

CS 107e

Lecture 4: From ASM to C Part 1

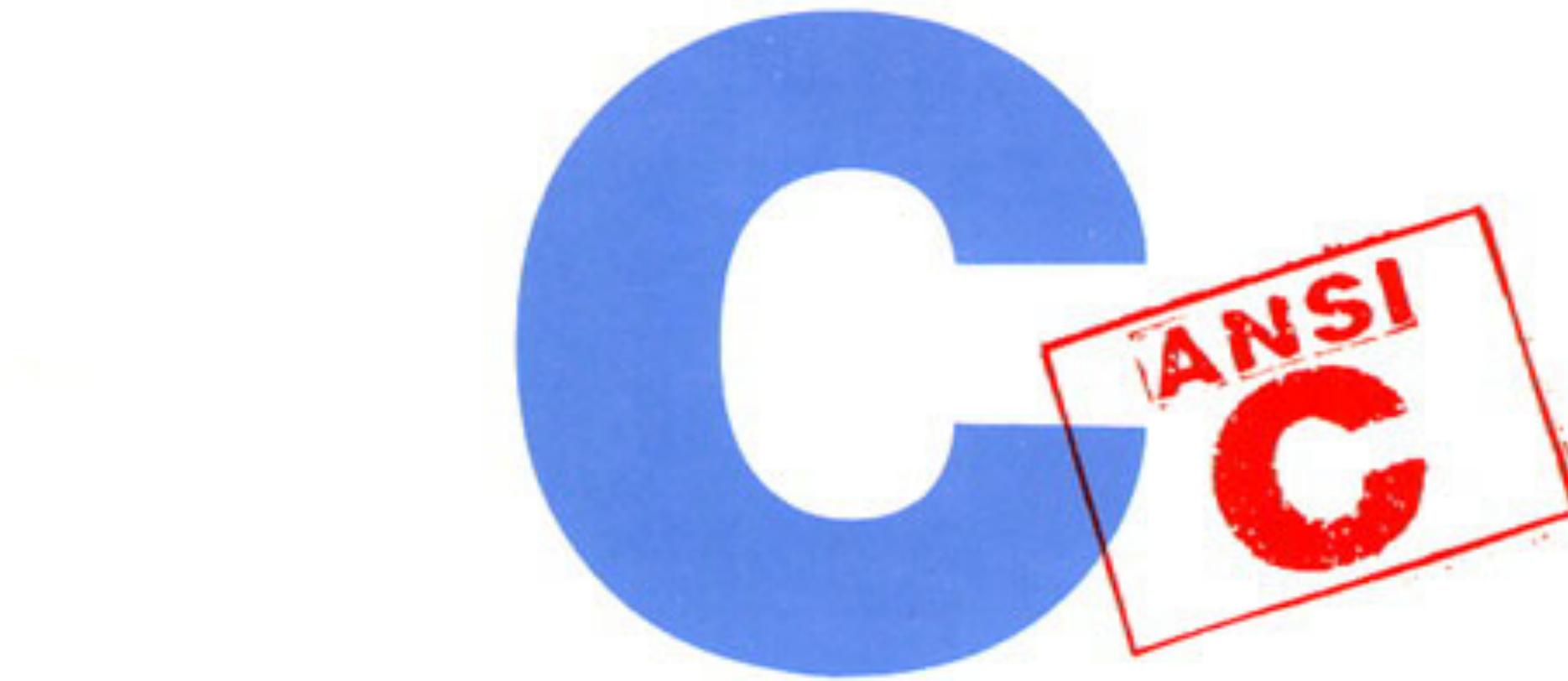
Friday, October 5, 2018

Computer Systems from the Ground Up
Fall 2018
Stanford University
Computer Science Department

Lecturer: Chris Gregg

SECOND EDITION

THE



PROGRAMMING
LANGUAGE

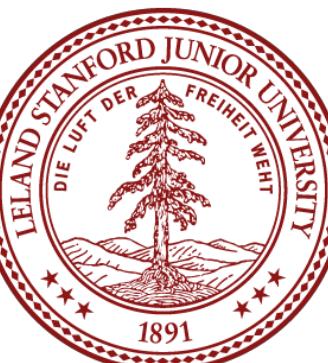
BRIAN W. KERNIGHAN
DENNIS M. RITCHIE

PRENTICE HALL SOFTWARE SERIES



Logistics

- Assignment 1 deadline on Wednesday, October 10th, 2018 at 11:30 AM
(i.e., before Wednesday lab)



Question



If it takes one monkey one minute to eat one banana, how long does it take three monkeys to eat three bananas?



Question



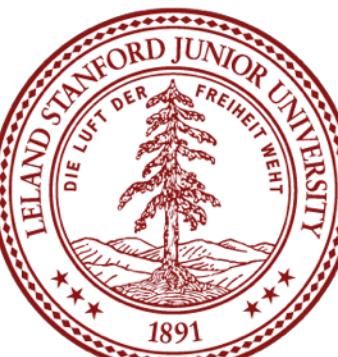
If it takes one monkey one minute to eat one banana, how long does it take three monkeys to eat three bananas?

Answer: one minute



Today's Topics

- ARM condition codes and branch instructions
- Instruction Pipelining
- C language as "high-level" assembly
- How does C relate to ASM?
- What does a compiler do?



Control Flow in Assembly

- Assembly instructions are held in contiguous memory. Let's look at this tiny portion of a program:

```
// configure GPIO 20 for output  
ldr r0, FSEL2  
mov r1, #1  
str r1, [r0]  
  
FSEL2: .word 0x20200008
```

- If we disassemble it, this is what we get:

Notice that each instruction is four bytes, and they come right after another in memory (0, 4, 8 represent the memory locations). This is called *straight-line* code, because the instructions come one after the other, in a line.

```
$ arm-none-eabi-objdump -d partial.o  
partial.o: file format ELF32-arm-little  
  
Disassembly of section .text:  
$a:  
    0 : 04 00 9f e5 ldr r0, [pc, #4 ]  
    4 : 01 10 a0 e3 mov r1, #1  
    8 : 00 10 80 e5 str r1, [r0]  
  
FSEL2:  
    c:08 00 20 20 .word 0x20200008
```



Control Flow in Assembly

- As we do in high level languages, we want to be able to control the flow of programs based on *conditions*. Think about an **if** statement in C/C++/Java:

```
if (a == 42) {  
    b = 7;  
}
```

- The condition that must be met to go into the **if** statement body is that a is equal to 42.

In ARM assembly, we can have an instruction set *the condition flags* based on the result of an operation:

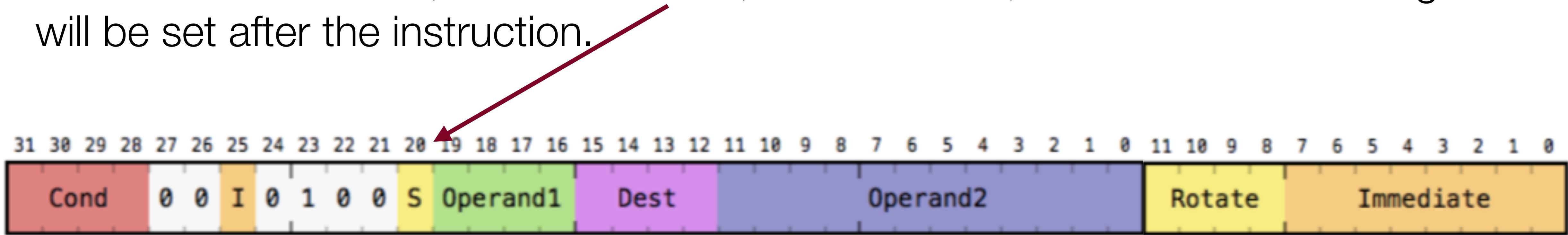
```
add r0, r1, r1 ; does not set condition flags  
adds r0, r1, r1 ; sets condition flags
```

The "s" on "adds" sets the condition flags, which we can then look at.



Control Flow in Assembly

- In an ARM instruction, there is an S bit, and if it is a 1, then the condition flags will be set after the instruction.



- The condition codes that can be set are as follows (set = 1, clear = 0):

Z : set if result is 0, clear otherwise

N : set if result is < 0, clear otherwise (this is the sign flag)

C : set if result generated a carry

we'll cover carry and overflow later

V : set if the result had arithmetic overflow

But here is a great tutorial:

http://teaching.idallen.com/dat2343/10f/notes/040_overflow.txt



Control Flow in Assembly

Code	Suffix	Description	Flags
0000	EQ	Equal / equals zero	Z
0001	NE	Not equal	!Z
0010	CS / HS	Carry set / unsigned higher or same	C
0011	CC / LO	Carry clear / unsigned lower	!C
0100	MI	Minus / negative	N
0101	PL	Plus / positive or zero	!N
0110	VS	Overflow	V
0111	VC	No overflow	!V
1000	HI	Unsigned higher	C and !Z
1001	LS	Unsigned lower or same	!C or Z
1010	GE	Signed greater than or equal	N == V
1011	LT	Signed less than	N != V
1100	GT	Signed greater than	!Z and (N == V)
1101	LE	Signed less than or equal	Z or (N != V)
1110	AL	Always (default)	any

Branching is based on what the status codes are at a given moment. For example:

```
b target // always branches
beq target // branches if zero flag is 1
bne target // branches if zero flag is 0
bge target // read as "branch if greater than or equal";
branches if N == V
```



Control Flow in Assembly

Code	Suffix	Description	Flags
0000	EQ	Equal / equals zero	Z
0001	NE	Not equal	!Z
0010	CS / HS	Carry set / unsigned higher or same	C
0011	CC / LO	Carry clear / unsigned lower	!C
0100	MI	Minus / negative	N
0101	PL	Plus / positive or zero	!N
0110	VS	Overflow	V
0111	VC	No overflow	!V
1000	HI	Unsigned higher	C and !Z
1001	LS	Unsigned lower or same	!C or Z
1010	GE	Signed greater than or equal	N == V
1011	LT	Signed less than	N != V
1100	GT	Signed greater than	!Z and (N == V)
1101	LE	Signed less than or equal	Z or (N != V)
1110	AL	Always (default)	any

Branches simply read the current condition codes, and take the branch if the condition is satisfied.

We also have two other instructions that simply set the condition flags:

`cmp r0, r1 // performs r0 - r1 and sets the condition flags`

`tst r0, r1 // performs r0 AND r1 and sets the condition flags`



Control Flow in Assembly

Code	Suffix	Description
0000	EQ	Equal / equals zero
0001	NE	Not equal
0010	CS / HS	Carry set / unsigned higher or same
0011	CC / LO	Carry clear / unsigned lower
0100	MI	Minus / negative
0101	PL	Plus / positive or zero
0110	VS	Overflow
0111	VC	No overflow
1000	HI	Unsigned higher
1001	LS	Unsigned lower or same
1010	GE	Signed greater than or equal
1011	LT	Signed less than
1100	GT	Signed greater than
1101	LE	Signed less than or equal
1110	AL	Always (default)

Examples: which branches will be taken?

L1	mov	r0, #1	
	mov	r1, #2	
	mov	r2, #3	
	adds	r3, r0, r1	
	bge	L1	
	adds	r4, r0, r0	
	subs	r4, r1, r2 ; subs ra, rb, ;rc puts rb - rc into ra	
	bge	L2	
L2	cmp	r0, r1	
	beq	L3	
	cmp	r2, r3	
L3	beq	L4	
	tst	r1, r2	
	blt	L5	
L4	add	r5, r4, r3	
	tst	r4, r4	
	bmi	L6	
L5	add	r0, r1, r1	
L6			



Coding challenge: count the "on" bits in a number

Write assembly program to count the number of "on" bits in a given number :

```
mov    r0, #0x3e  
mov    r1, #0  
;   count on bits in val in r0  
;   put result in r1
```



Coding challenge: count the "on" bits in a number

Write assembly program to count the number of "on" bits in a given 8-bit number :

```
mov  r0, #0x3e
mov  r1, #0
;  count on bits in val in r0
;  put result in r1
mov  r2, #1
loop:
tst  r0, r2
addne r1, r1, #1
lsl1 r2, r2, #1
cmp  r2, #0x100
blt  loop
```

Lots of possible solutions!



