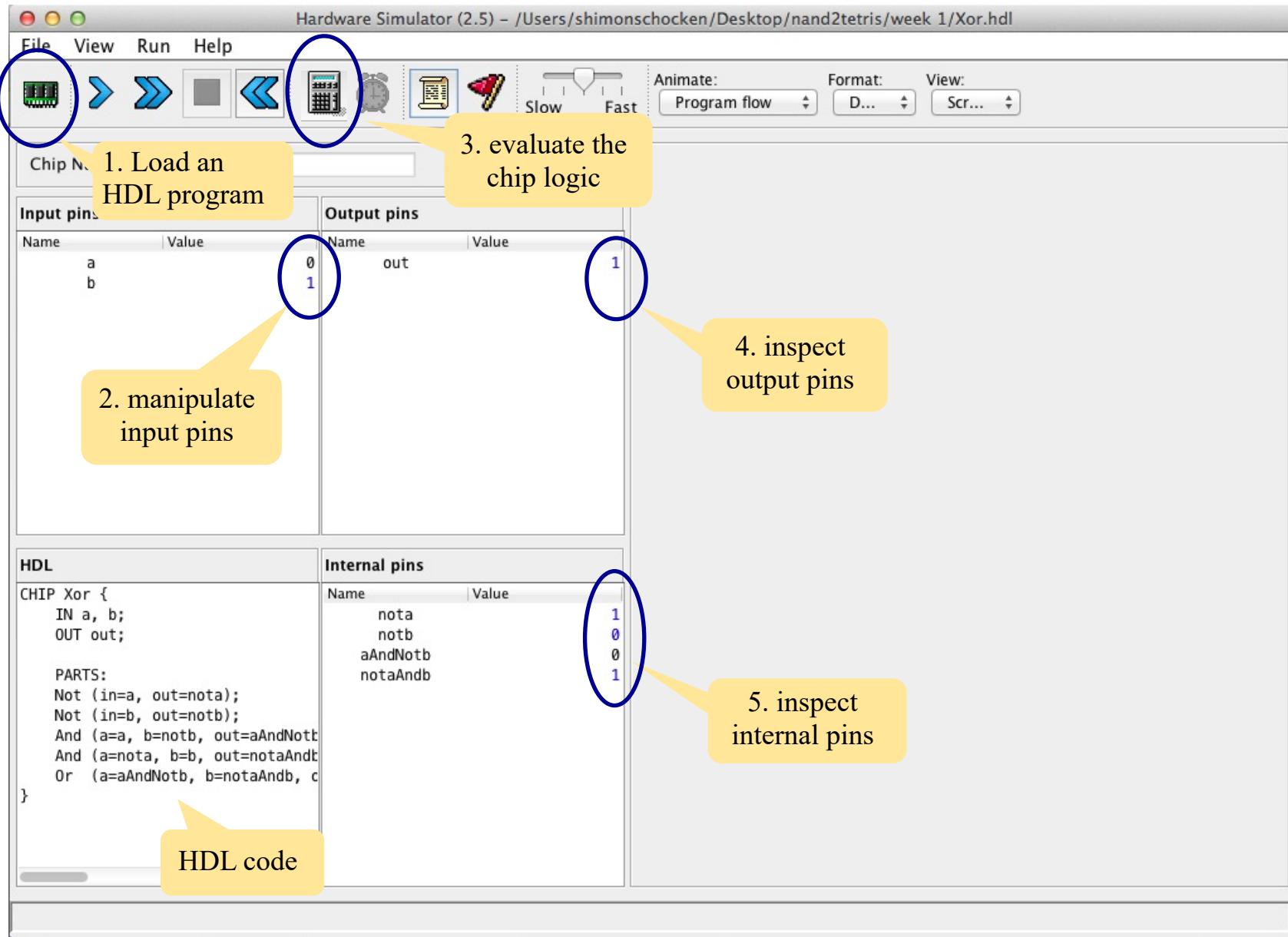
→ Interactive

- Script-based.

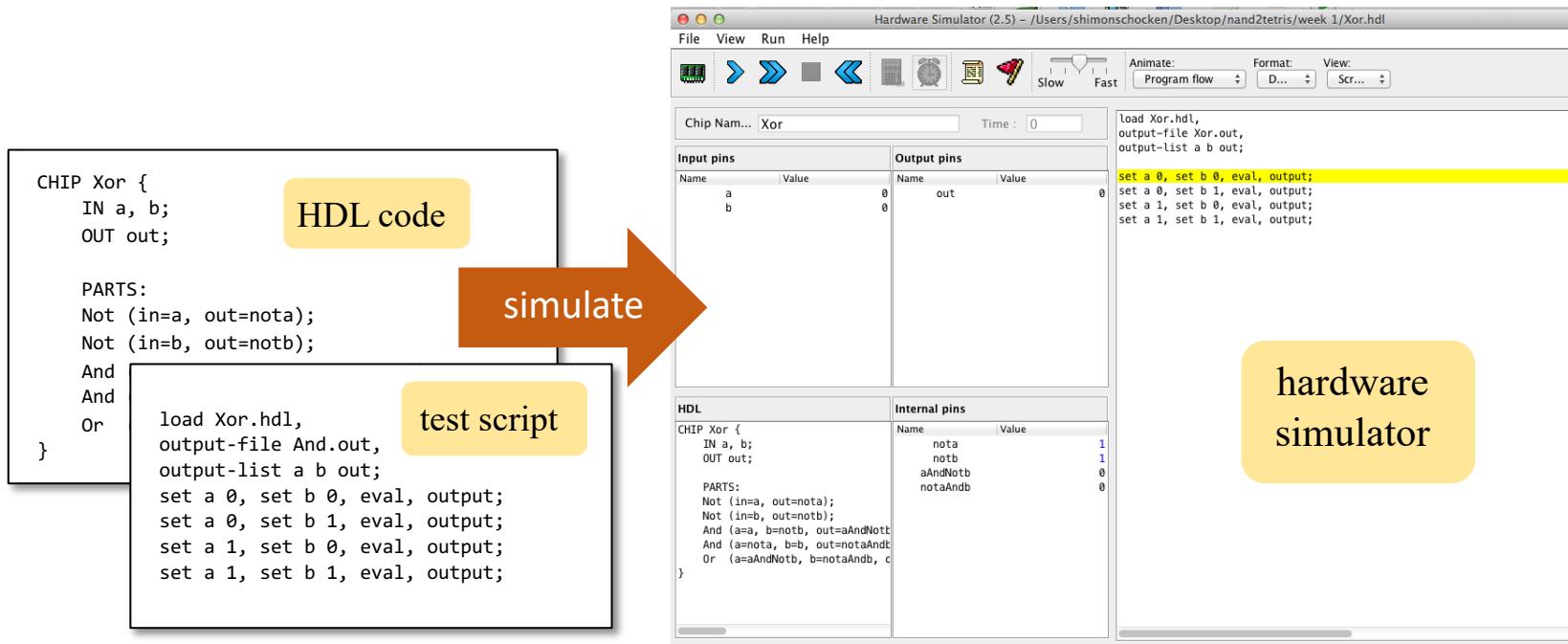
Interactive simulation



Interactive simulation



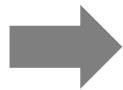
Hardware simulation in a nutshell



Simulation options



Interactive



Script-based.

