

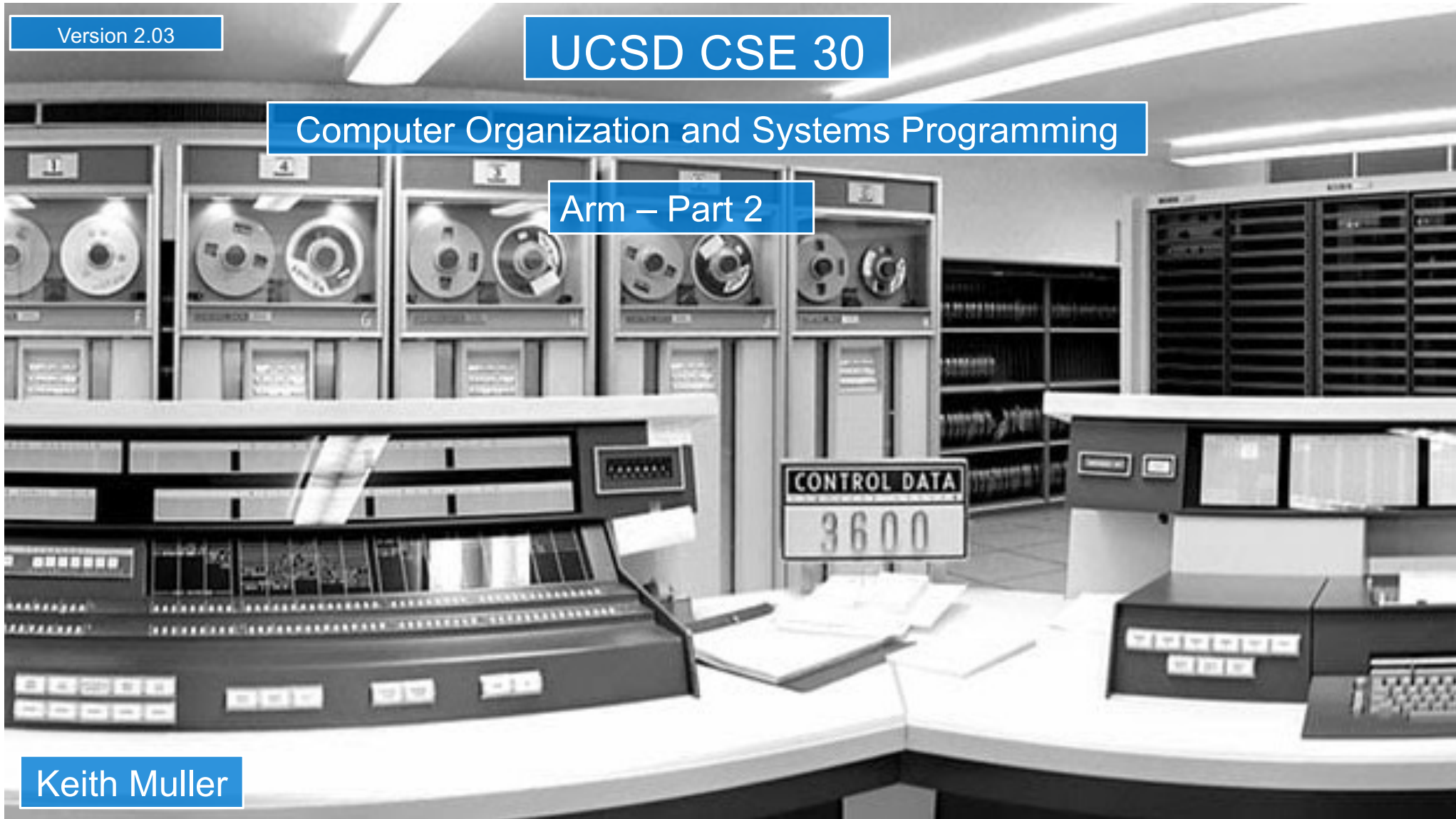
Version 2.03

UCSD CSE 30

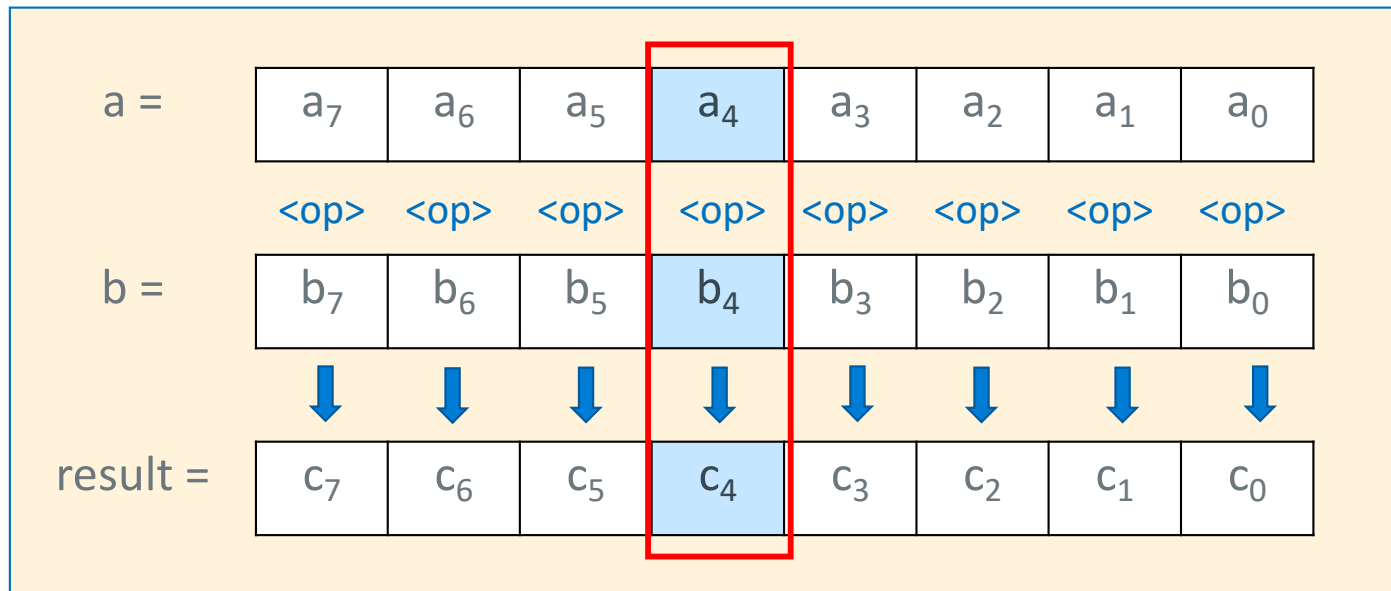
Computer Organization and Systems Programming