Coding challenge: count the "on" bits in a number

Write assembly program to count the number of "on" bits in a given 8-bit number :

```
mov  r0, #0x3e
mov  r1, #0
;  count on bits in val in r0
;  put result in r1
mov  r2, #1
loop:
tst  r0, r2
beq  nope
add  r1, r1, #1
nope:
lsl  r2, r2, #1
cmp  r2, #0x100
blt  loop
```

Here's a different solution



Coding challenge: count the "on" bits in a number

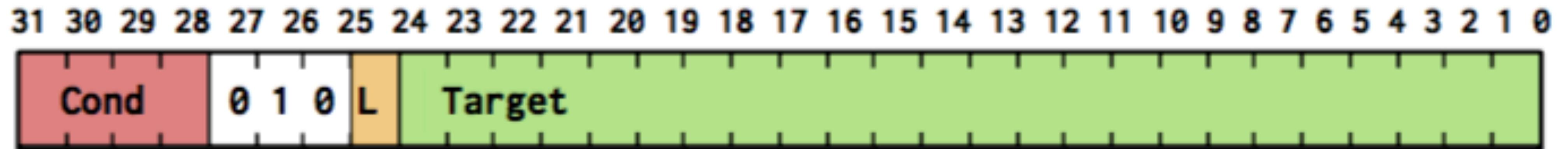
Write assembly program to count the number of "on" bits in a given 8-bit number :

```
mov  r0, #0x3e
mov  r1, #0
;  count on bits in val in r0
;  put result in r1
loop:
    ands r2, r0, #1
    addne r1, r1, #1
    lsrs r0, r0, #1
    bne loop
```

Lots of possible solutions!
This one has fewer instructions!



Branch instruction encoding



b (bal) branch always

1110 1010 tttt tttt tttt tttt tttt tttt

beq branch if zero flag set

0000 1010 tttt tttt tttt tttt tttt tttt

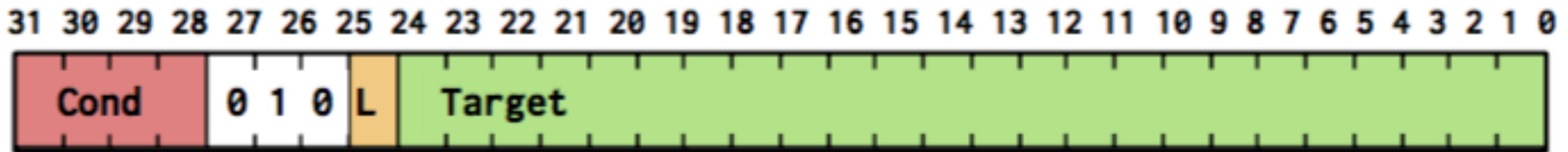
The branch target is a *PC-relative offset*

The green above encode the offset, counted in 4-byte words.

Q: How far can this reach?



Branch instruction encoding



b (bal) branch always

1110 1010 tttt tttt tttt tttt tttt tttt

beq branch if zero flag set

0000 1010 tttt tttt tttt tttt tttt tttt

The branch target is a *PC-relative* offset

The green above encode the offset, counted in 4-byte words.

Q: How far can this reach? **24 bits = $(1 << 24) = 16,777,216$**

$16,777,216 * 4 = 67,108,864$. Half go forward, half backwards, so there is a range of $67,108,864/2 = 33,554,432 = \pm 32\text{MB}$ in either direction.



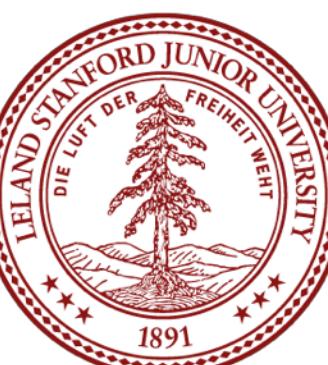
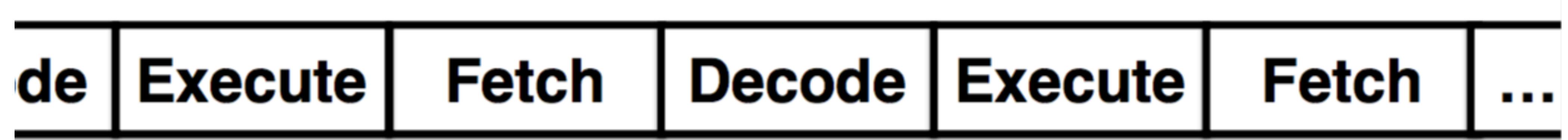
3 Steps Per Instruction

Fetch

Decode

Execute

3 instructions takes 9 steps in sequence



Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



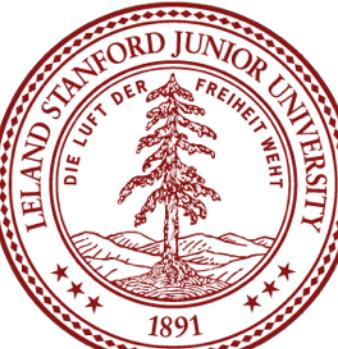
Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



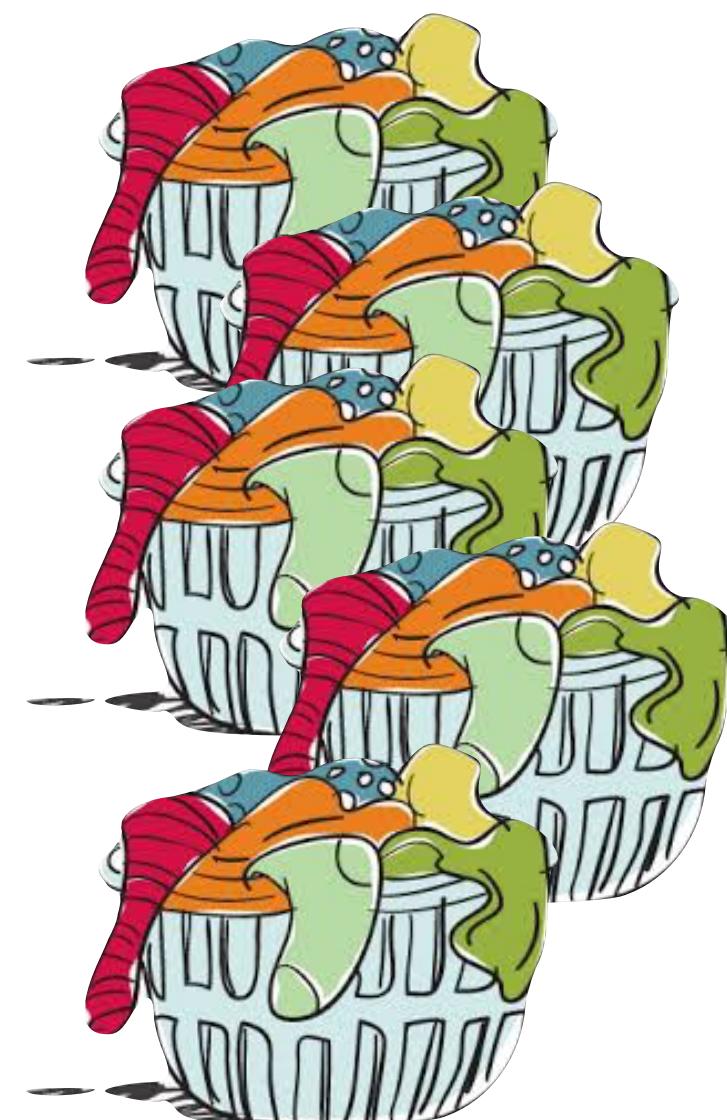
Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



Pipelining

To speed things up, steps are overlapped, or *pipelined*. You can think of pipelining as doing laundry: let's say you have a washer and a dryer. You can do one wash initially, but then you can move the first load to the dryer and wash the next load at *the same time* as you are drying the first load. When those two finish, you can move the first load to the folding table, the second load to the drier, and the third load to the washer. Then you can continuously work on three loads at the same time, assuming they all take the same amount of time.



Pipelining

If each step takes 30 minutes, what is the overall *throughput* of a load of laundry?
In other words, if you kept doing laundry, what would the average amount of time per load be?



Pipelining

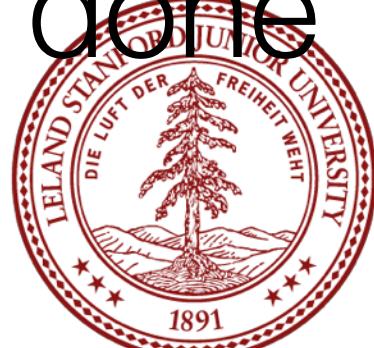
If each step takes 30 minutes, what is the overall *throughput* of a load of laundry?
In other words, if you kept doing laundry, what would the average amount of time per load be?

Answer: 30 minutes per load (think banana-eating monkeys)

This is the general idea of pipelining.



Loads
1,2,3
done



Pipelining

On an ARM processor, instructions are pipelined:



During the cycle that instruction A is executing, the PC has already advanced twice so it holds the address of the instruction being fetched (C). This is two instructions past A ($PC + 8$).



Pipelining

How does this manifest itself in a branch instruction?

```
$ arm-none-eabi-objdump -d branch_ex2.o
0: e3a029ff    mov r2, #4177920 ; 0x3fc000

00000004 <loop>:
 4: e2522001    subs r2, r2, #1
 8: 1affffffd   bne 4 <loop>
```

1a branch if not equal opcode
fffffd -3 in two's complement offset
PC is already 8 ahead, or at 16. (`offset * 4`) is
the number to add to the PC, so $(-3 * 4) + 16$
= address 4 is the next instruction

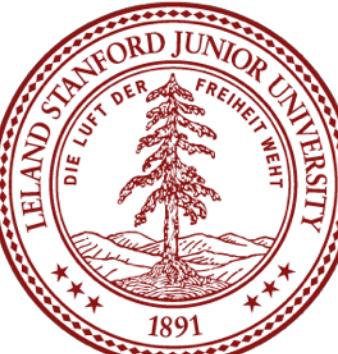


Diversion #1: Why is this so complicated?

Okay, let's pause for a second. The previous slide seems crazy:

1a branch if not equal opcode
fffffd -3 in *two's complement* offset
PC is already 8 ahead, or at 16. ($\text{offset} * 4$) is
the number to add to the PC, so $(-3 * 4) + 16$
= address 4 is the next instruction

Why is it so complicated? Design is all about choices, and all about fitting together the puzzle pieces so that things work. To really understand the details, you need to dig into the references, and you need to understand the pieces *from the ground up*. It turns out that the pipelining hardware design choices lead to the fact that the PC is already advanced by 8, for instance. This stuff is complicated because there are a ton of design choices that have to fit together. We want you to appreciate this, even though it can get confusing!



ISA design is an art form!

Some neat things about ARM design

Commonalities across operations

- Register vs. immediate operands

- Use of barrel shifter

- All registers treated same (with a few caveats)

- Predicated execution

- Set condition code (or not)



Diversion #2: Integer Representations

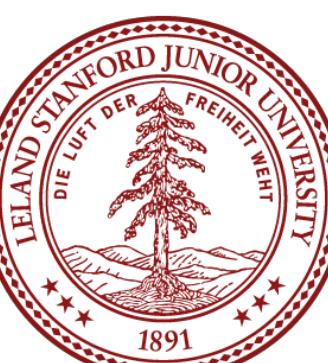
We will talk about two different ways to represent integers, *unsigned* and *signed*:

unsigned: can only represent non-negative numbers

signed: can represent negative, zero, and positive numbers

To be clear: The ARM processor does not care about the representation in binary -- a number is a number. But, we can interpret numbers as unsigned or signed.

Let's take a few minutes to look at some details about integers.



Unsigned Integers

So far, we have talked about converting from decimal to binary and vice-versa, which is a nice one-to-one relationship between the decimal number and its binary representation. Examples:

0b0001 = 1

0b0101 = 5

0b1011 = 11

0b1111 = 15

The range of an unsigned number is $0 \rightarrow 2^w - 1$, where w is the number of bits in our integer. For example, a 32-bit `int` can represent numbers from 0 to $2^{32} - 1$, or 0 to 4,294,967,295.