Script-based simulation

Xor.hdl

```
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        Not (in=a, out=nota);  
        Not (in=b, out=notb);  
        And (a=a, b=notb, out=aAndNotb);  
        And (a=nota, b=b, out=notaAndb);  
        Or  (a=aAndNotb, b=notaAndb, out=out);  
}
```

Xor.tst

```
load Xor.hdl;  
set a 0, set b 0, eval;  
set a 0, set b 1, eval;  
set a 1, set b 0, eval;  
set a 1, set b 1, eval;
```

test script = sequence of commands to the simulator

Benefits:

- “Automatic” testing
- Replicable testing.

Script-based simulation, with an output file

Xor.hdl

```
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        Not (in=a, out=nota);  
        Not (in=b, out=notb);  
        And (a=a, b=notb, out=aAndNotb);  
        And (a=nota, b=b, out=notaAndb);  
        Or  (a=aAndNotb, b=notaAndb, out=out);  
}
```

Xor.tst

```
load Xor.hdl,  
output-file Xor.out,  
output-list a b out;  
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 logic of a typical test script

- Initialize:
 - Loads an HDL file
 - Creates an empty output file
 - Lists the names of the pins whose values will be written to the output file
- Repeat:
 - **set – eval - output**

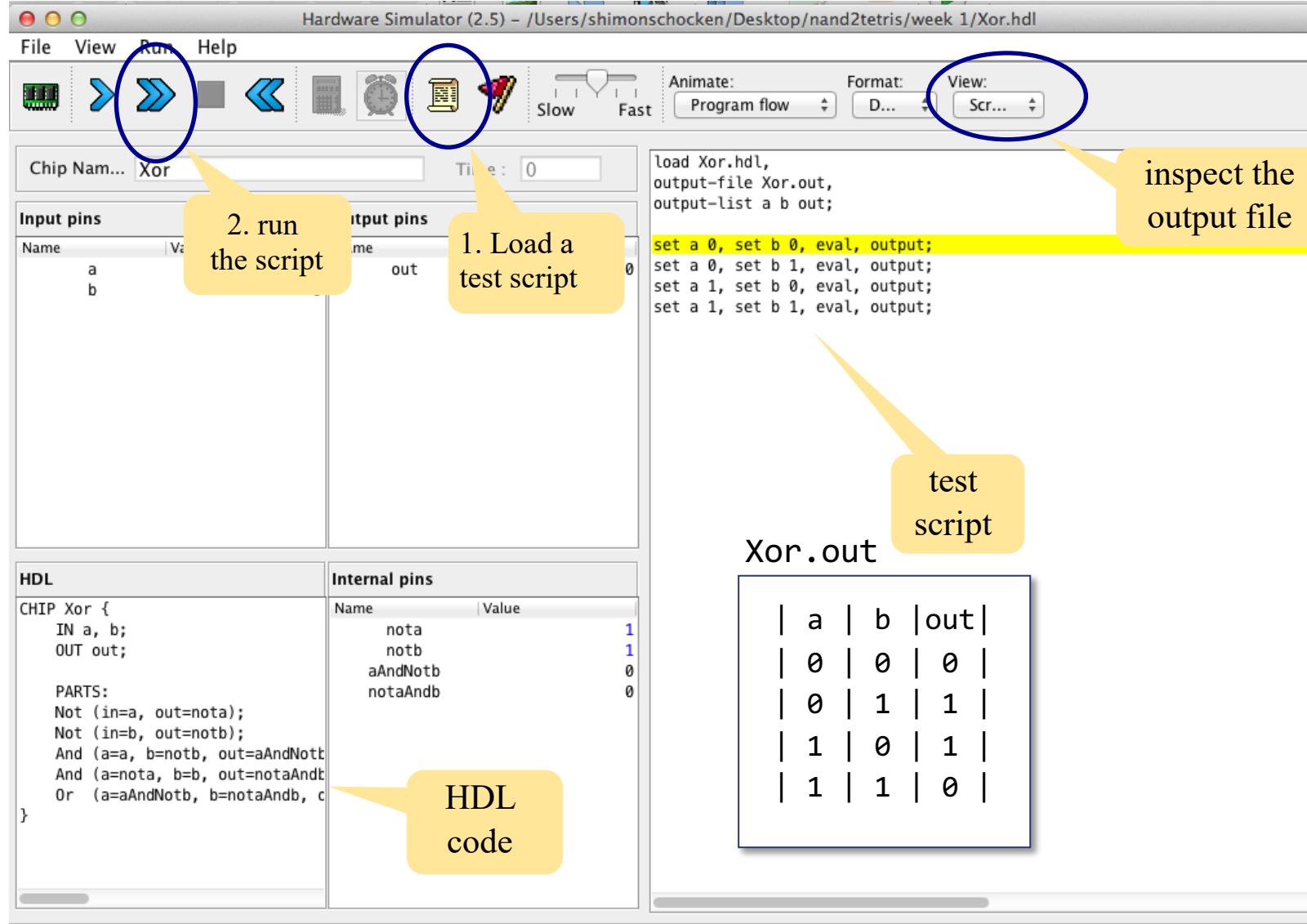
test
script

Xor.out

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

Output File, created by the test script, as a side-effect of the simulation process

Script-based simulation



Script-based simulation, with a compare file

Xor.hdl

```
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        Not (in=a, out=nota);  
        Not (in=b, out=notb);  
        And (a=a, b=notb, out=aAndNotb);  
        And (a=nota, b=b, out=notaAndb);  
        Or (a=aAndNotb, b=notaAndb, out=out);  
}
```

Xor.tst

```
load Xor.hdl,  
output-file Xor.out,  
compare-to Xor.cmp,  
output-list a b out;  
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 diagram illustrates the process of simulation with a compare file. It starts with the **Xor.tst** script, which contains commands to load the **Xor.hdl** file, output to **Xor.out**, compare the output to **Xor.cmp**, and provide an output list. An orange arrow points from the **Xor.tst** box down to the **Xor.out** and **Xor.cmp** boxes. Below these boxes is another orange arrow labeled "compare" pointing from **Xor.out** to **Xor.cmp**.

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

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

Simulation-with-compare-file logic

- When each **output** command is executed, the outputted line is compared to the corresponding line in the **compare** file
- If the two lines are not the same, the simulator throws a comparison error.