Arm – Part 2

Keith Muller



What is a Bitwise Operation?



- Bitwise operators are applied independently to each of the corresponding bit positions in each variable
- Each bit position of the result depends only on bits in the **same bit position** within the operands

Bitwise (Bit to Bit) Operators in C

output = \sim a;

a	\sim a
0	1
1	0

output = a & b;

a	b	a & b
0	0	0
0	1	0
1	0	0
1	1	1

& with 1 to let a bit through
& with 0 to set a bit to 0

output = a | b;

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

| with 1 to set a bit to 1
| with 0 to let a bit through

output = a ^ b; //EOR

a	b	a ^ b
0	0	0
0	1	1
1	0	1
1	1	0

^ with 1 will flip the bit
^ with 0 to let a bit through

Bitwise
NOT

\sim 1100

0011

Bitwise
AND

0110
& 1100

0100

Bitwise
OR

0110
1100

1110

Bitwise
EOR

0110
^ 1100

1010

Bitwise Not (vs Boolean Not)

in C
int output = ~a;

a	~a
0	1
1	0

Bitwise NOT

~ 1100
-- --
0011

	Bitwise Not
number	0101 1010 0101 1010 1111 0000 1001 0110
~number	1010 0101 1010 0101 0000 1111 0110 1001

Meaning	Operator	Operator	Meaning
Boolean NOT	!b	~b	Bitwise NOT

Boolean operators act on the entire value not the individual bits

Type	Operation	result
bitwise	~0x01	1111 1111 1111 1111 1111 1111 1111 1110
Boolean	!0x01	0000 0000 0000 0000 0000 0000 0000 0000

MVN (not)

mvn r0, r1

```
// Copies all 32 bits  
// of the value held  
// in register r1 into  
// the register r0  
// then does a bitwise NOT
```

register r1



register r0

mvn r0, 12

```
// Expands an imm8 value 0x0c  
// stored in the instruction  
// into a register then does  
// a bitwise NOT
```

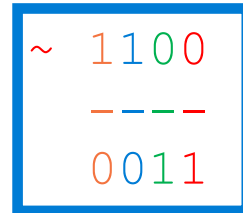
register r0

0x0c



0xffff fff3

Bitwise NOT



- A **bitwise NOT** operation

0x 0c

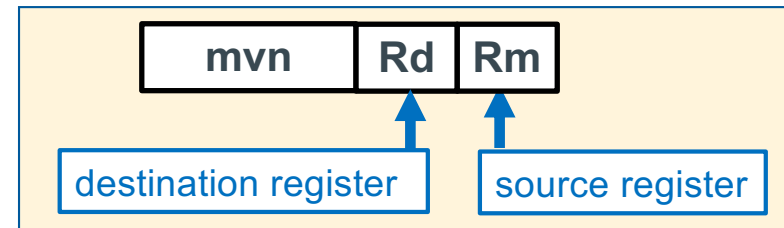
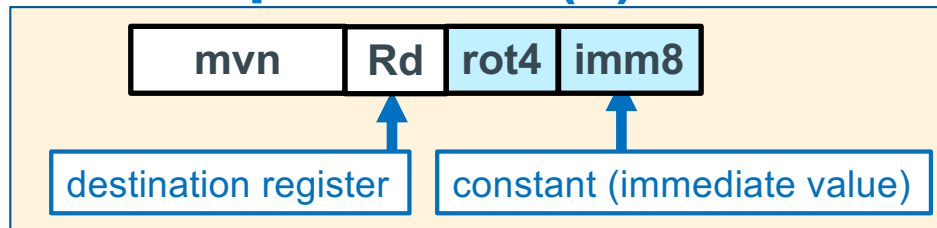
↓ imm8 expansion

0x0000000c

↓ bitwise not

0xfffffffff3

mvn – Copies NOT (~)