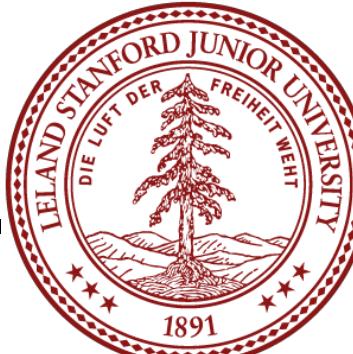
Signed Integers: How do we represent them?

What if we want to represent negative numbers? We have choices!

One way we could encode a negative number is simply to designate some bit as a "sign" bit, and then interpret the rest of the number as a regular binary number and then apply the sign. For instance, for a four-bit number:

0 001 = 1	1 001 = -1
0 010 = 2	1 010 = -2
0 011 = 3	1 011 = -3
0 100 = 4	1 100 = -4
0 101 = 5	1 101 = -5
0 110 = 6	1 110 = -6
0 111 = 7	1 111 = -7

This might be okay...but we've only represented 14 of our 16 available numbers...



Signed Integers: How do we represent them?

0 001 = 1

0 010 = 2

0 011 = 3

0 100 = 4

0 101 = 5

0 110 = 6

0 111 = 7

1 001 = -1

1 010 = -2

1 011 = -3

1 100 = -4

1 101 = -5

1 110 = -6

1 111 = -7

What about 0 000 and 1 000? What should they represent?

Well...this is a bit tricky!



Signed Integers: How do we represent them?

0 001 = 1

0 010 = 2

0 011 = 3

0 100 = 4

0 101 = 5

0 110 = 6

0 111 = 7

1 001 = -1

1 010 = -2

1 011 = -3

1 100 = -4

1 101 = -5

1 110 = -6

1 111 = -7

What about 0 000 and 1 000? What should they represent?

Well...this is a bit tricky!

Let's look at the bit patterns: 0 000 1 000

Should we make the 0 000 just represent decimal 0? What about 1 000? We could make it 0 as well, or maybe -8, or maybe even 8, but none of the choices are nice.



Signed Integers: How do we represent them?

0 001 = 1

0 010 = 2

0 011 = 3

0 100 = 4

0 101 = 5

0 110 = 6

0 111 = 7

1 001 = -1

1 010 = -2

1 011 = -3

1 100 = -4

1 101 = -5

1 110 = -6

1 111 = -7

What about 0 000 and 1 000? What should they represent?

Well...this is a bit tricky!

Let's look at the bit patterns: 0 000 1 000

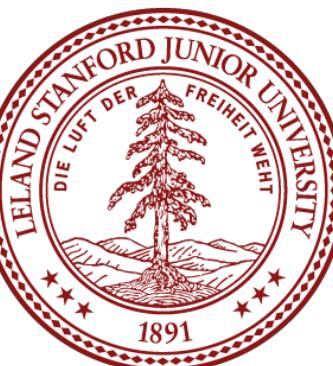
Should we make the 0 000 just represent decimal 0? What about 1 000? We could make it 0 as well, or maybe -8, or maybe even 8, but none of the choices are nice.

Fine. Let's just make 0 000 to be equal to decimal 0. How does arithmetic work? Well...to add two numbers, you need to know the sign, then you might have to subtract (borrow and carry, etc.), and the sign might change...this is going to get ugly!



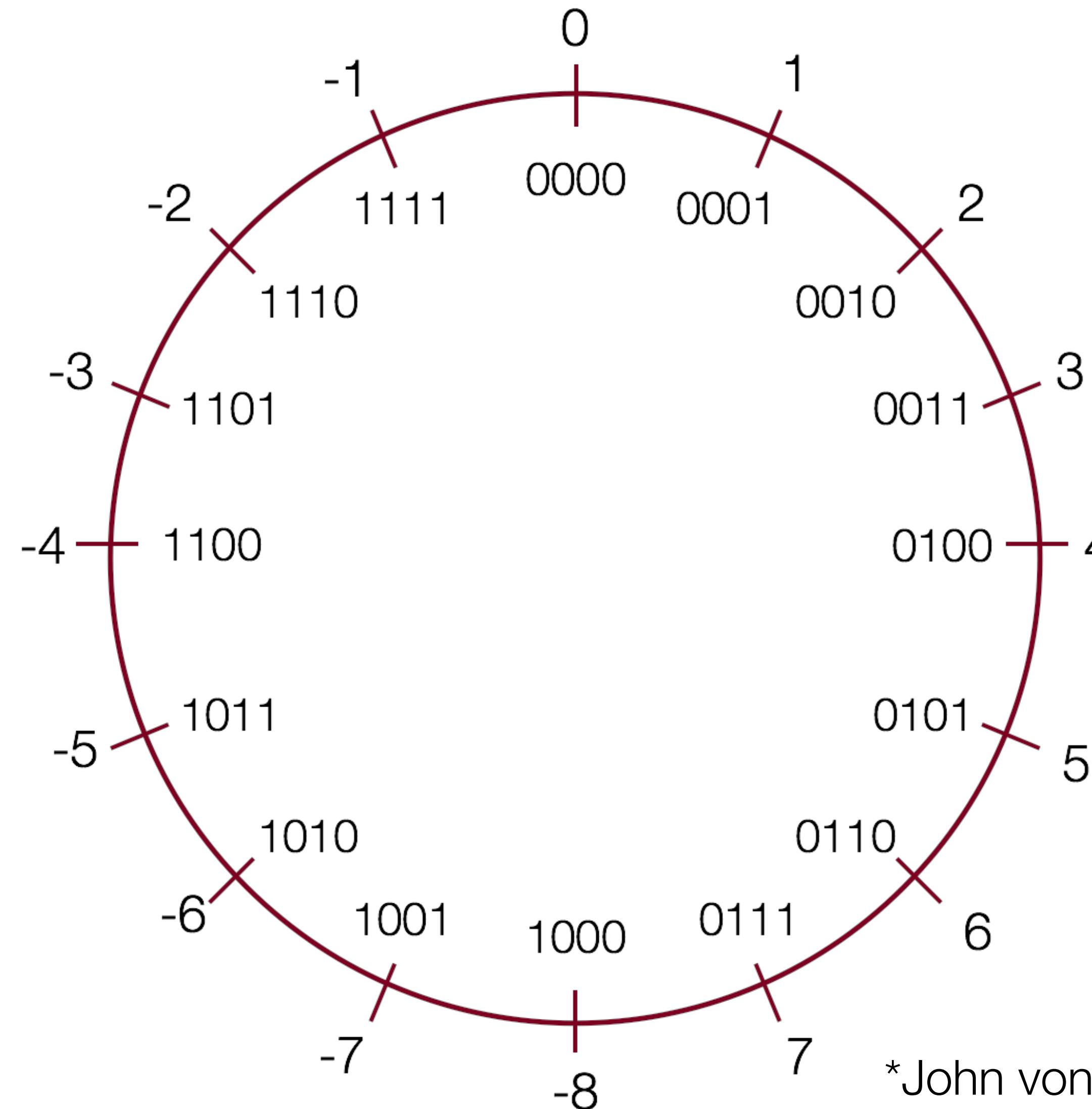
Signed Integers: How do we represent them?

There is a better way!



Signed Integers: How do we represent them?

Behold: the "two's complement" circle:



In the early days of computing*, two's complement was determined to be an excellent way to store binary numbers.

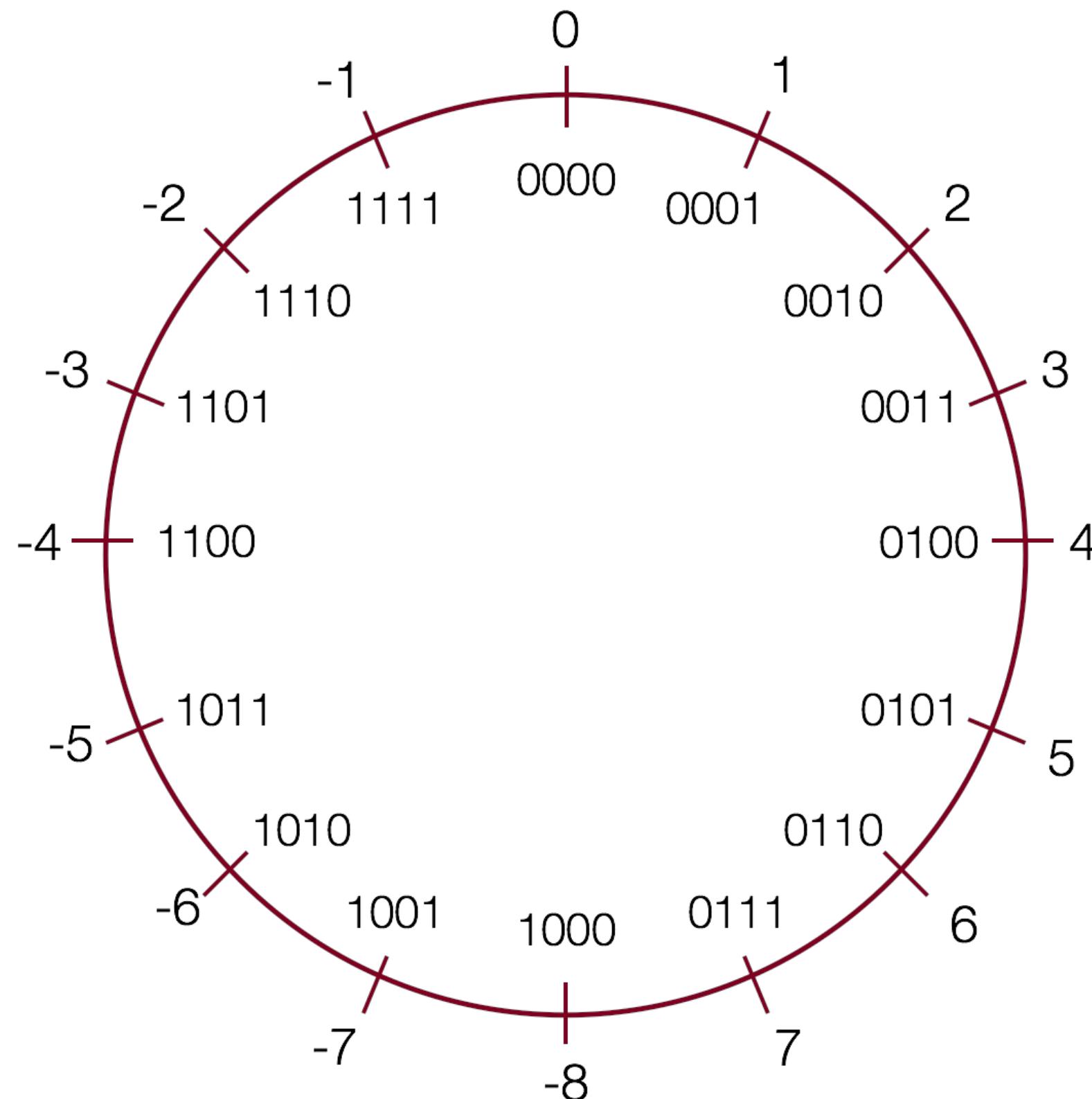
In two's complement notation, positive numbers are represented as themselves (phew), and negative numbers are represented as the *two's complement* of themselves (definition to follow).

This leads to some amazing arithmetic properties!

*John von Neumann suggested it in 1945, for the EDVAC computer.



Two's Complement



A two's-complement number system encodes positive and negative numbers in a binary number representation. The weight of each bit is a power of two, except for the most significant bit, whose weight is the negative of the corresponding power of two.