Script-based simulation, with a compare file

Xor.hdl

```
CHIP Xor {
    IN a, b;
    OUT out;

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

Xor.tst

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

Demos:

[Experimenting with Built-In Chips](#)

[Building and Testing HDL-based Chips](#)

[Script-Based Chip Testing](#)

Xor.out

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

Xor.cmp

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

compare

Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

Practice

- ✓ Logic gates
- ✓ HDL
- ✓ Hardware simulation
- Multi-bit buses

Project 1

- Introduction
- Chips
- Guidelines

Multi-bit bus

- Sometimes we wish to manipulate a *sequence of bits* as a single entity
- Such a multi-bit entity is termed “bus”

Example: 16-bit bus

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	0	0	1	1	0	1	1	1	0	1

MSB = Most significant bit

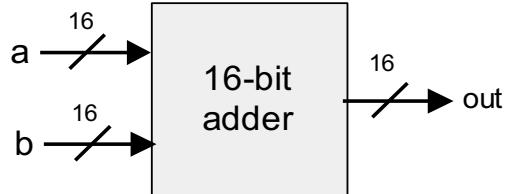
LSB = Least significant bit

Working with buses: Example

```
/* Adds two 16-bit values. */
CHIP Adder {
    IN a[16], b[16];
    OUT out[16];

    PARTS:
    ...
}
```

15	...	1	0	
a:	1	...	1	1
b:	0	...	1	0
c:	0	...	0	1
out:	1	...	1	0



```
/* Adds three 16-bit inputs. */
CHIP Adder3Way {
    IN a[16], b[16], c[16];
    OUT out[16];

    PARTS:
    Adder(a=a , b=b, out=ab);
    Adder(a=ab, b=c, out=out);
}
```

n-bit value (bus) can be treated as a single entity

Creates an internal bus pin (ab)

Working with individual bits within buses

```
/* Returns 1 if a==1 and b==1,  
0 otherwise. */  
  
CHIP And {  
    IN a, b;  
    OUT out;  
    ...  
}
```

a:

3	2	1	0
0	1	1	1

out:

0

```
/* 4-way And: Ands 4 bits. */  
  
CHIP And4Way {  
    IN a[4];  
    OUT out;  
  
    PARTS:  
        And(a=a[0], b=a[1], out=and01);  
        And(a=and01, b=a[2], out=and012);  
        And(a=and012, b=a[3], out=out);  
}
```

Input bus pins can
be subscripted.

Working with individual bits within buses

```
/* Returns 1 if a==1 and b==1,  
0 otherwise. */  
  
CHIP And {  
    IN a, b;  
    OUT out;  
    ...  
}
```

a:

3	2	1	0
0	1	1	1

out:

0

```
/* 4-way And: Ands 4 bits. */  
  
CHIP And4Way {  
    IN a[4];  
    OUT out;  
  
    PARTS:  
        And(a=a[0], b=a[1], out=and01);  
        And(a=and01, b=a[2], out=and012);  
        And(a=and012, b=a[3], out=out);  
}
```

Input bus pins can
be subscripted.

a:

3	2	1	0
0	1	0	1

b:

0	0	1	1
---	---	---	---

out:

0	0	0	1
---	---	---	---

```
/* Bit-wise And of two 4-bit inputs */  
  
CHIP And4 {  
    IN a[4], b[4];  
    OUT out[4];  
  
    PARTS:  
        And(a=a[0], b=b[0], out=out[0]);  
        And(a=a[1], b=b[1], out=out[1]);  
        And(a=a[2], b=b[2], out=out[2]);  
        And(a=a[3], b=b[3], out=out[3]);  
}
```

Output bus pins
can be subscripted

Chapter 1: Boolean logic

Theory

- Basic concepts
- ✓ • Boolean algebra
- Boolean functions
- Nand

Practice

- Logic gates
- ✓ • HDL
- Hardware simulation
- Multi-bit buses

Project 1

- Introduction
- Chips
- Guidelines



Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

Practice

- Logic gates
- HDL
- Hardware simulation
- Multi-bit buses

Project 1



Introduction

- Chips
- Guidelines

Built-in chips

We provide built-in versions of the chips built in this course (in `tools/builtInChips`).

For example:

`Xor.hdl`

```
/** Sets out to a Xor b */
CHIP Xor {
    IN a, b;           Implemented
    OUT out;          in HDL
}

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

`Xor.hdl`

```
/** Sets out to a Xor b */
CHIP Xor {
    IN a, b;           Implemented
    OUT out;          in Java
}

BUILTIN Xor;
// implemented by a Xor.java class.
}
```

A built-in chip has the same interface as the regular chip, but a different implementation

Behavioral simulation

- Before building a chip in HDL, one can implement the chip logic in a high-level language
- Enables experimenting with / testing the chip abstraction before actually building it
- Enables high-level planning and testing of hardware architectures.

Demo: [Loading and testing a built-in chip in the hardware simulator](#)

Hardware construction projects

Key players:

- Architect:
 - Decides which chips are needed
 - Specifies the chips
- Developers:
 - Build / test the chips



In Nand to Tetris:

The architect is the course instructor; the developers are the students

For each chip, the architect supplies:

- Built-in chip
- Chip API (skeletal HDL program = stub file)
- Test script
- Compare file

Given these resources, the developers (students) build the chips.

The developer's view (of, say, a xor gate)

Xor.hdl

```
/** Sets out to a Xor b */
CHIP Xor {
    IN a, b;
    OUT out;

    PARTS:
        // Implementation missing
}
```

stub
file

Xor.tst

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

test
script

These files specify:

- The chip interface (.hdl)
- How the chip is supposed to behave (.cmp)
- How to test the chip (.tst)