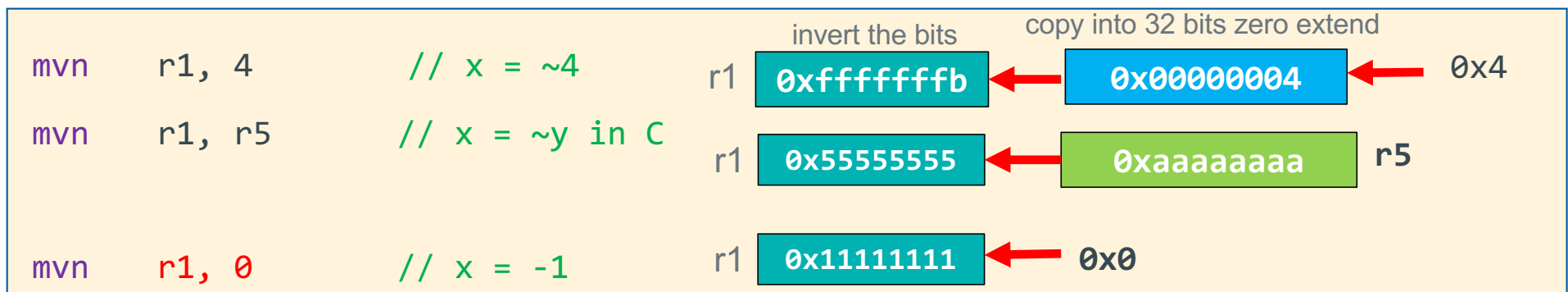


```
mvn  Rd, constant    // Rd = constant
mvn  Rd,  Rm         // Rd = Rm
```

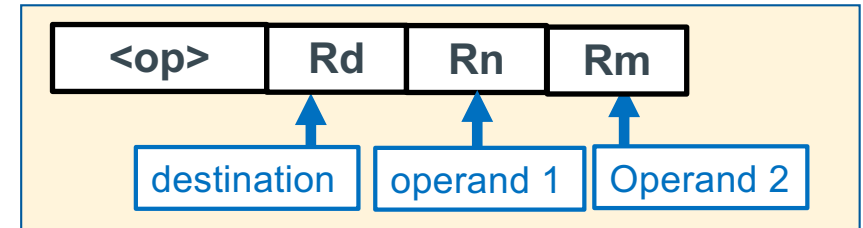
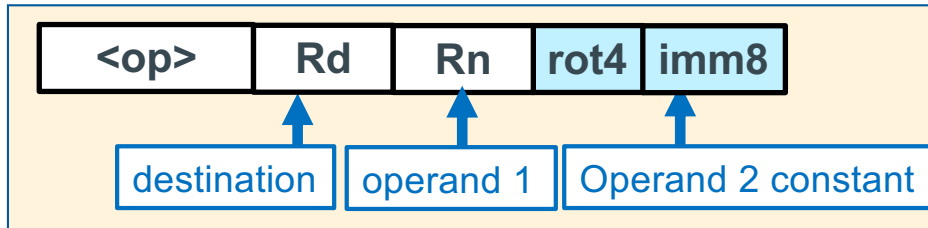


bitwise NOT operation. Immediate (constant) version copies to 32-bit register, then does a bitwise NOT

imm8	extended imm8	inverted imm8	signed base 10
0x00	0x00 00 00 00	0xff ff ff ff	-1
0xff	0x00 00 00 ff	0xff ff ff 00	-256



Bitwise Instructions



`<op> Rd, Rn, constant // Rd = Rn <op> constant`
`<op> Rd, constant // Rd = Rd <op> constant`
`<op> Rd, Rn, Rm // Rd = Rn <op> Rm`

Bytes: $0 \leq \text{imm8} \leq 255$ + values from "rotating" rot 4 bits

Bitwise <code><op></code> description	C Syntax	Arm <code><op></code> Syntax <i>Op2: either register or constant value</i>	Operation
Bitwise AND	<code>a & b</code>	<code>and Rd, Rn, Op2</code>	$R_d = R_n \& Op2$
Bitwise OR	<code>a b</code>	<code>orr Rd, Rn, Op2</code>	$R_d = R_n Op2$
Exclusive OR	<code>a ^ b</code>	<code>eor Rd, Rn, Op2</code>	$R_d = R_n \wedge Op2$
Bitwise NOT	<code>a = ~b</code>	<code>mvn Rd, Rn</code>	$R_d = \sim R_n$

Bitwise versus C Boolean Operators

Boolean Operators

Bitwise Operators

Meaning	Operator		Operator	Meaning
Boolean AND	<code>a && b</code>		<code>a & b</code>	Bitwise AND
Boolean OR	<code>a b</code>		<code>a b</code>	Bitwise OR
Boolean NOT	<code>!b</code>		<code>~b</code>	Bitwise NOT

Boolean operators **act on the entire value not the individual bits**

bitwise & versus boolean &&

`0x10 & 0x01 = 0x00 (bitwise)`

`0x10 && 0x01 = 0x01 (Boolean)`

bitwise ~ versus boolean !