Definition: For vector $\vec{x} = [x_{w-1}, x_{w-2}, \dots, x_0]$ of an w -bit integer $x_{w-1}x_{w-2}\dots x_0$ is given by the following formula:

$$B2T_w(\vec{x}) = -x_{w-1}2^{w-1} + \sum_{i=0}^{w-2} x_i 2^i.$$

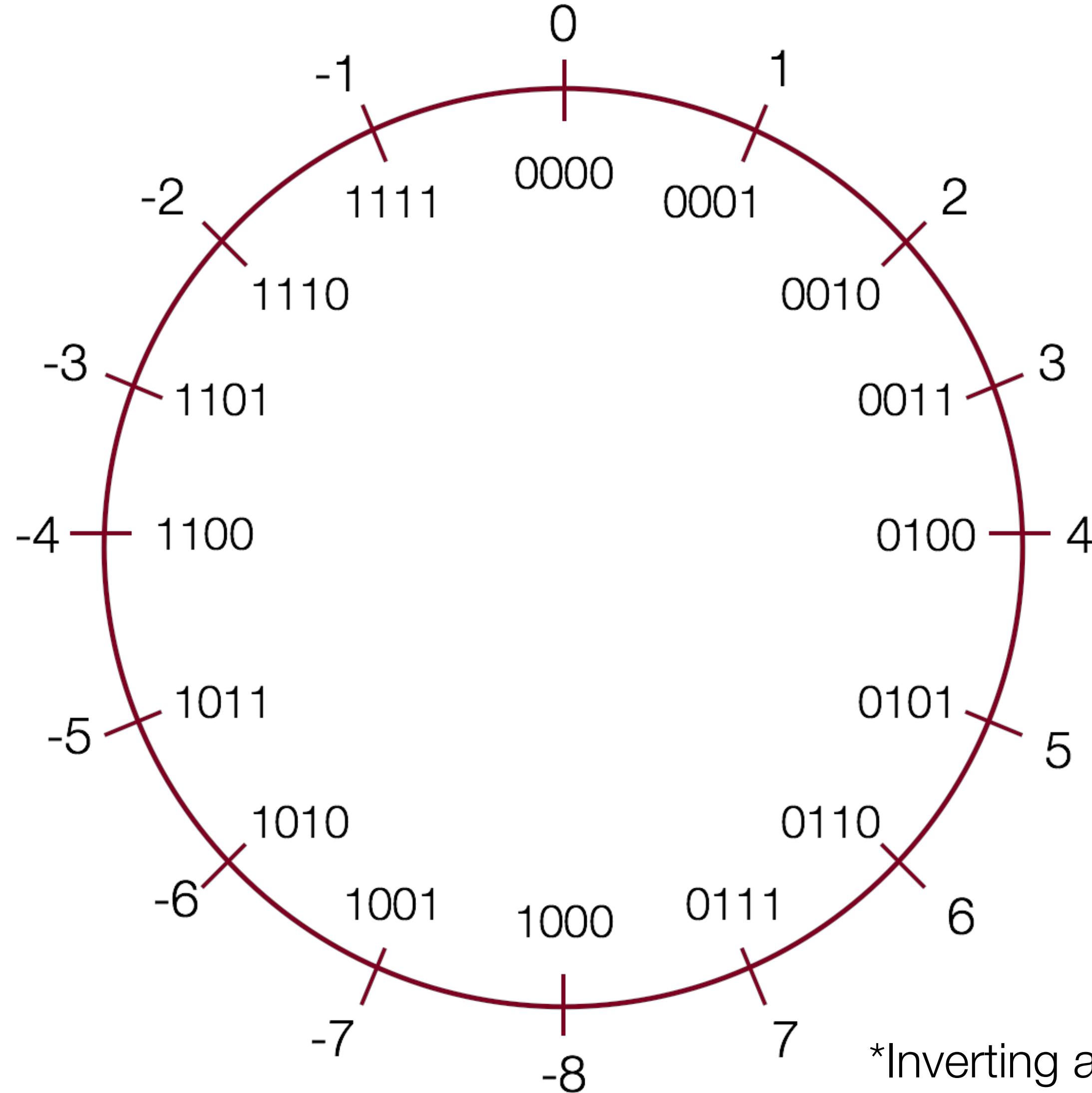
$B2T_w$ means "Binary to Two's complement function"

In practice, a negative number in two's complement is obtained by inverting all the bits of its positive counterpart*, and then adding 1.

*Inverting all the bits of a number is its "one's complement"



Two's Complement



In practice, a negative number in two's complement is obtained by inverting all the bits of its positive counterpart*, and then adding 1, or: $x = \sim x + 1$

Example: The number 2 is represented as normal in binary: 0010

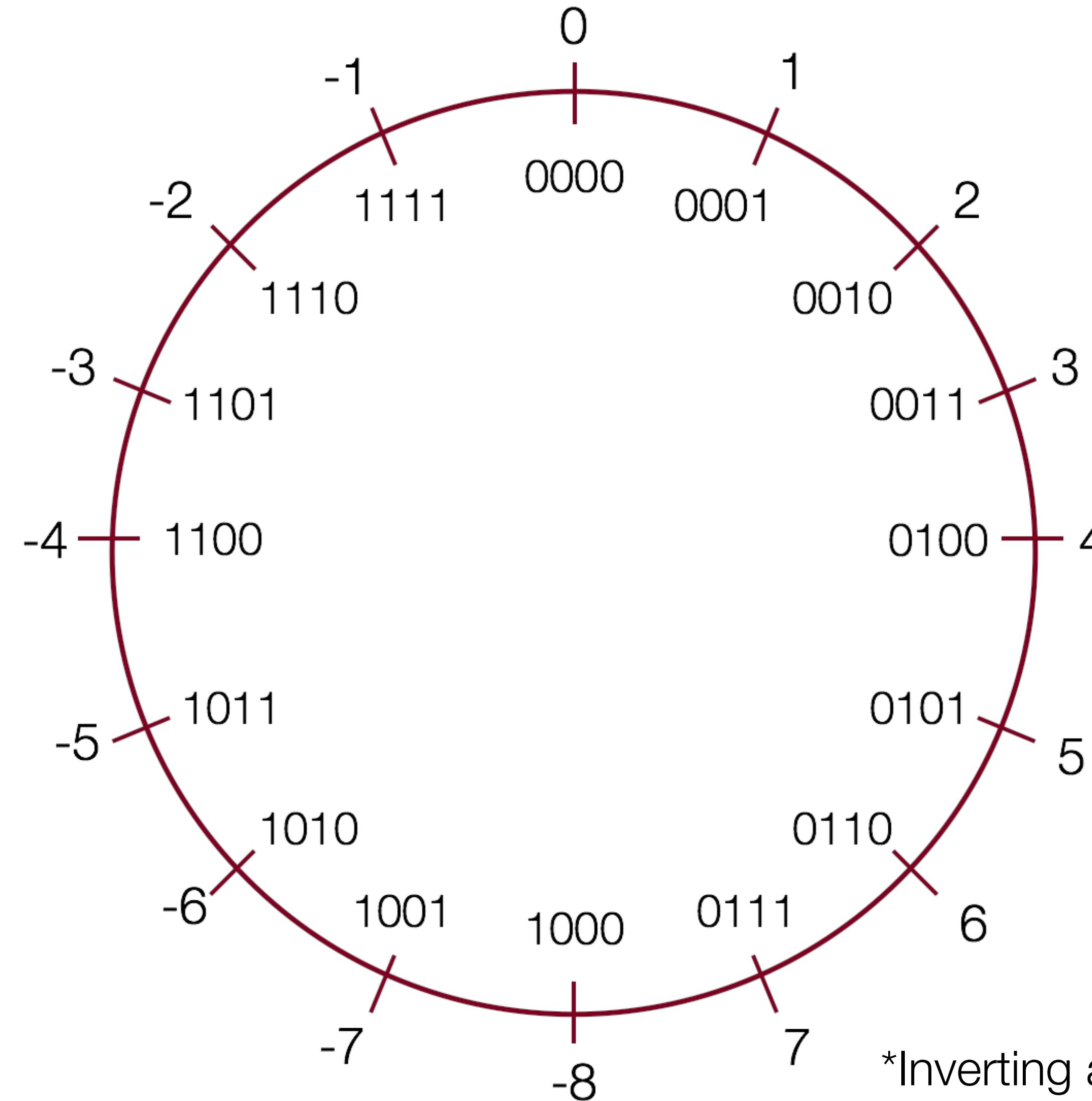
-2 is represented by inverting the bits, and adding 1:

$$\begin{array}{r} 0010 \\ \hbox{\scriptsize \(\rightarrow\)} 1101 \\ 1101 \\ + 1 \\ \hline 1110 \end{array}$$

*Inverting all the bits of a number is its "one's complement"



Two's Complement



Trick: to convert a positive number to its negative in two's complement, start from the right of the number, and write down all the digits until you get to a 1. Then invert the rest of the digits:

Example: The number 2 is represented as normal in binary: 0010

Going from the right, write down numbers until you get to a 1:

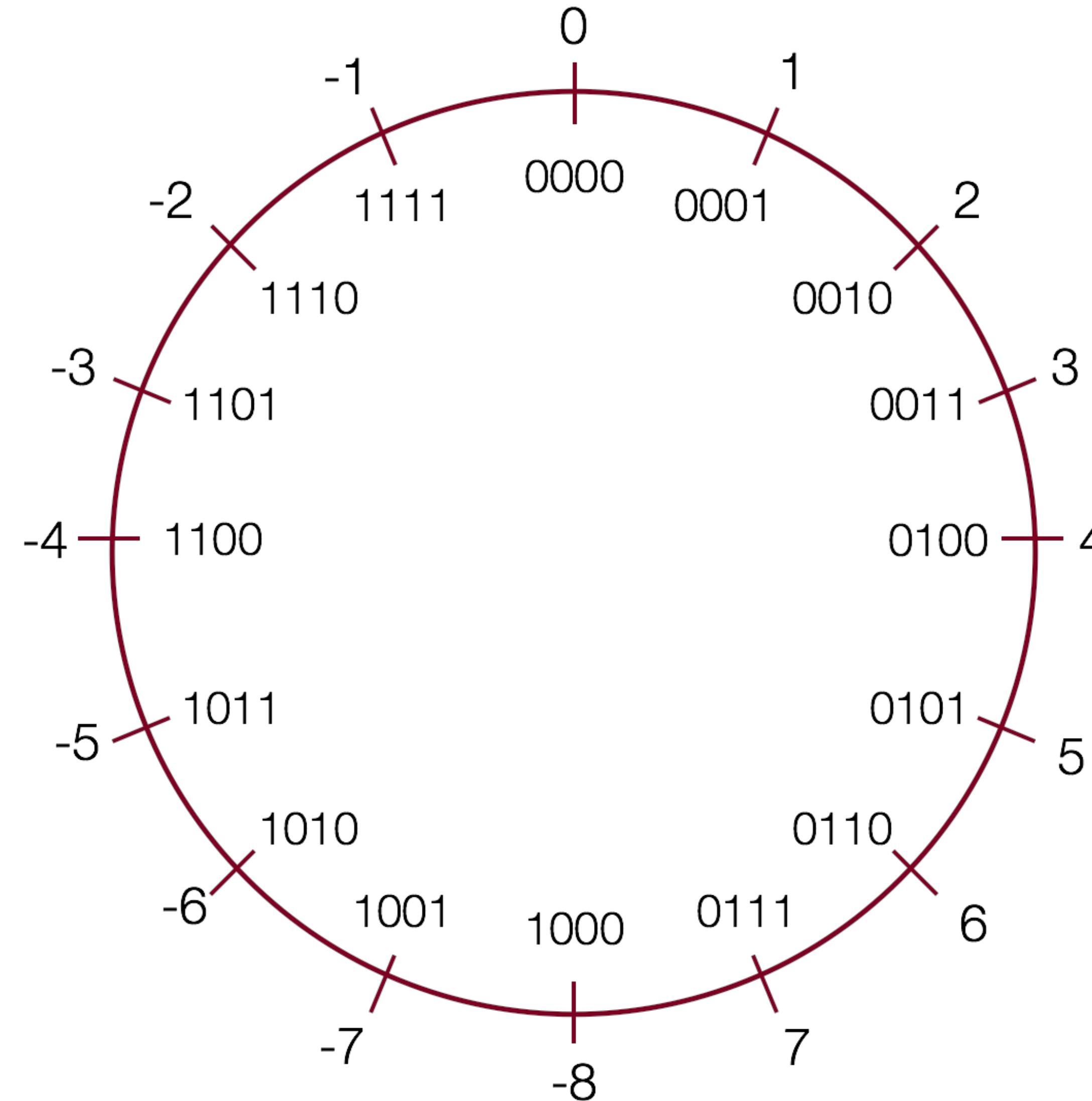
10

Then invert the rest of the digits:
1110

*Inverting all the bits of a number is its "one's complement"



Two's Complement



To convert a negative number to a positive number, perform the same steps!