compare
file

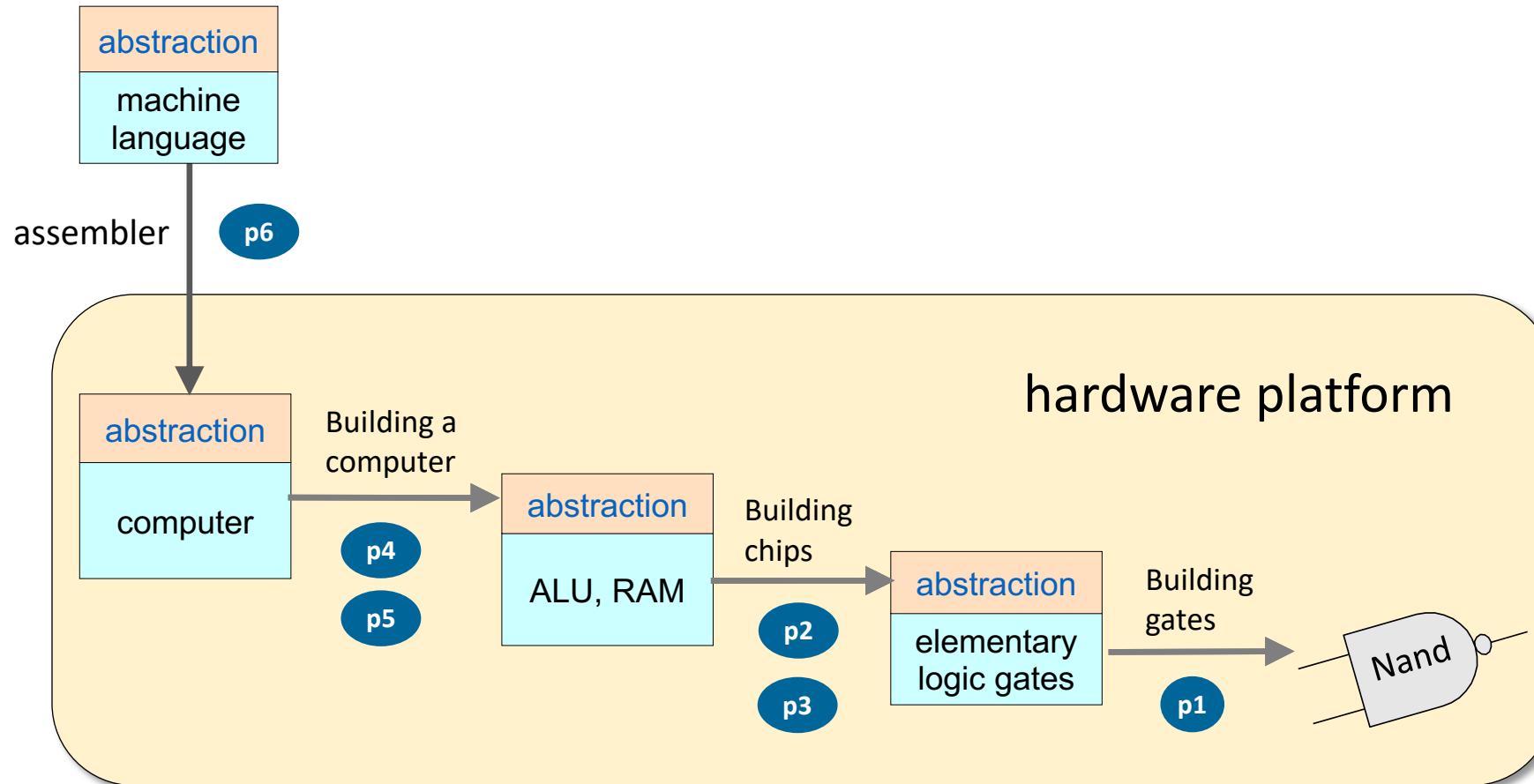
Xor.cmp

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

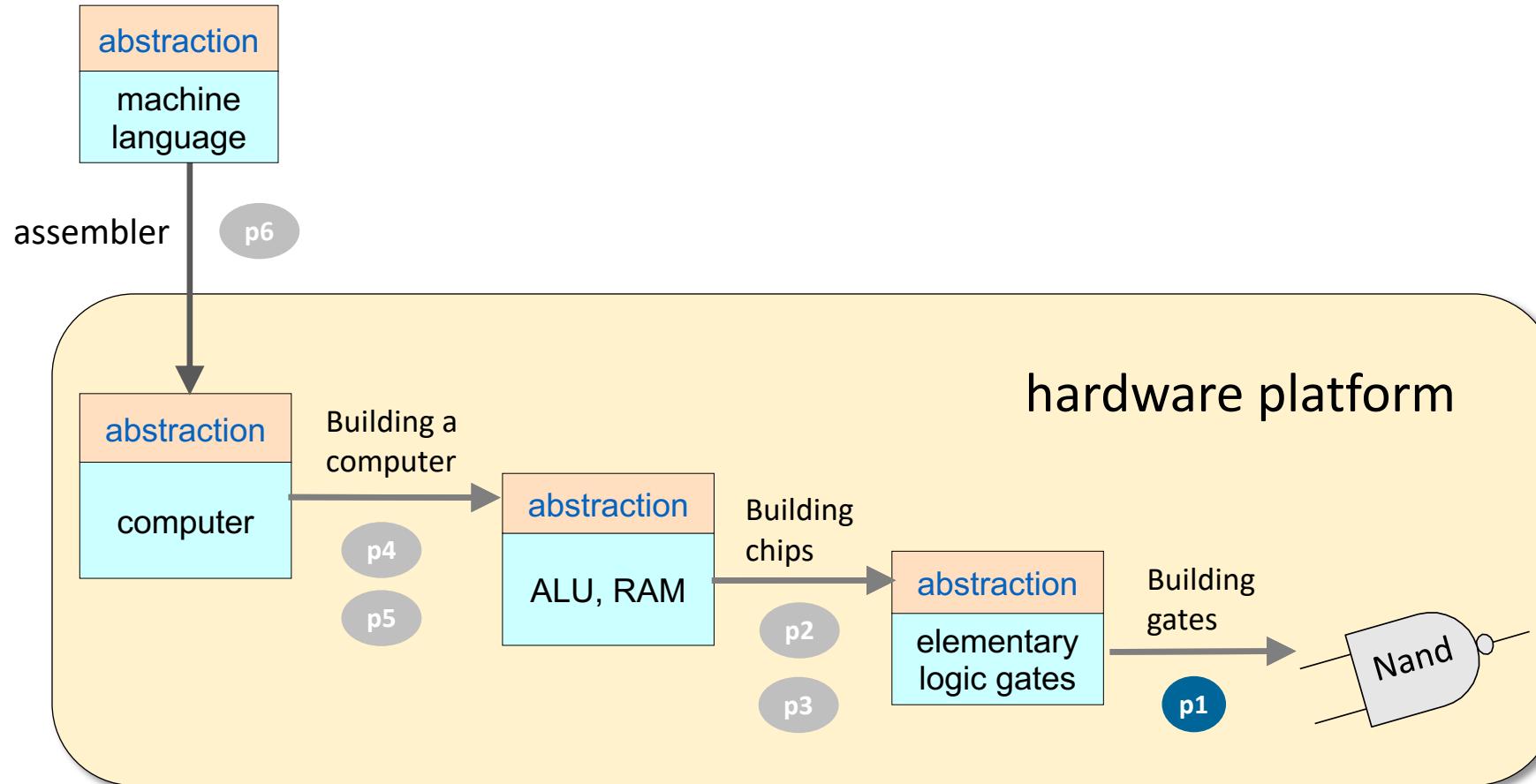
The developer's task:

Implement the chip (complete the supplied .hdl file),
using these resources.