`~0x01 = 0xfffffffffe (bitwise)`

`!0x01 = 0x0 (Boolean)`

The act (operation) of *Masking*

a =	a ₇	a ₆	a ₅	a ₄	a ₃	a ₂	a ₁	a ₀
	<op>	<op>	<op>	<op>	<op>	<op>	<op>	<op>
b =	b ₇	b ₆	b ₅	b ₄	b ₃	b ₂	b ₁	b ₀
result =	c ₇	c ₆	c ₅	c ₄	c ₃	c ₂	c ₁	c ₀

- Bit masks access/modify specific bits in memory
- Masking act of applying a mask to a value with a specific op:
 - **orr**: 0 passes bit unchanged, 1 sets bit to 1 `(a = b | c; // in C)`
 - **eor**: 0 passes bit unchanged, 1 inverts the bit `(a = b ^ c; // in C)`
 - **and**: 0 clears the bit, 1 passes bit unchanged `(a = b & c; // in C)`

Mask on

force bits to 1 "**mask on**" operation

- 1 to **set a bit to 1**
- 0 to let a **bit through unchanged**

```
orr r1, r2, r3
```

```
r1 = r2 | r3; // in C
```

Example: force lower 16 bits to 1

DATA: r2 0xab ab ab 77

orr

MASK: r3 0x00 00 ff ff

unchanged

forces to a 1

RSLT: r1 0xab ab ff ff

Example: force lower 8 bits to 1

DATA: r2 0xab ab ab 77

```
orr r1 r2, 0xff
```

```
r1 = r2 | 0xff; // in C
```

RSLT: r1 0xab ab ff ff

Mask off

force bits to 0 "**mask off**" operation

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

and r1, r2, r3

r1 = r2 & r3; // in C

Example: force lower 8 bits to 0

DATA: r2 0xab ab ab 77

and

MASK: r3 0xff ff ff 00

unchanged

forces to a 0

RSLT: r1 0xab ab ab 00

Example: force lower 8 bits to 0

DATA: r2 0xab ab ab 77

and r1 r2, 0xffffffff00

r1 = r2 & 0xffffffff00; // in C

RSLT: r1 0xab ab ab 00

Extracting (Isolate) a Field of Bits with a mask

extract top 8 bits of r2 into r1

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

and r1, r2, r3

DATA: r2 0xab ab ab 77

and

MASK: r3 0xff 00 00 00

unchanged

RSLT: r1 0xab 00 00 00

forces to a 0

extract top 8 bits of r2 into r1

DATA: r2 0xab ab ab 77

and r1, r2, 0xff000000

RSLT: r1 0xab 00 00 00

r1 = r2 & 0xff000000; // in C

Finding if a bit is set

query the status of a bit "**bit status**" operation

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

```
and r1, r2, 0x02
```

```
cmp r1, 0
```

```
beq .Lendif
```

```
// code for is set
```

```
.Lendif:
```

```
unsigned int r1, r2;  
// code  
r1 = r2 & 0x02  
if (r1 != 0) {  
    // code for is set  
}
```

Example is bit 1 set

DATA: r2 0xab ab ab 77

and

MASK: 0x00 00 00 02 is bit 1 set?

forces to a 0 unchanged

RSLT: r1 0x00 00 00 02 != 0 if set

```
unsigned int r2;  
// code  
if ((r2 & 0x02) != 0) {  
    // code for is set  
}
```

Even/Odd

Even or odd, check LSB (same as mod %2)

check LSB (bit 0) if set then odd, else even

```
and r1, r2, 0x01
```

```
cmp r1, 0x01
```

```
bne .Lendif
```

```
// code for handling odd numbers
```

```
.Lendif:
```

```
unsigned int r2;
```

```
// code
```

```
if ((r2 & 0x01) != 0) {
```

```
    // code for handling odd numbers
```

```
}
```

DATA: r2 0xab ab ab 77

and

MASK: r3 0x00 00 00 01 (mod 2 even or odd)

forces to a 0 unchanged

RSLT: r1 0x00 00 00 01 (odd)

MOD %<power of 2>

remainder (mod): num \% d where $\text{num} \geq 0$ and $d = 2^k$
 $\text{mask} = 2^k - 1$ so for mod 16, $\text{mask} = 16 - 1 = 15$
 and r1, r2, r3

Example: %2

DATA: r2 0xab ab ab 77

and

MASK: r3 0x00 00 00 01 (mod 2 even or odd)

forces to a 0 unchanged

RSLT: r1 0x00 00 00 01 (odd)

Example: Mod 16

DATA: r2 0xab ab ab 77

and

MASK: r3 0x00 00 00 0f (mod 16)

forces to a 0 unchanged

RSLT: r1 0x00 00 00 07

Flipping bits: bit toggle Used in PA7/PA8

invert (*flip*) bits "bit toggle" operation

- 1 **will flip the bit**
- 0 to **let a bit through**

eor r1, r2, r3

- Observation: When applied twice, it returns the original value (symmetric encoding)
- With a mask of all 1's is a 1's compliment

Example: *flip* the lower 8-bits

eor r1, r2, 0xff

```
unsigned int r1, r2;
r1 = r2 ^ 0xff;
```

Example: invert (*flip*) the lower 8-bits

DATA: r2 0xab ab ab **77** **77: 0111 0111**

eor

MASK: r3 0x00 00 00 ff

unchanged

inverts (flips)