Example: The number -5 is represented in two's complements as: 1011

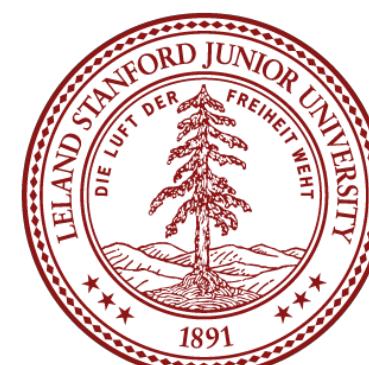
5 is represented by inverting the bits, and adding 1:

$$\begin{array}{r} 1011 \text{ ↗ } 0100 \\ 0100 \\ + 1 \\ \hline 0101 \end{array}$$

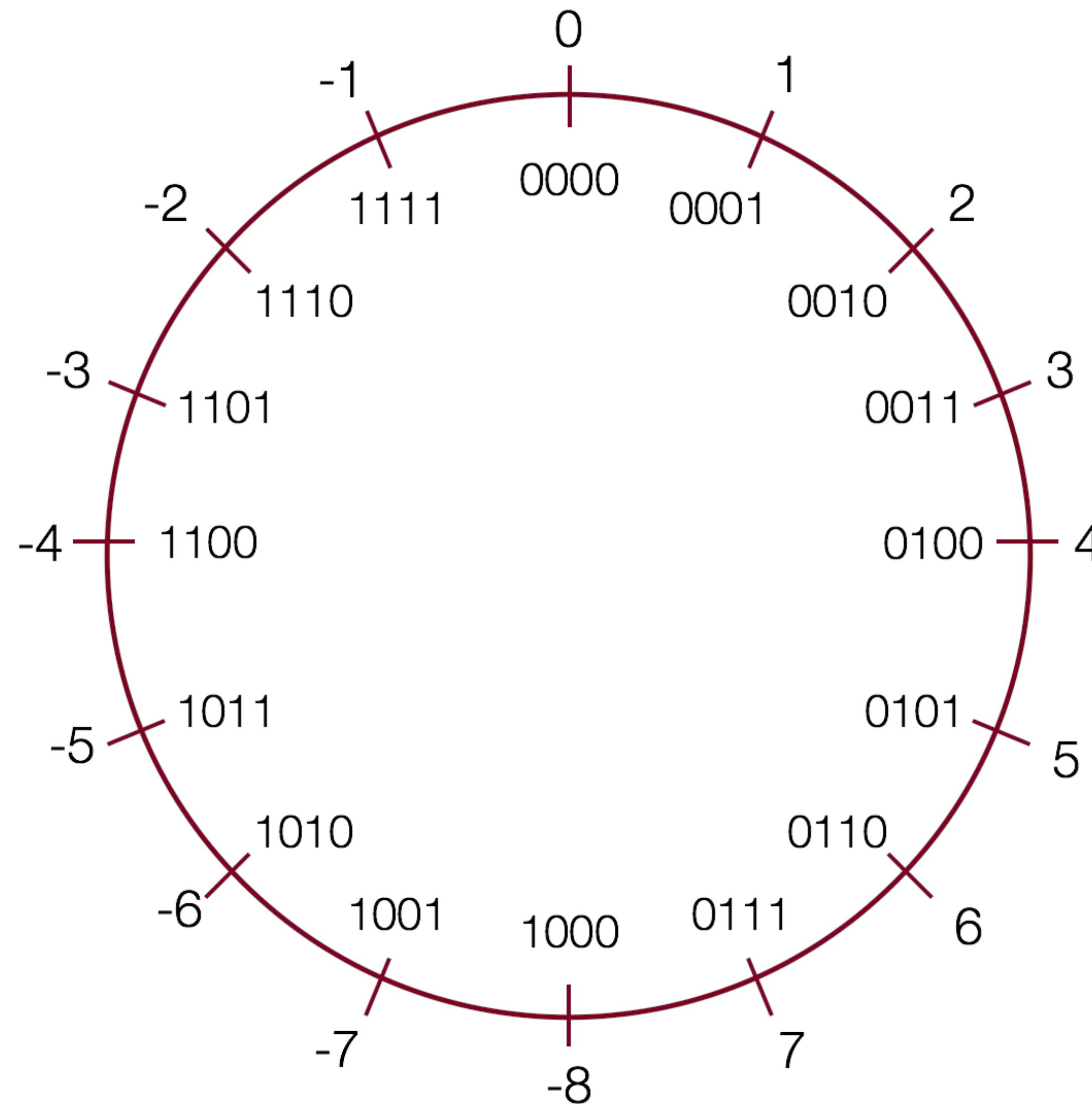
Shortcut: start from the right, and write down numbers until you get to a 1:

1

Now invert all the rest of the digits:
0101



Two's Complement: Neat Properties



There are a number of useful properties associated with two's complement numbers:

1. There is only one zero (yay!)
2. The highest order bit (left-most) is 1 for negative, 0 for positive (so it is easy to tell if a number is negative)
3. Adding two numbers is just...adding!

Example:

$$2 + -5 = -3$$

$$\begin{array}{r} 0010 \\ +1011 \end{array}$$

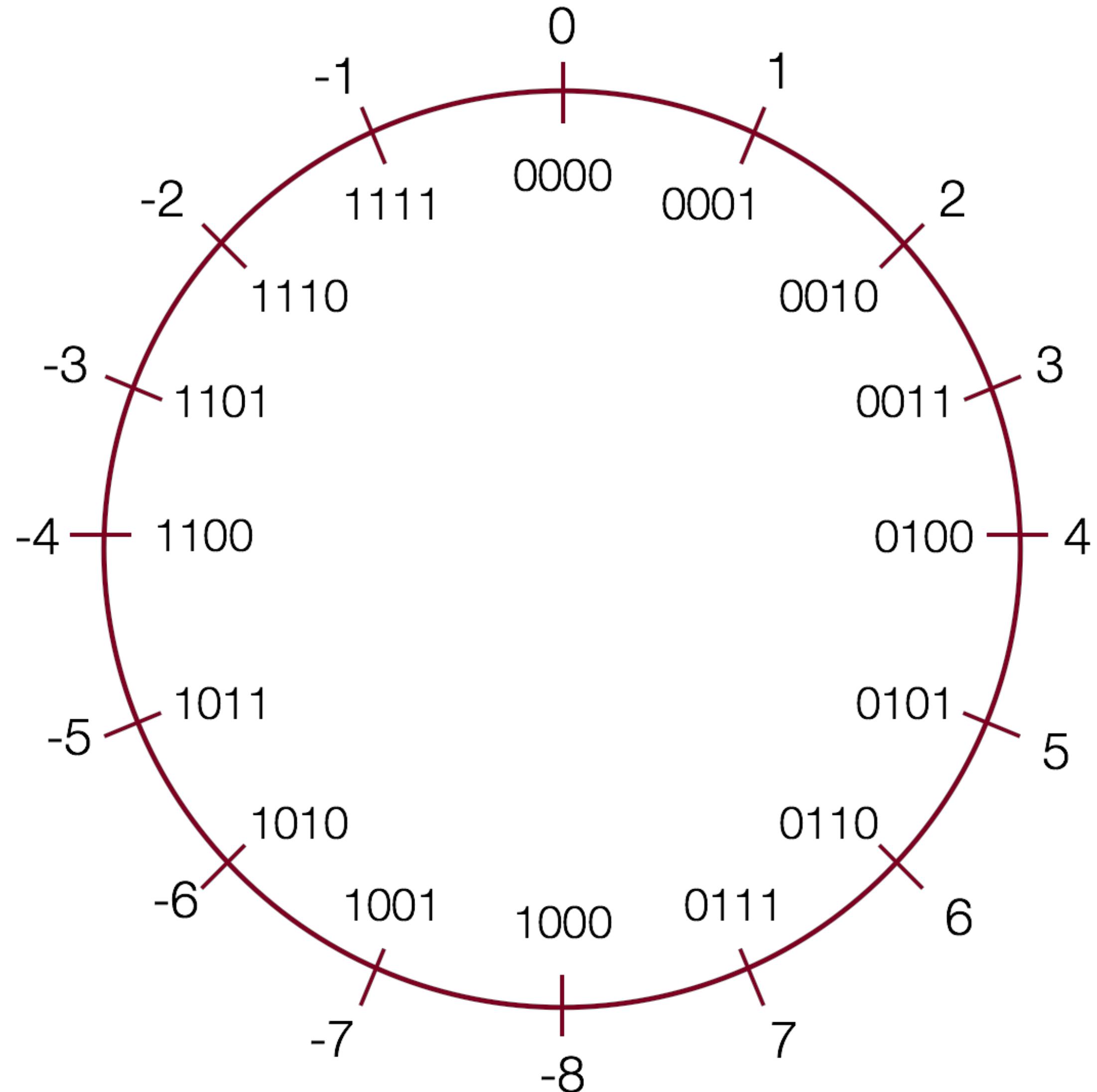
$$\underline{\quad\quad\quad}$$

1101 ➔ -3 decimal (wow!)



Two's Complement: Neat Properties

More useful properties:



- Subtracting two numbers is simply performing the two's complement on one of them and then adding.

Example:

$$4 - 5 = -1$$

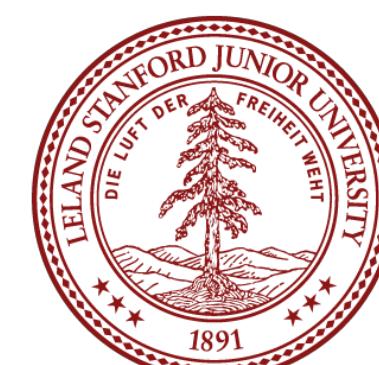
$$0100 \rightarrow 4, 0101 \rightarrow 5$$

Find the two's complement of 5: 1011
add:

$$0100 \rightarrow 4$$

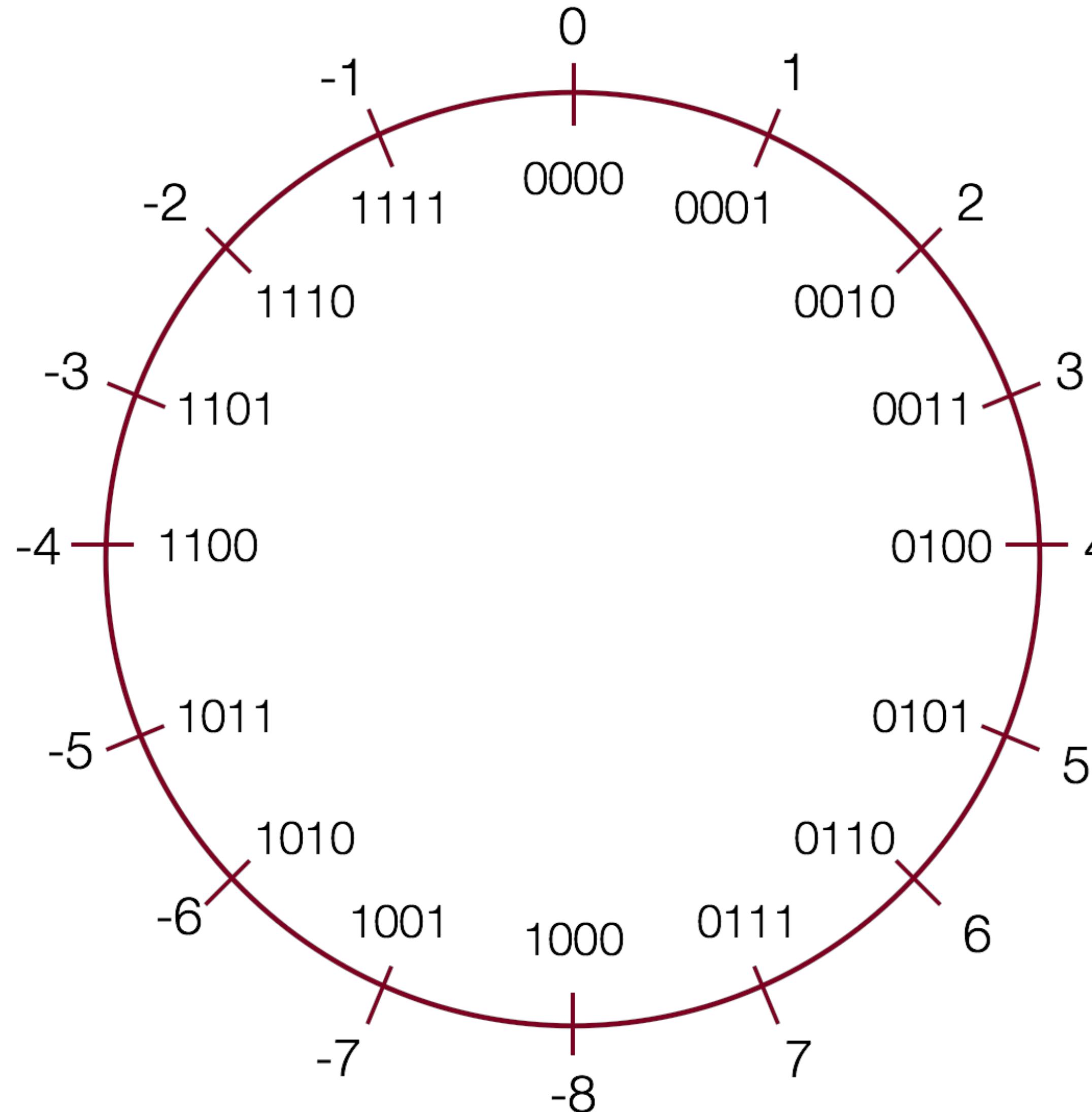
$$\underline{+1011} \rightarrow -5$$

$$1111 \rightarrow -1 \text{ decimal}$$



Two's Complement: Neat Properties

More useful properties:



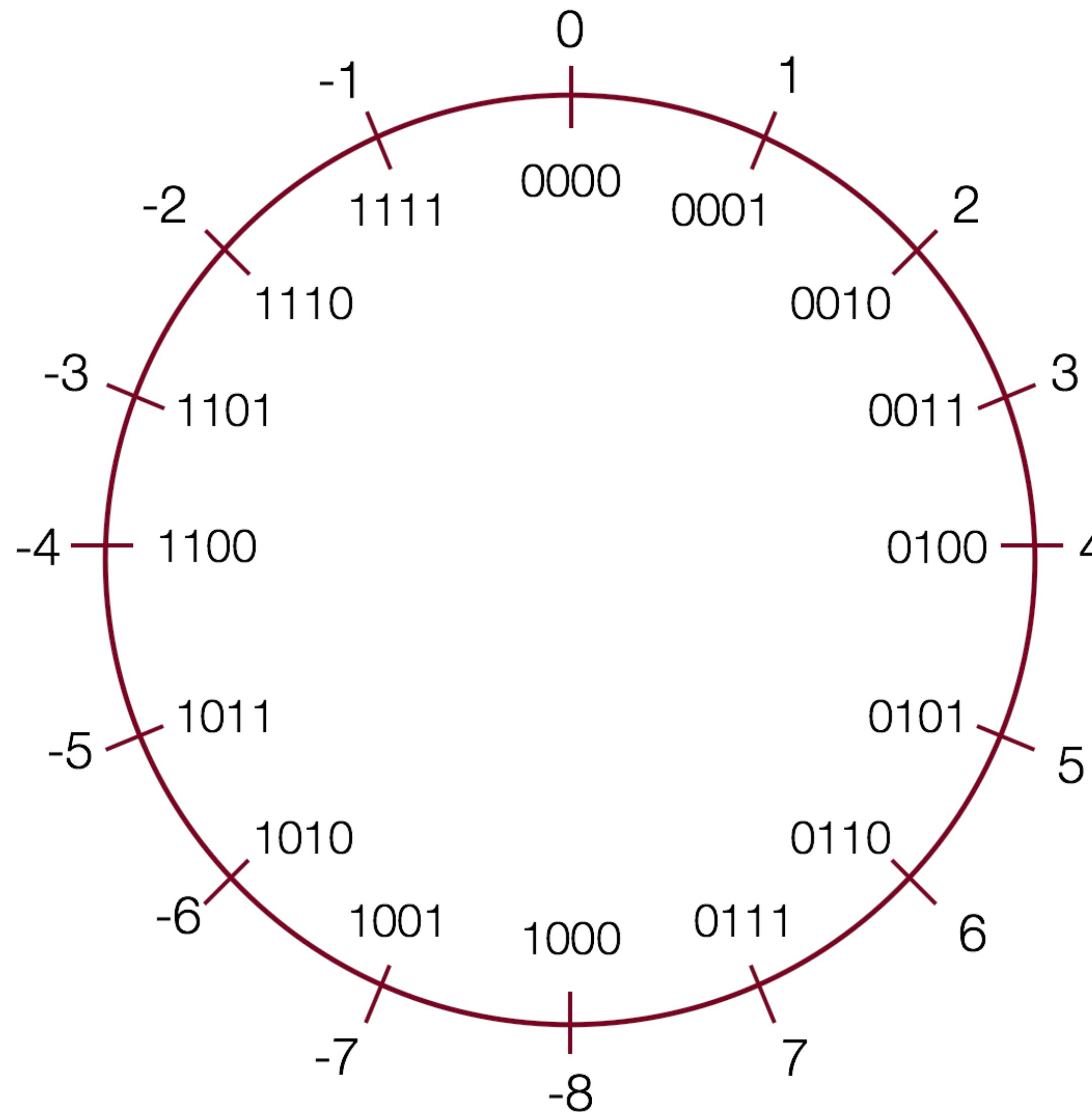
5. Multiplication of two's complement works just by multiplying (throw away overflow digits).

Example: $-2 * -3 = 6$

$$\begin{array}{r} 1110 \text{ } \xrightarrow{\hspace{1cm}} \text{ } -2 \\ \times 1101 \text{ } \xrightarrow{\hspace{1cm}} \text{ } -3 \\ \hline 1110 \\ 0000 \\ 1110 \\ +1110 \\ \hline 10110110 \xrightarrow{\hspace{1cm}} 6 \end{array}$$



Practice



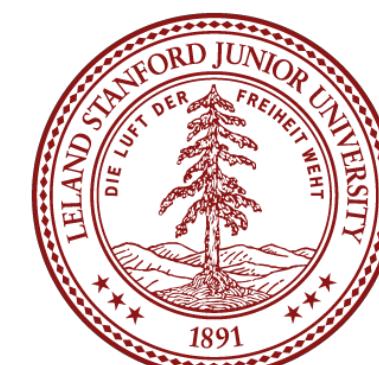
Convert the following 4-bit numbers from positive to negative, or from negative to positive using two's complement notation:

a. -4 (1100) ➡

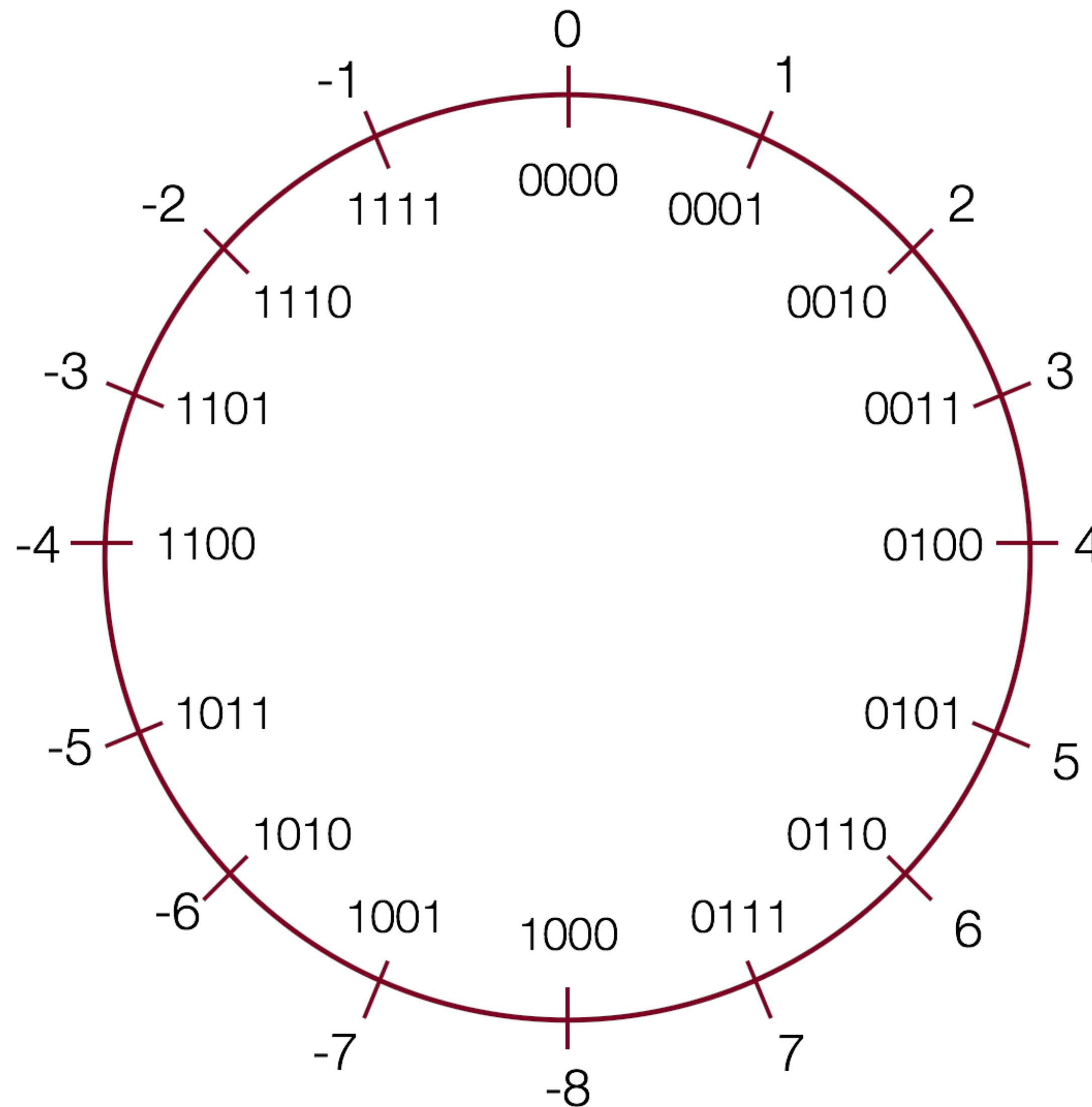
b. 7 (0111) ➡

c. 3 (0011) ➡

d. -8 (1000) ➡



Practice



Convert the following 4-bit numbers from positive to negative, or from negative to positive using two's complement notation:

a. -4 (1100) ➡ 0100

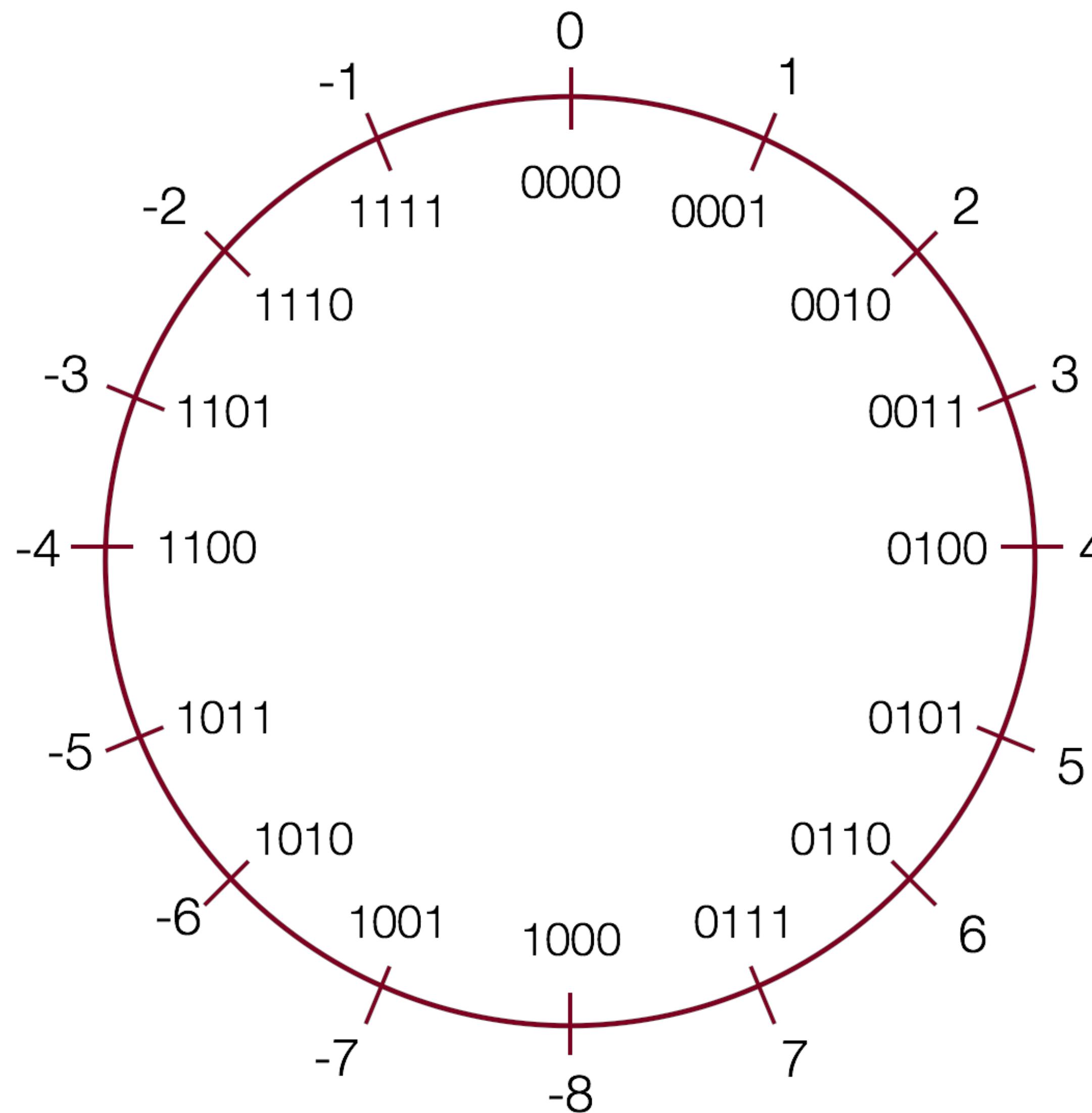
b. 7 (0111) ➡ 1001

c. 3 (0011) ➡ 1101

d. -8 (1000) ➡ 1000 (! If you look at the chart, +8 cannot be represented in two's complement with 4 bits!)

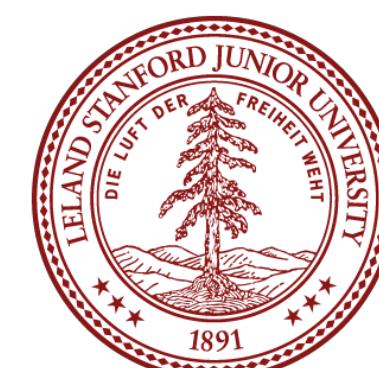


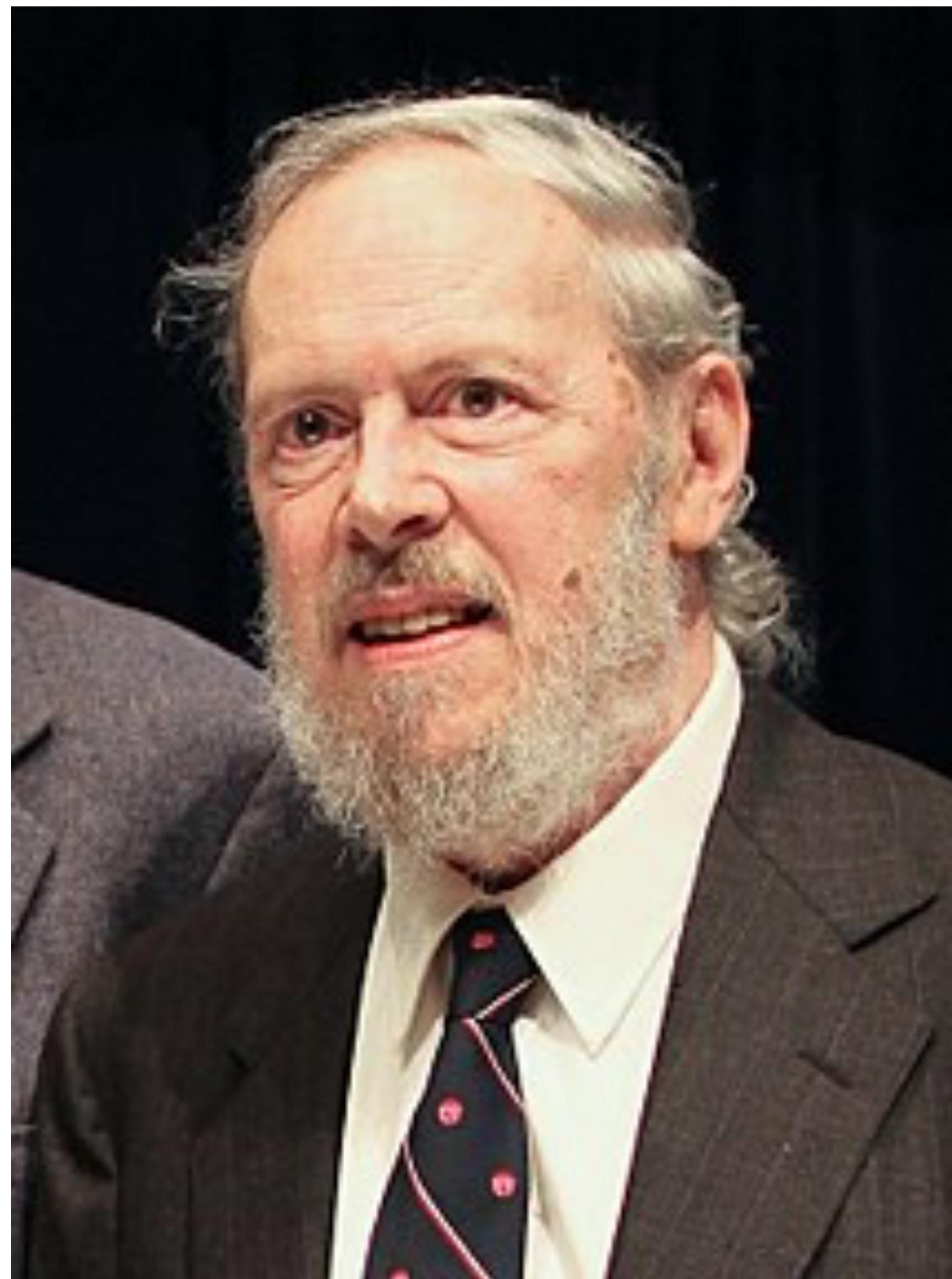
Practice



Convert the following 8-bit numbers from positive to negative, or from negative to positive using two's complement notation:

- 4 (11111100) ➡ 00000100
- 27 (00011011) ➡ 11100101
- 127 (10000001) ➡ 01111111
- 1 (00000001) ➡ 11111111





Dennis Ritchie

C

SECOND EDITION

THE



PROGRAMMING
LANGUAGE

BRIAN W. KERNIGHAN
DENNIS M. RITCHIE

PRENTICE HALL SOFTWARE SERIES



C



Ken Thompson built UNIX using C

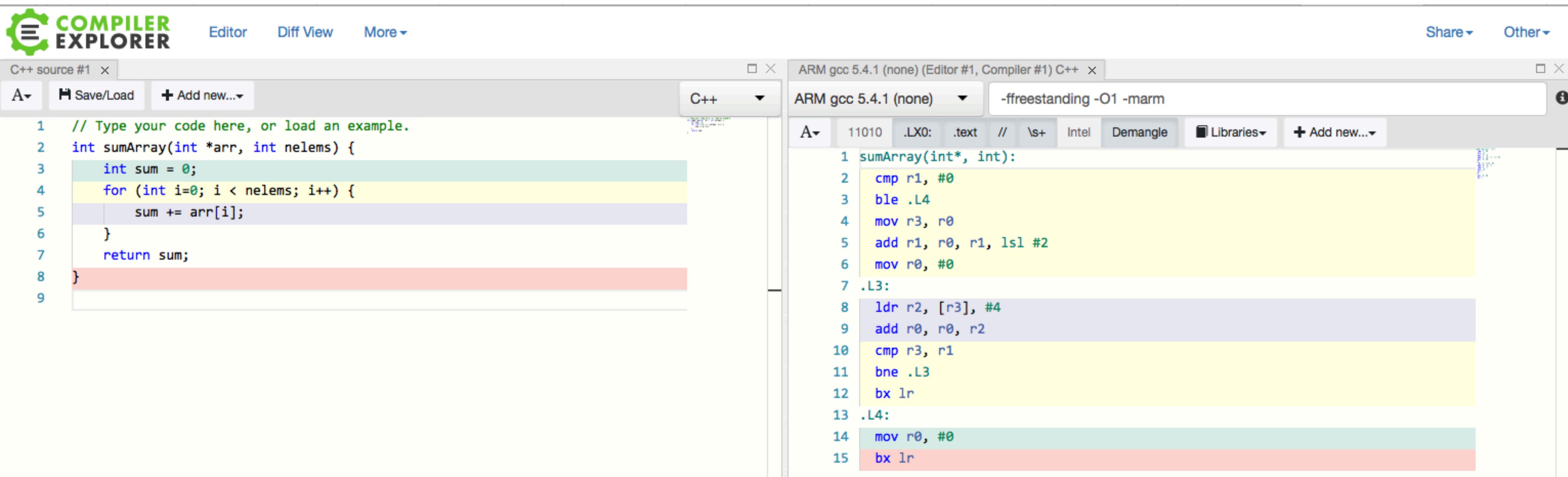
The C programming language, invented in 1972 (!) is a high level language that makes it easy to work at a low level. It allows open access to the underlying hardware, yet it is still generally portable across machines, and compilers have been built for virtually every computer going back to the 1970s.



C

C language features closely model the ISA of many machines: data types, arithmetic / logical operators, control flow, access to memory, etc.