Nand to Tetris Roadmap (Part I: Hardware)



Project 1



Project 1
Build 15 elementary logic gates

Project 1

Given: Nand

Goal: Build the following gates:

<u>Elementary logic gates</u>	<u>16-bit variants</u>	<u>Multi-way variants</u>
<input type="checkbox"/> Not	<input type="checkbox"/> Not16	<input type="checkbox"/> Or8Way
<input type="checkbox"/> And	<input type="checkbox"/> And16	<input type="checkbox"/> Mux4Way16
<input type="checkbox"/> Or	<input type="checkbox"/> Or16	<input type="checkbox"/> Mux8Way16
<input type="checkbox"/> Xor	<input type="checkbox"/> Mux16	<input type="checkbox"/> DMux4Way
<input type="checkbox"/> Mux		<input type="checkbox"/> DMux8Way
<input type="checkbox"/> DMux		

Why these 15 particular gates?

- Commonly used gates
- Comprise all the elementary logic gates needed to build our computer.

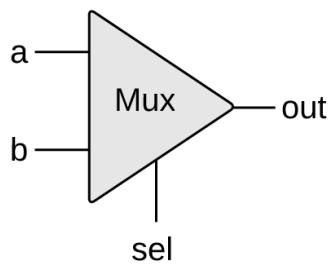
Project 1

Given: Nand

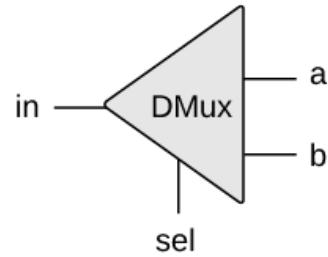
Goal: Build the following gates:

<u>Elementary logic gates</u>	<u>16-bit variants</u>	<u>Multi-way variants</u>
<input type="checkbox"/> Not	<input type="checkbox"/> Not16	<input type="checkbox"/> Or8Way
<input type="checkbox"/> And	<input type="checkbox"/> And16	<input type="checkbox"/> Mux4Way16
<input type="checkbox"/> Or	<input type="checkbox"/> Or16	<input type="checkbox"/> Mux8Way16
<input type="checkbox"/> Xor	<input type="checkbox"/> Mux16	<input type="checkbox"/> DMux4Way
 Mux		<input type="checkbox"/> DMux8Way
 DMux		

Multiplexor / Demultiplexor



```
if (sel == 0)
    out = a
else
    out = b
```

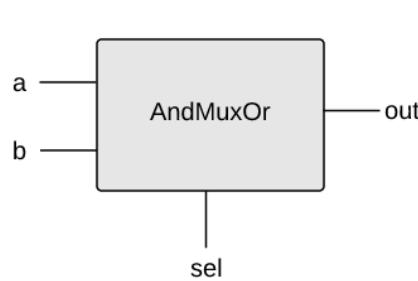


```
if (sel == 0)
    {a, b} = {in, 0}
else
    {a, b} = {0, in}
```

Widely used in:

- Hardware design
- Communications networks.

Example 1: Using Mux logic to build a programmable gate

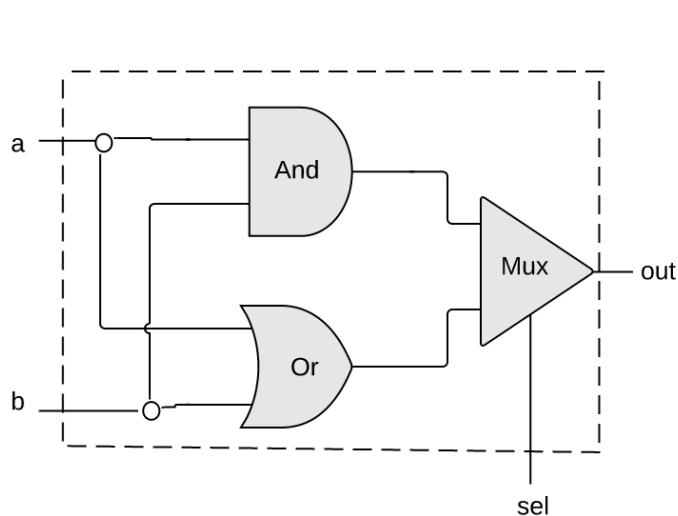


```
if (sel == 0)
    out = a And b
else
    out = a Or b
```

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

When $\text{sel} == 0$
the gate acts like an And gate

When $\text{sel} == 1$
the gate acts like an Or gate

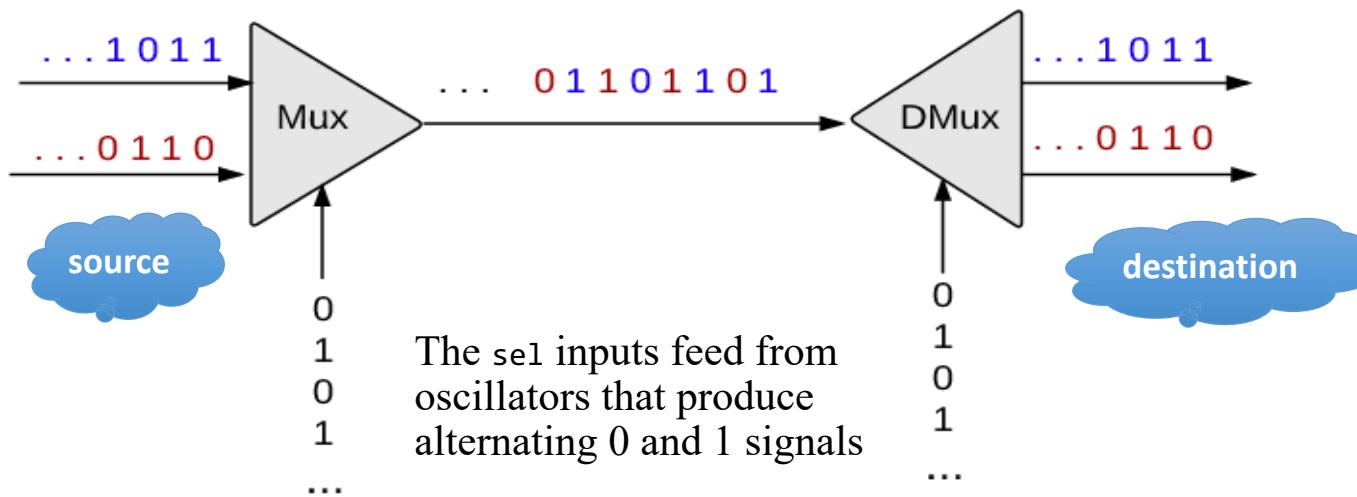


Mux.hdl

```
CHIP AndMuxOr {
    IN a, b, sel;
    OUT out;

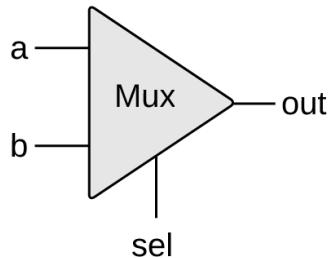
    PARTS:
        And (a=a, b=b, out=andOut);
        Or (a=a, b=b, out=orOut);
        Mux (a=andOut, b=orOut, sel=sel, out=out);
}
```

Example 2: Using Mux logic in communications networks



- Enables transmitting multiple messages simultaneously using a single, shared communications line
- Unrelated to this course.