RSLT: r1 0xab ab ab **88** **88: 1000 1000**

DATA: r1 0xab ab ab **88**

eor

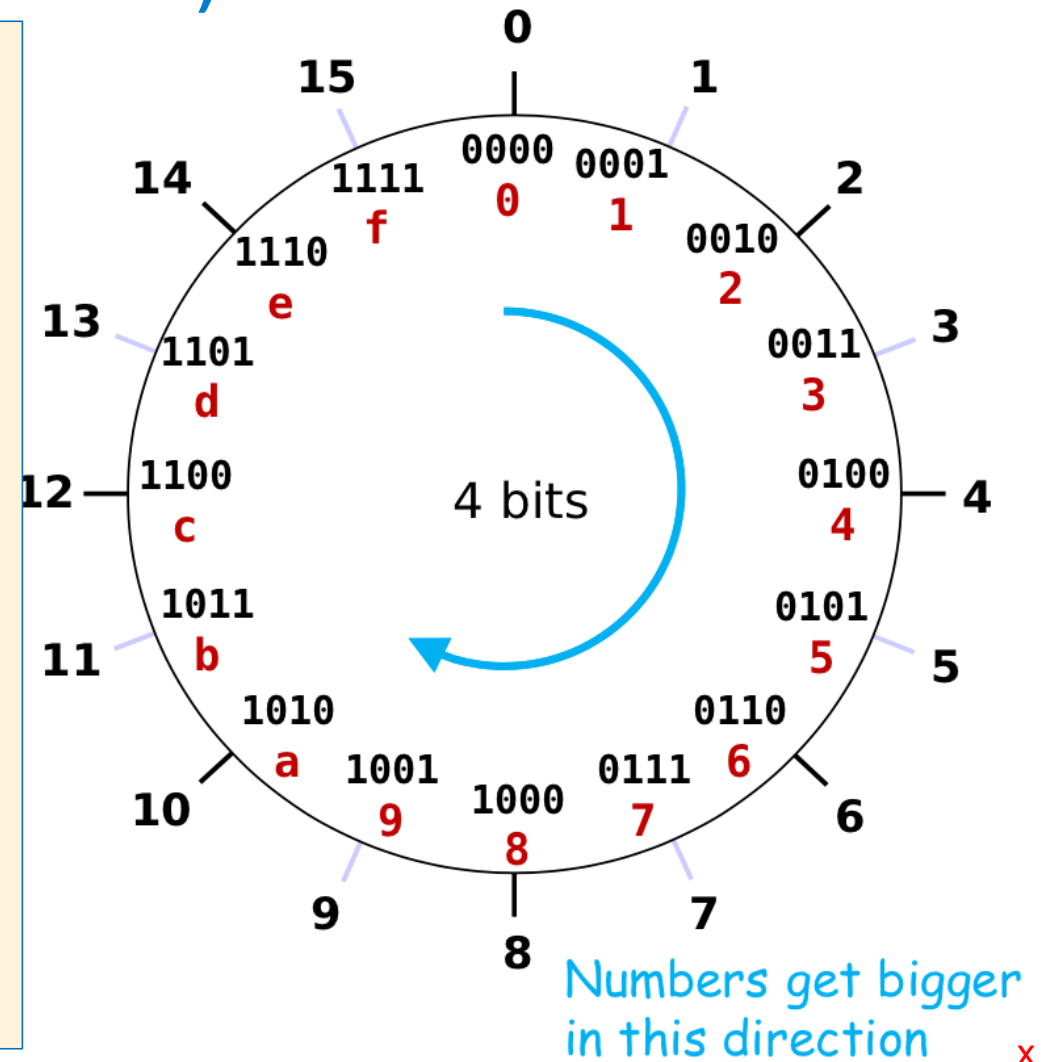
MASK: r3 0x00 00 00 ff **apply a 2nd time**

inverts (flips)

RSLT: r1 0xab ab ab **77 original value!**

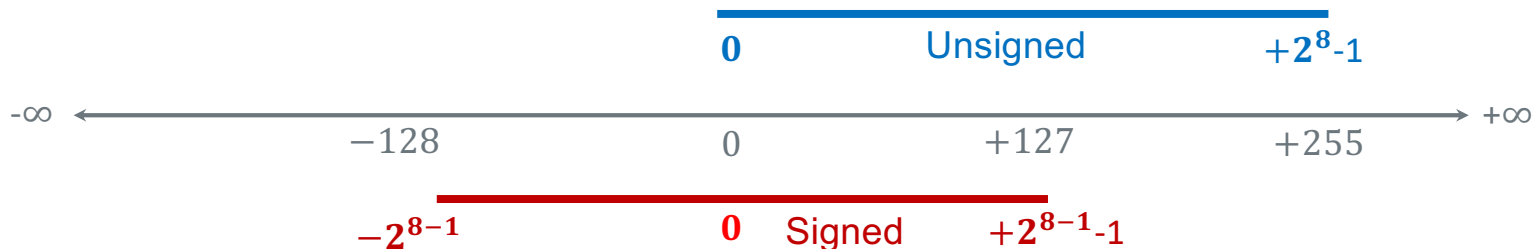
Unsigned Integers (positive numbers) with Fixed # of Bits

- 4 bits is $2^4 = \text{ONLY } 16$ distinct values
- **Modular** (C operator: `%`) or **clock math**
 - Numbers start at 0 and “wrap around” after 15 and go back to 0
- Keep **adding** 1
 - wraps (**clockwise**)
 - 0000 \rightarrow 0001 ... \rightarrow 1111 \rightarrow 0000
- Keep **subtracting** 1
 - wraps (**counter-clockwise**)
 - 1111 \rightarrow 1110 ... \rightarrow 0000 \rightarrow 1111
- Addition and subtraction use normal “**carry**” and “**borrow**” rules, just operate in binary



Problem: How to Encode Both Positive and Negative Integers

- How do we represent the negative numbers within a fixed number of bits?
 - Allocate some bit patterns to negative and others to positive numbers (and zero)
- 2^n distinct bit patterns to encode positive and negative values
- Unsigned values:** $0 \dots 2^n - 1$ ← -1 comes from counting 0 as a "positive" number
- Signed values:** $-2^{n-1} \dots 2^{n-1} - 1$ (dividing the range in ~ half including 0)
- On a number line (below):** 8-bit integers – signed and unsigned (e.g., `char` in C)