The *Compiler Explorer* is a cool interactive tool to see the translation from C to assembly:



The screenshot shows the Compiler Explorer interface with two panes. The left pane is a C++ code editor with the following code:

```
1 // Type your code here, or load an example.
2 int sumArray(int *arr, int nelems) {
3     int sum = 0;
4     for (int i=0; i < nelems; i++) {
5         sum += arr[i];
6     }
7     return sum;
8 }
```

The right pane shows the assembly output for an ARM compiler (ARM gcc 5.4.1) with the command line options: -ffreestanding -O1 -marm. The assembly code is:

```
1 sumArray(int*, int):
2     cmp r1, #0
3     ble .L4
4     mov r3, r0
5     add r1, r0, r1, lsl #2
6     mov r0, #0
7 .L3:
8     ldr r2, [r3], #4
9     add r0, r0, r2
10    cmp r3, r1
11    bne .L3
12    bx lr
13 .L4:
14    mov r0, #0
15    bx lr
```

<https://godbolt.org/g/oWrqRf>



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)

loop:
ldr r0, SET0
str r1, [r0]

mov r2, #DELAY
wait1:
    subs r2, #1
    bne wait1

ldr r0, CLR0
str r1, [r0]

mov r2, #DELAY
wait2:
    subs r2, #1
    bne wait2

b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)
```

```
loop:
ldr r0, SET0
str r1, [r0]
```

```
mov r2, #DELAY
```

```
wait1:
    subs r2, #1
    bne wait1
```

```
ldr r0, CLR0
str r1, [r0]
```

```
mov r2, #DELAY
```

```
wait2:
    subs r2, #1
    bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;
unsigned int *SET0 = (unsigned int *)0x2020001c;
unsigned int *CLR0 = (unsigned int *)0x20200028;
```

```
#define DELAY 0x3f0000
```

```
void main(void)
{
```

```
    *FSEL2 = 1;
```

```
    while (1) {
```

```
        *SET0 = 1 << 20;
```

```
        for (int c = DELAY; c != 0; c--) ;
```

```
        *CLR0 = 1 << 20;
```

```
        for (int c = DELAY; c != 0; c--) ;
```

```
}
```

```
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)

loop:
ldr r0, SET0
str r1, [r0]

mov r2, #DELAY
wait1:
    subs r2, #1
    bne wait1

ldr r0, CLR0
str r1, [r0]

mov r2, #DELAY
wait2:
    subs r2, #1
    bne wait2

b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```

Globals

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;
unsigned int *SET0  = (unsigned int *)0x2020001c;
unsigned int *CLR0  = (unsigned int *)0x20200028;
```

```
#define DELAY 0x3f0000

void main(void)
{
    *FSEL2 = 1;

    while (1) {
        *SET0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
        *CLR0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
    }
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000  
  
ldr r0, FSEL2  
mov r1, #1  
str r1, [r0]  
mov r1, #(1<<20)
```

```
loop:  
    ldr r0, SET0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
    wait1:  
        subs r2, #1  
        bne wait1
```

```
    ldr r0, CLR0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
    wait2:  
        subs r2, #1  
        bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008  
SET0:  .word 0x2020001C  
CLR0:  .word 0x20200028
```

Constant

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;  
unsigned int *SET0 = (unsigned int *)0x2020001C;  
unsigned int *CLR0 = (unsigned int *)0x20200028;
```

```
#define DELAY 0x3f0000
```

```
void main(void)  
{  
    *FSEL2 = 1;  
  
    while (1) {  
        *SET0 = 1 << 20;  
        for (int c = DELAY; c != 0; c--) ;  
        *CLR0 = 1 << 20;  
        for (int c = DELAY; c != 0; c--) ;  
    }  
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000  
  
ldr r0, FSEL2  
mov r1, #1  
str r1, [r0]  
mov r1, #(1<<20)
```

```
loop:  
    ldr r0, SET0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
    wait1:  
        subs r2, #1  
        bne wait1
```

```
    ldr r0, CLR0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
    wait2:  
        subs r2, #1  
        bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008  
SET0:  .word 0x2020001C  
CLR0:  .word 0x20200028
```

Assignment to a memory address

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;  
unsigned int *SET0 = (unsigned int *)0x2020001c;  
unsigned int *CLR0 = (unsigned int *)0x20200028;  
  
#define DELAY 0x3f0000  
  
void main(void)  
{  
    *FSEL2 = 1;  
  
    while (1) {  
        *SET0 = 1 << 20;  
        for (int c = DELAY; c != 0; c--) ;  
        *CLR0 = 1 << 20;  
        for (int c = DELAY; c != 0; c--) ;  
    }  
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)
```

```
loop:
    ldr r0, SET0
    str r1, [r0]
```

```
    mov r2, #DELAY
    wait1:
        subs r2, #1
        bne wait1
```

```
    ldr r0, CLR0
    str r1, [r0]
```

```
    mov r2, #DELAY
    wait2:
        subs r2, #1
        bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```

More assignments

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;
unsigned int *SET0 = (unsigned int *)0x2020001c;
unsigned int *CLR0 = (unsigned int *)0x20200028;
```

```
#define DELAY 0x3f0000

void main(void)
{
    *FSEL2 = 1;
    while(1) {
        *SET0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
        *CLR0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
    }
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)
```

```
loop:
    ldr r0, SET0
    str r1, [r0]
```

```
    mov r2, #DELAY
    wait1:
        subs r2, #1
        bne wait1
```

```
    ldr r0, CLR0
    str r1, [r0]
```

```
    mov r2, #DELAY
    wait2:
        subs r2, #1
        bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```

Inner loops (note that in C there is no body!)

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;
unsigned int *SET0 = (unsigned int *)0x2020001c;
unsigned int *CLR0 = (unsigned int *)0x20200028;
```

```
#define DELAY 0x3f0000
```

```
void main(void)
{
```

```
    *FSEL2 = 1;
```

```
    while (1) {
```

```
        *SET0 = 1 << 20;
```

```
        for (int c = DELAY; c != 0; c--) ;
```

```
        *CLR0 = 1 << 20;
```

```
        for (int c = DELAY; c != 0; c--) ;
```

```
}
```

```
}
```



Let's convert some assembly to C!

```
.equ DELAY, 0x3F0000

ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)
```

```
loop:
ldr r0, SET0
str r1, [r0]
```

```
mov r2, #DELAY
```

```
wait1:
    subs r2, #1
    bne wait1
```

```
ldr r0, CLR0
str r1, [r0]
```

```
mov r2, #DELAY
```

```
wait2:
    subs r2, #1
    bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C
CLR0:  .word 0x20200028
```

Outer loop (goes forever)

```
unsigned int *FSEL2 = (unsigned int *)0x20200008;
unsigned int *SET0 = (unsigned int *)0x2020001c;
unsigned int *CLR0 = (unsigned int *)0x20200028;

#define DELAY 0x3f0000

void main(void)
{
    *FSEL2 = 1;

    while (1) {
        *SET0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
        *CLR0 = 1 << 20;
        for (int c = DELAY; c != 0; c--) ;
    }
}
```



How do we get the C onto the Pi?

We use a *Makefile*, which has the commands in it (more on Makefiles later!):

```
$ make
arm-none-eabi-gcc -g -Wall -Og -std=c99 -ffreestanding -c cblink.c -o cblink.o
arm-none-eabi-gcc -nostdlib -T memmap cblink.o -o cblink.elf
arm-none-eabi-objcopy cblink.elf -O binary cblink.bin
rm cblink.elf

$ rpm-install.py cblink.bin
```



Can we see what the C code produces? Yes!

```
.equ DELAY, 0x3F0000
```

```
    ldr r0, FSEL2  
    mov r1, #1  
    str r1, [r0]  
    mov r1, #(1<<20)
```

```
loop:
```

```
    ldr r0, SET0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
wait1:  
    subs r2, #1  
    bne wait1
```

```
    ldr r0, CLR0  
    str r1, [r0]
```

```
    mov r2, #DELAY  
wait2:  
    subs r2, #1  
    bne wait2
```

```
b loop
```

```
FSEL2: .word 0x20200008  
SET0: .word 0x2020001C  
CLR0: .word 0x20200028
```

Use objdump
on the .elf file:

```
$ arm-none-eabi-objdump -D cblink.elf  
  
cblink.elf:      file format elf32-littlearm  
Disassembly of section .text:  
  
00008000 <main>:  
  8000: e59f3050  ldr   r3, [pc, #80]    ; 8058 <main+0x58>  
  8004: e5933000  ldr   r3, [r3]  
  8008: e3a02001  mov   r2, #1  
  800c: e5832000  str   r2, [r3]  
  8010: e59f0040  ldr   r0, [pc, #64]    ; 8058 <main+0x58>  
  8014: e3a01601  mov   r1, #1048576   ; 0x100000  
  8018: e3a0283f  mov   r2, #4128768   ; 0x3f0000  
  801c: e5903004  ldr   r3, [r0, #4]  
  8020: e5831000  str   r1, [r3]  
  8024: e1a03002  mov   r3, r2  
  8028: ea000000  b    8030 <main+0x30>  
  802c: e2433001  sub   r3, r3, #1  
  8030: e3530000  cmp   r3, #0  
  8034: 1afffffc  bne   802c <main+0x2c>  
  8038: e5903008  ldr   r3, [r0, #8]  
  803c: e5831000  str   r1, [r3]  
  8040: e1a03002  mov   r3, r2  
  8044: ea000000  b    804c <main+0x4c>  
  8048: e2433001  sub   r3, r3, #1  
  804c: e3530000  cmp   r3, #0  
  8050: 1afffffc  bne   8048 <main+0x48>  
  8054: eaafffff0 andeq r8, r0, ip, asr r0  
  8058: 0000805c  Disassembly of section .data:  
  
0000805c <FSEL2>:  
  805c: 20200008  eorcs r0, r0, r8  
  
00008060 <SET0>:  
  8060: 2020001c  eorcs r0, r0, ip, lsl r0  
  
00008064 <CLR0>:  
  8064: 20200028  eorcs r0, r0, r8, lsr #32
```



Know Your Tools!

- Assembler (as)
 - Transform assembly code (text) into object code (binary machine instructions)
 - This is a mechanical translation, with few surprises
- Compiler (gcc)
 - Transform C code (text) into object code (likely first translated into asm then into object form, C \Rightarrow asm \Rightarrow object)
 - This is a *complex* translation, with a large potential for optimization



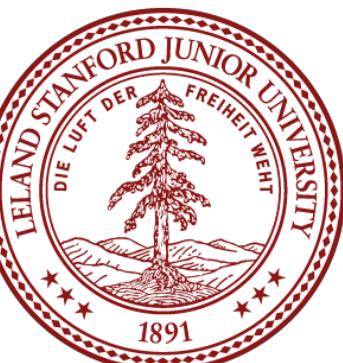
Know Your Tools!

- When coding directly in assembly, *the instructions you see are the instructions you get*, with no surprises!
- For C source, you may need to drop down to see what the compiler has generated to be sure of what you're getting.
- What transformations are *legal*?
- What transformations are *desirable*?



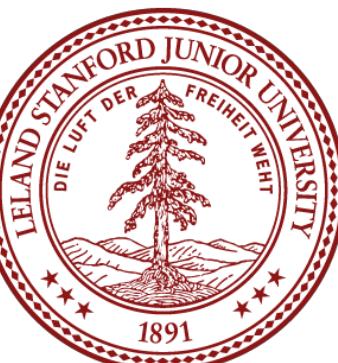
Extra Slides

Extra Slides



Extra Slides

The Compiler sometimes needs hints when you are dealing
with real hardware!



Extra Slides

Calculating the number of instructions per second of your Pi

Based on the blinking LED, you can get a good idea of how many instructions your Pi is running under the current configuration:

1. Time ten on/off flashes (8 seconds on my Pi). **8sec / 10 flashes**
2. Look at the number of instructions in a on/off loop:

```
wait1:  
    subs r2, #1  
    bne wait1
```

2 instructions
3. Each loop is executed **0x3F0000** (decimal: **4128768**) times, and there are two loops, so there are a total of **2 inst. * 4128768 * 2 = 16515072 instructions per flash.**
4. Therefore:

$$16515072 \text{ inst/flash} * 10 \text{ flashes} / 8 \text{ sec} = 20,643,840 \text{ instructions per second}$$



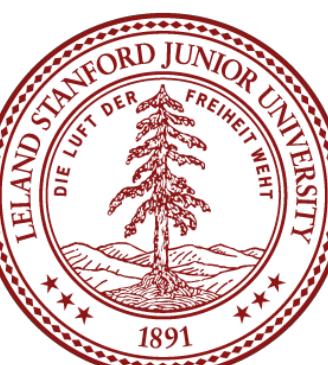
Extra Slides

```
16515072 inst/flash * 10 flashes / 8 sec = 20,643,840 instructions per second
```

The Raspberry Pi has a clock frequency of 700MHz
Why are our Pis only running 20M instructions per second?

There are a number of factors:

1. Caches are turned off, and memory is slow. All instructions must be read from memory, so this makes things much slower. Memory reads are 50x slower than caches, and 100x slower than registers.
2. There are other hardware factors that can change the instructions per second count, too.



Code	Suffix	Description	Flags
0000	EQ	Equal / equals zero	Z
0001	NE	Not equal	!Z
0010	CS / HS	Carry set / unsigned higher or same	C
0011	CC / LO	Carry clear / unsigned lower	!C
0100	MI	Minus / negative	N
0101	PL	Plus / positive or zero	!N
0110	VS	Overflow	V
0111	VC	No overflow	!V
1000	HI	Unsigned higher	C and !Z
1001	LS	Unsigned lower or same	!C or Z
1010	GE	Signed greater than or equal	N == V
1011	LT	Signed less than	N != V
1100	GT	Signed greater than	!Z and (N == V)
1101	LE	Signed less than or equal	Z or (N != V)
1110	AL	Always (default)	any