Multiplexor



```
if (sel == 0)
    out = a
else
    out = b
```

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

sel	out
0	a
1	b

abbreviated
truth table

Mux.hdl

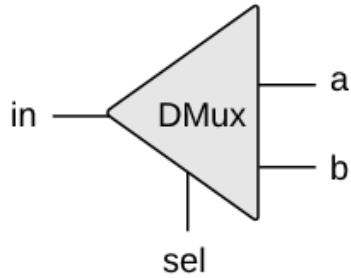
```
CHIP Mux {
    IN a, b, sel;
    OUT out;

    PARTS:
        // Put your code here:
}
```

Implementation tip

Can be implemented from the gates And, Or, Not.

Demultiplexor



```
if (sel == 0)
    {a, b} = {in, 0}
else
    {a, b} = {0, in}
```

in	sel	a	b
0	0	0	0
0	1	0	0
1	0	1	0
1	1	0	1

- Acts like the “inverse” of a multiplexor
- Channels the single input value into one of two possible destinations

DMux.hdl

```
CHIP DMux {
    IN in, sel;
    OUT a, b;

    PARTS:
        // Put your code here:
}
```

Implementation tip

Similar to the Mux implementation.

Project 1

Elementary logic gates

- Not
- And
- Or
- Xor
- Mux
- DMux

16-bit variants

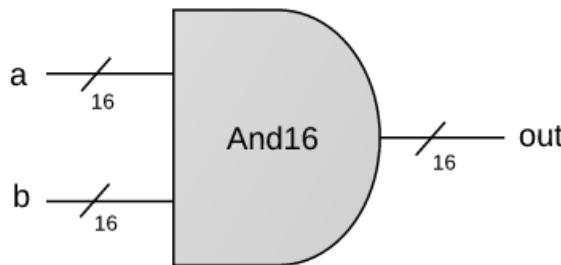
- Not16
- And16**
- Or16
- Mux16

Multi-way variants

- Or8Way
- Mux4Way16
- Mux8Way16
- DMux4Way
- DMux8Way



And16



Example:

$$\begin{array}{r} a = 1\ 0\ 1\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 1\ 1\ 0\ 0 \\ b = 0\ 0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1\ 0 \\ \hline \text{out} = 0\ 0\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0 \end{array}$$

```
CHIP And16 {  
    IN a[16], b[16];  
    OUT out[16];  
  
    PARTS:  
        // Put your code here:  
}
```

Implementation tip

A straightforward 16-bit extension of the elementary And gate

(See notes about working with *multi-bit buses*).

Project 1

Elementary logic gates

- Not
- And
- Or
- Xor
- Mux
- DMux

16-bit variants

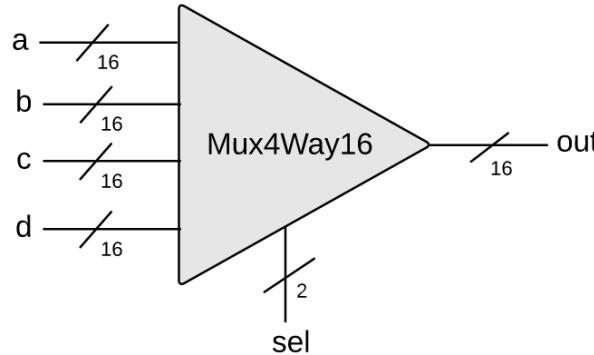
- Not16
- And16
- Or16
- Mux16

Multi-way variants

- Or8Way
- Mux8Way16
- DMux4Way
- DMux8Way

 **Mux4Way16**

16-bit, 4-way multiplexor



sel[1]	sel[0]	out
0	0	a
0	1	b
1	0	c
1	1	d

Mux4Way16.hdl

```
CHIP Mux4Way16 {  
    IN a[16], b[16], c[16], d[16],  
        sel[2];  
    OUT out[16];  
  
    PARTS:  
        // Put your code here:  
}
```

Implementation tip:

Can be built from several Mux16 gates.

Chapter 1: Boolean logic

Theory

- Basic concepts
- Boolean algebra
- Boolean functions
- Nand

Practice

- Logic gates
- HDL
- Hardware simulation
- Multi-bit buses

Project 1

✓ Introduction

✓ Chips

→ Guidelines

Project 1

Elementary logic gates

- Not
- And
- Or
- Xor
- Mux
- DMux

16-bit variants

- Not16
- And16
- Or16
- Mux16

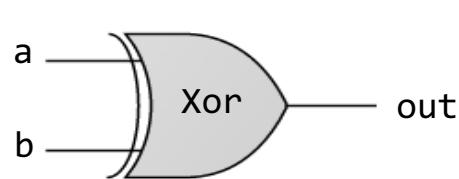
Multi-way variants

- Or8Way
- Mux4Way16
- Mux8Way16
- DMux4Way
- DMux8Way



How to actually build these gates?

Files



```
if((a == 0 and b == 1) or  
    (a == 1 and b == 0))  
    sets out = 1  
  
else  
    sets out = 0
```

Xor.cmp

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

For every chip built in the course
(using xor as an example), we supply
these three files

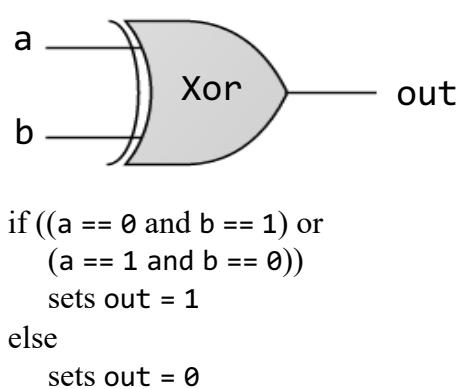
Xor.hdl (stub file)

```
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        // Put your code here  
}
```

Xor.tst

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

Files



Xor.cmp		
a	b	out
0	0	0
0	1	1
1	0	1
1	1	0

The contract:

When running your `Xor.hdl` on the supplied `xor.tst`, your `Xor.out` should be the same as the supplied `xor.cmp`

Xor.hdl (stub file)

```
CHIP Xor {  
    IN a, b;  
    OUT out;  
  
    PARTS:  
        // Put your code here  
}
```