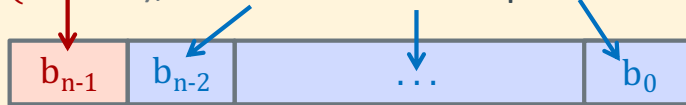


Same "width" (same number of encodings), just shifted in value

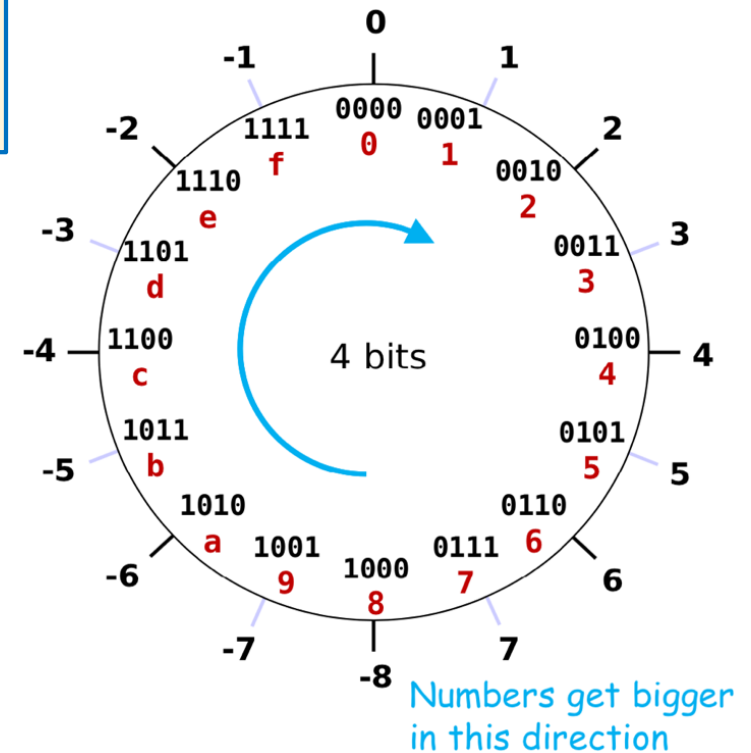
Two's Complement: The MSB Has a *Negative Weight*

$$2's\ Comp = -b_{n-1}2^{n-1} + b_{n-2}2^{n-2} + \dots + b_12^1 + b_02^0$$

b_{n-1} weight is (-2^{n-1}) , all other bits: have positive weights $(+2^i)$

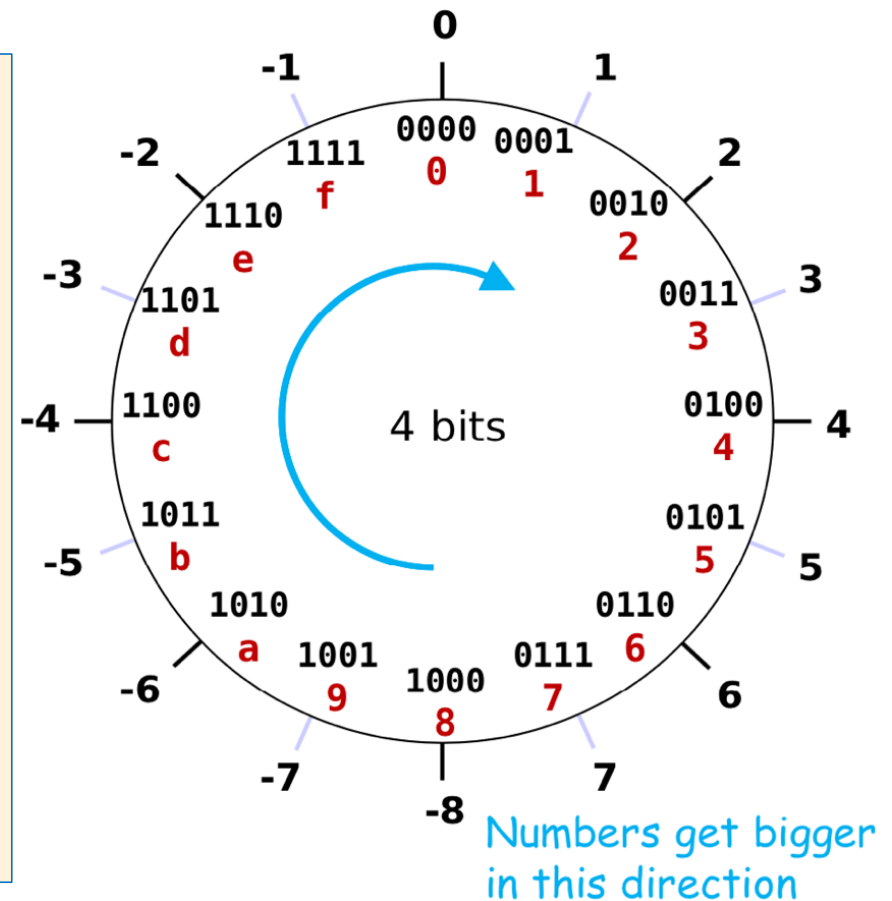


- 4-bit ($w = 4$) weight = $-2^{4-1} = -2^3 = -8$
 - 1010_2 **unsigned**:
 $1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = 10$
 - 1010_2 **two's complement**:
 $-1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = -8 + 2 = -6$
 - -8 in **two's complement**:
 $1000_2 = -2^3 + 0 = -8$
 - -1 in **two's complement**:
 $1111_2 = -2^3 + (2^3 - 1) = -8 + 7 = -1$