Xor.tst

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

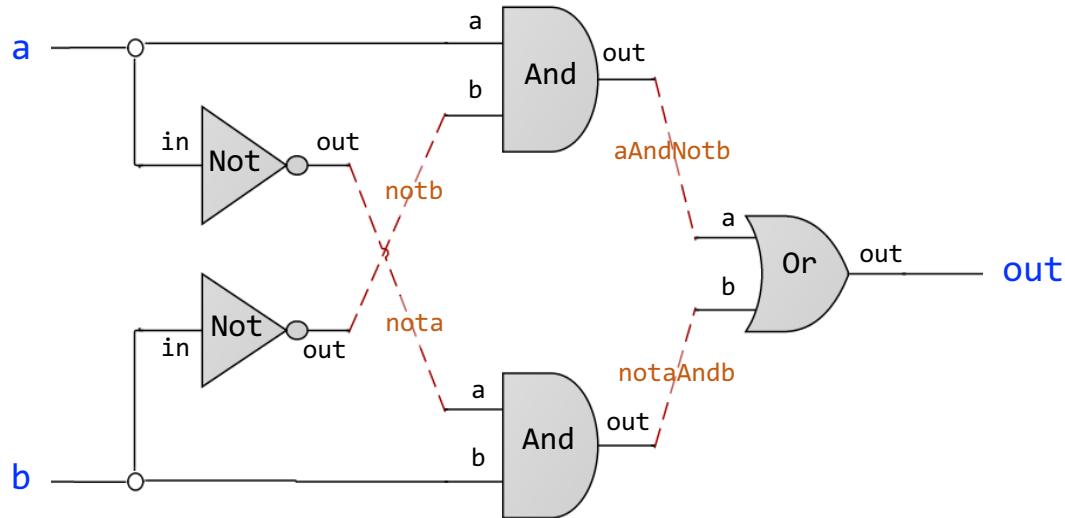
Project 1 folder

(.hdl, .tst, .cmp files):
`nand2tetris/projects/01`

Tools:

- Text editor
(for completing the .hdl files)
- Hardware simulator:
`nand2tetris/tools`

Chip interfaces



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

If I want to use some chip-parts,
how do I figure out their signatures?



Chip interfaces: [Hack chip set API](#)

Open the Hack chip set API in a window, and copy-paste
chip signatures into your HDL code, as needed

```
Add16 (a= ,b= ,out= );
ALU (x= ,y= ,zx= ,nx= ,zy= ,ny= ,f= ,no= ,out= ,zr= ,ng= );
And16 (a= ,b= ,out= );
And (a= ,b= ,out= );
Aregister (in= ,load= ,out= );
Bit (in= ,load= ,out= );
CPU (inM= ,instruction= ,reset= ,outM= ,writeM= ,ad=
DFF (in= ,out= );
DMux4Way (in= ,sel= ,a= ,b= ,c= ,d= );
DMux8Way (in= ,sel= ,a= ,b= ,c= ,d= ,e= ,f= ,g= ,h=
DMux (in= ,sel= ,a= ,b= );
Dregister (in= ,load= ,out= );
FullAdder (a= ,b= ,c= ,sum= ,carry= );
HalfAdder (a= ,b= ,sum= , carry= );
Inc16 (in= ,out= );
Keyboard (out= );
Memory (in= ,load= ,address= ,out= );
Mux16 (a= ,b= ,sel= ,out= );
Mux4Way16 (a= ,b= ,c= ,d= ,sel= ,out= );
Mux8Way16 (a= ,b= ,c= ,d= ,e= ,f= ,g= ,h= ,sel= ,ou
Mux8Way (a= ,b= ,c= ,d= ,e= ,f= ,g= ,h= ,sel= ,out= );
Mux (a= ,b= ,sel= ,out= );
Nand (a= ,b= ,out= );
Not16 (in= ,out= );
Not (in= ,out= );
Or16 (a= ,b= ,out= );
Or8Way (in= ,out= );
Or (a= ,b= ,out= );
PC (in= ,load= ,inc= ,reset= ,out= );
PCLoadLogic (cinstr= ,j1= ,j2= ,j3= ,load= ,inc= );
RAM16K (in= ,load= ,address= ,out= );
RAM4K (in= ,load= ,address= ,out= );
RAM512 (in= ,load= ,address= ,out= );
RAM64 (in= ,load= ,address= ,out= );
RAM8 (in= ,load= ,address= ,out= );
Register (in= ,load= ,out= );
ROM32K (address= ,out= );
Screen (in= ,load= ,address= ,out= );
Xor (a= ,b= ,out= );
```

Built-in chips

```
CHIP Foo {  
    IN ...;  
    OUT ...;  
  
    PARTS:  
    ...  
    Bar(...)  
    ...  
}
```

Q: Suppose you want to use a chip-part before
you've implemented it. How to do it?

A: The simulator features built-in implementations
of all the project 1 chips

Forcing the simulator to use a built-in chip, say Bar:

- Typically, `Bar.hdl` will be either a given stub-file, or a file that has an incomplete implementation
- Remove, or rename, the file `Bar.hdl` from the project folder
- Whenever `Bar` will be mentioned as a chip-part in some chip definition, the simulator will fail to find `Bar.hdl` in the current folder. This will cause the simulator to invoke the built-in version of `Bar` instead.

Project 1

Guidelines: www.nand2tetris.org (projects section)

Files: nand2tetris/projects/01 (on your PC)

Tools

- Text editor (for completing the given .hdl stub-files)
- Hardware simulator: nand2tetris/tools (on your PC)

Guides

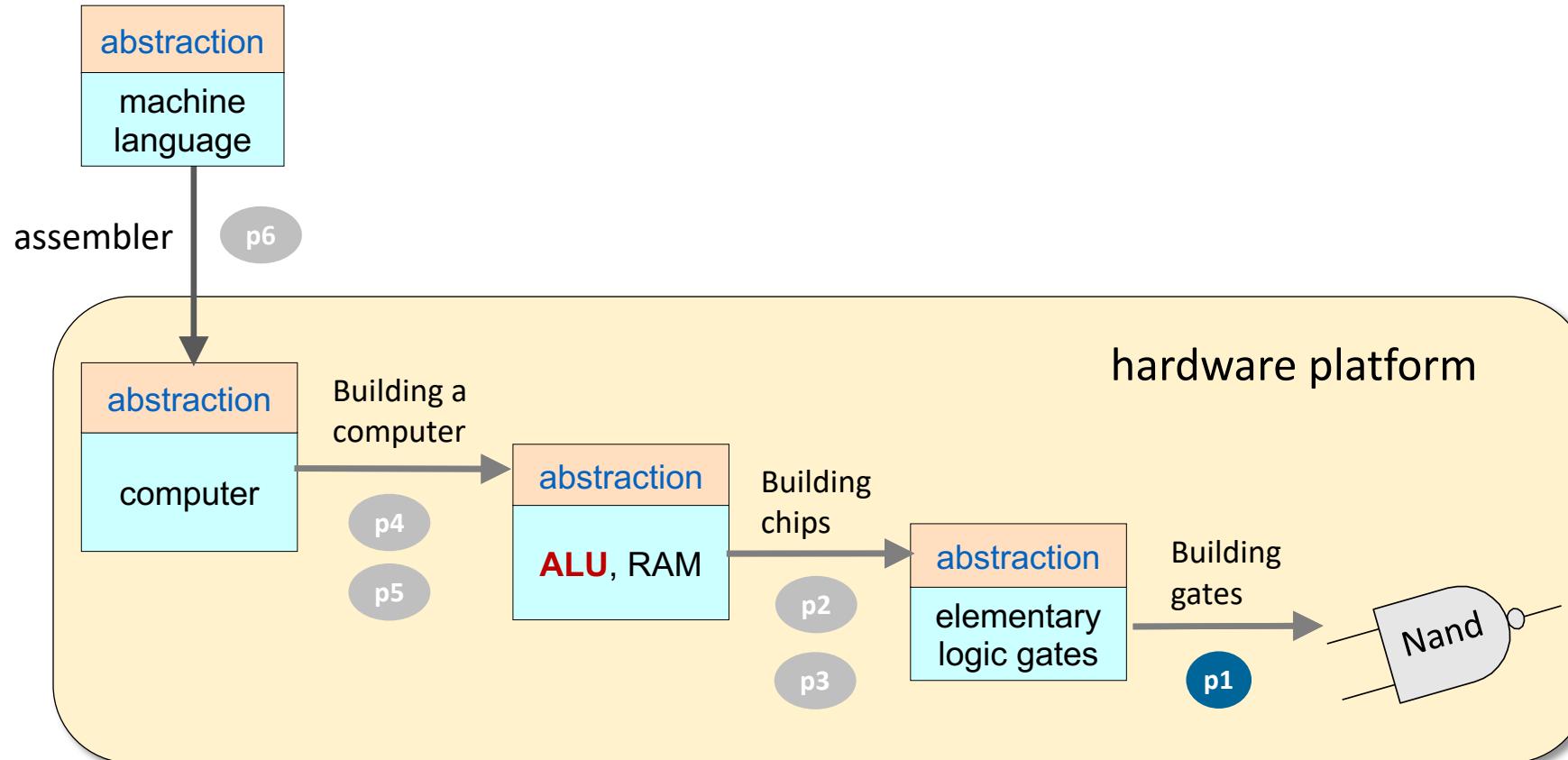
- [Hardware simulator tutorial](#)
- [HDL guide](#)
- [Hack chip set API](#)

Best practice advice

- Implement the chips in the order in which they appear in the project guidelines
- If you don't implement some chips, you can still use them as chip-parts in other chips (use their built-in implementations)
- You can invent additional, "helper chips"; However, this is not necessary.
Implement and use only the chips that we specified
- In each chip implementation, strive to use as few chip-parts as possible
- When defining 16-bit chips, the same chip-parts may appear many times.
That's fine, use copy-paste-edit.

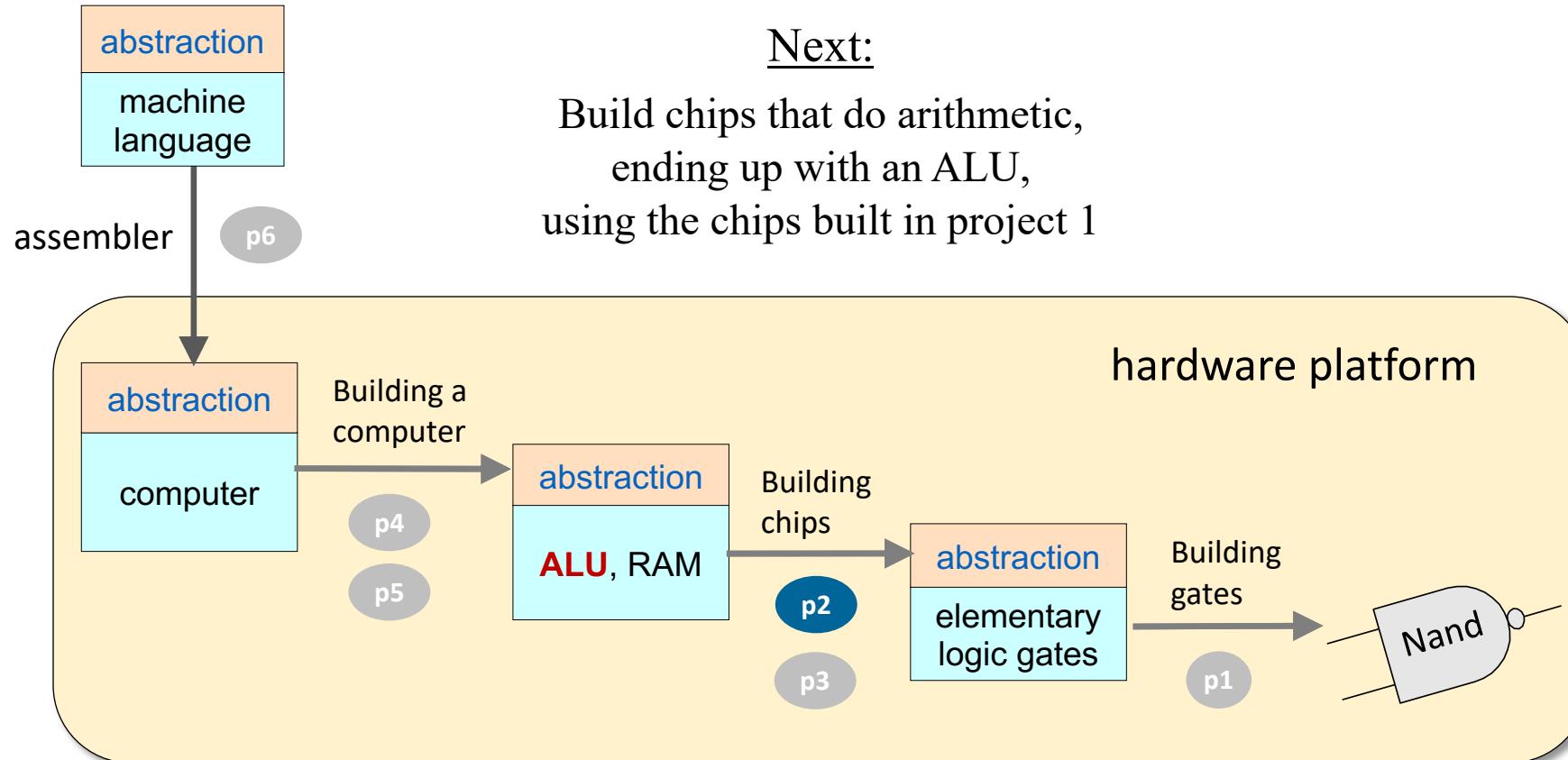
That's It!
Go Do Project 1!

What's next?



This lecture / project / chapter:
Build 15 elementary logic gates

What's next?



This lecture / project / chapter:
Build 15 elementary logic gates