2's Complement Signed Integer Method

- Positive numbers encoded same as unsigned numbers
- All **negative values** have a **one in the leftmost bit**
- All **positive values** have a **zero in the leftmost bit**
 - This implies that 0 is a positive value
- **Only one zero**
- **For n bits, Number range is $-(2^{n-1})$ to $+(2^{n-1} - 1)$**
 - Negative values “go 1 further” than the positive values
- Example: the range for 8 bits:
-128, -127, .. 0, .. 126, +127
- Example the range for 32 bits:
-2147483648 .. 0, .. +2147483647
- *Arithmetic is the same as with unsigned binary!*



Sign Extension (how type promotion works)

- Sometimes you need to work with integers encoded with different number of bits

8 bits (char) -> (16 bits) short -> (32 bits) int

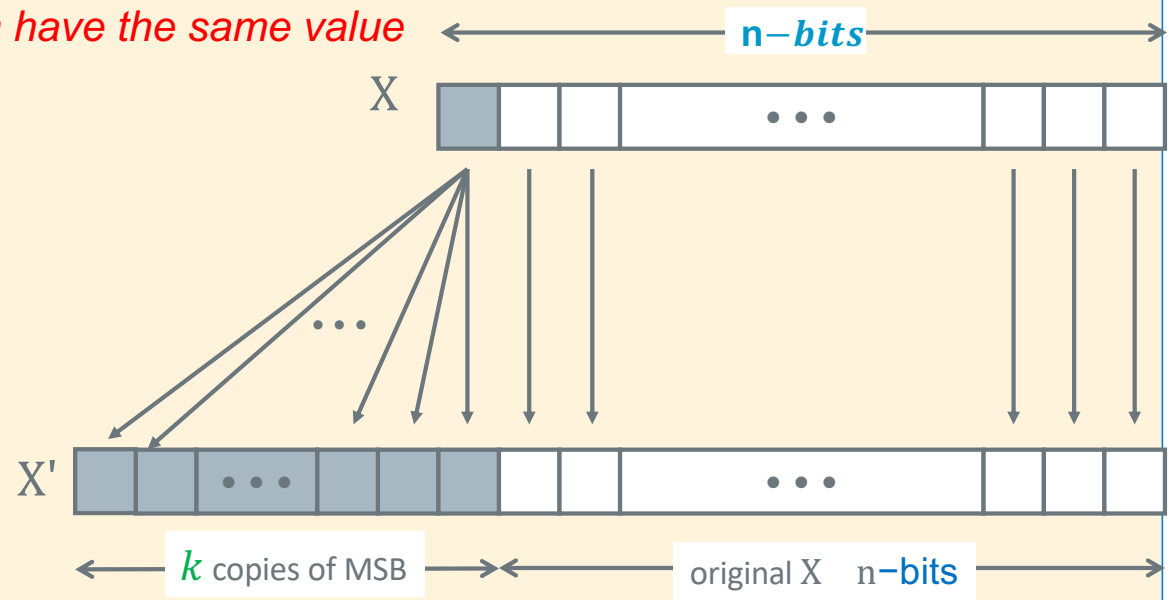
- Sign extension increases the number of bits:** n -bit wide signed integer X , **EXPANDS** to a **wider** n -bit + k -bit signed integer X' where **both have the same value**

Unsigned

- Just add leading zeroes to the left side

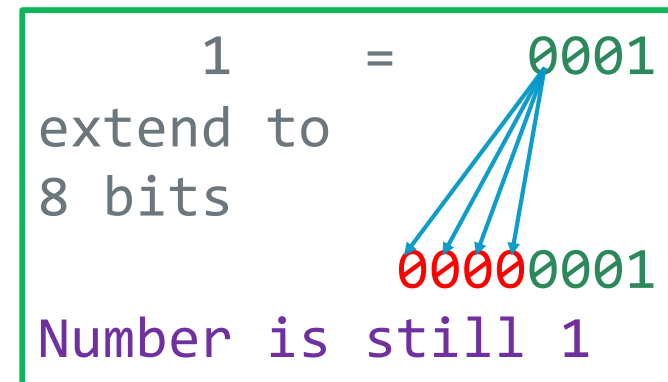
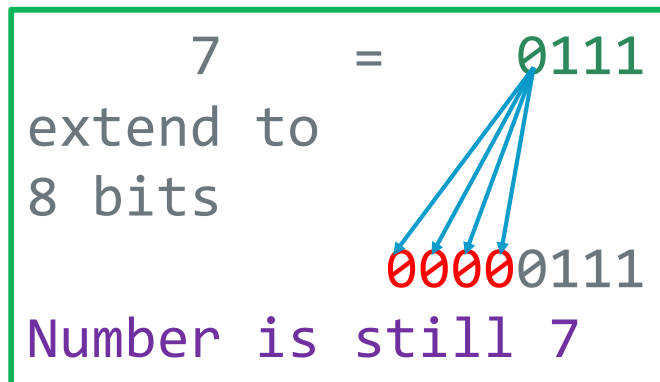
Two's Complement Signed:

- If **positive**, add leading **zeroes on the left**
 - Observe: Positive stay positive
- If **negative**, add **leading ones on the left**
 - Observe: Negative stays negative



Example: Two's Complement Sign or bit Extension - 1

- Adding 0's in front of a positive number does not change its value



Example: Two's Complement Sign or bit Extension -2

- Adding 1's if front of a negative number does not change its value

$$\begin{array}{rcl}
 7 & = & 0111 \\
 & & \downarrow \downarrow \downarrow \downarrow \\
 \text{invert} & = & 1000 \\
 \text{add } 1 & + & \quad 1 \\
 -7 & = & \underline{1001}
 \end{array}$$

$$\begin{array}{rcl}
 -7 & = & 1001 \\
 \text{extend to} & & \\
 \text{8 bits} & & \swarrow \swarrow \swarrow \swarrow \\
 & & 11111001
 \end{array}$$

$$\begin{aligned}
 1001 &= -8 + 1 = -7 \\
 11111001 &= \\
 (-128 + 64 + 32 + 16 + 8) + 1 &= \\
 = -8 + 1 &= -7
 \end{aligned}$$

$$\begin{array}{rcl}
 7 & = & 00000111 \\
 & & \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \\
 \text{invert} & = & 11111000 \\
 \text{add } 1 & + & \quad 1 \\
 -7 & = & \underline{11111001}
 \end{array}$$

Sign Extension in C: Type casts

- Convert from smaller to larger integral data types
- C and Java automatically performs sign extension
- Example (on pi-cluster with 32-bit int)

```
#include <stdlib.h>
#include <stdio.h>
int main(void)
{
    signed char c = -1;
    signed int i = c;
    unsigned char d = 1;
    unsigned int j = d;
    printf("c decimal = %hd\n", c);
    printf("c = 0x%hhx\n", c);
    printf("i decimal = %d\n", i);
    printf("i = 0x%x\n", i);
    printf("\nd decimal = %hd\n", d);
    printf("d = 0x%hhx\n", d);
    printf("j decimal = %d\n", j);
    printf("j = 0x%x\n", j);
    return EXIT_SUCCESS;
}
```

```
./a.out
c decimal = -1
c = 0xff
i decimal = -1
i = 0xffffffff

d decimal = 1
d = 0x1
j decimal = 1
j = 0x1
```


Different Type of Numbers each have a Fixed # of Bits

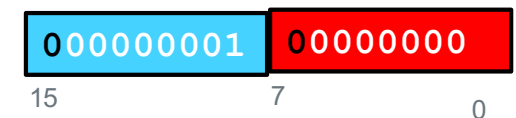
Spanning one or more contiguous bytes of memory

C Data Type	AArch-32 contiguous Bytes
char (arm unsigned)	1
short int	2
unsigned short int	2
int	4
unsigned int	4
long int	4
long long int	8
float	4
double	8
long double	8
pointer *	4

Byte 8-bit integer uses 1 byte



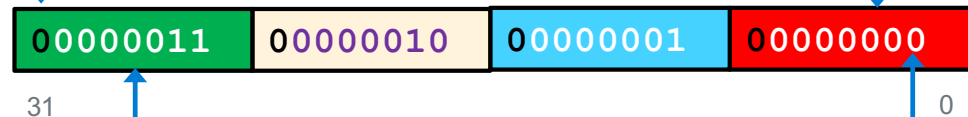
Half Word 16-bit integer uses 2 bytes



most significant bit (largest power of 2)

least significant byte

Word 32-bit integer uses 4 bytes

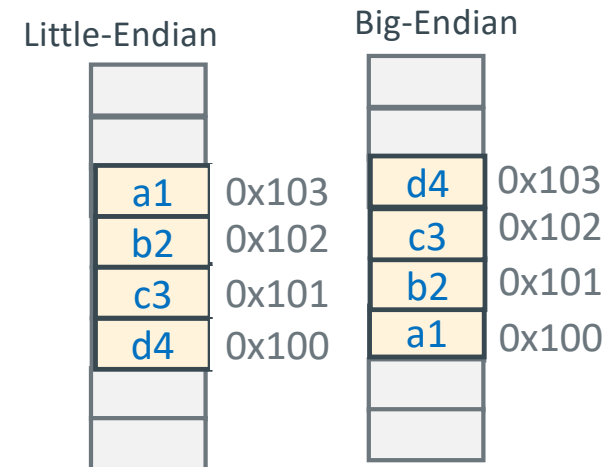
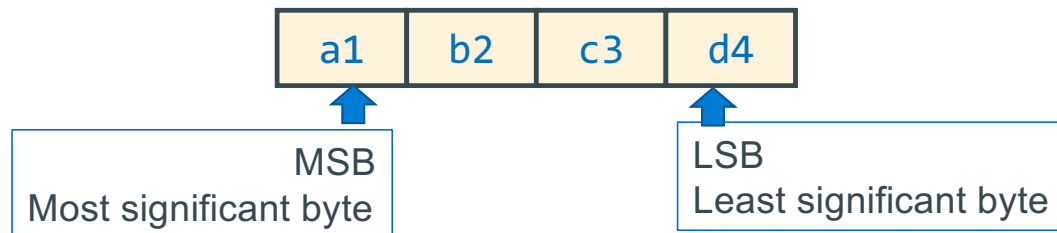


most significant byte

least significant bit (smallest power of 2)

Byte Ordering of Numbers In Memory: Endianness

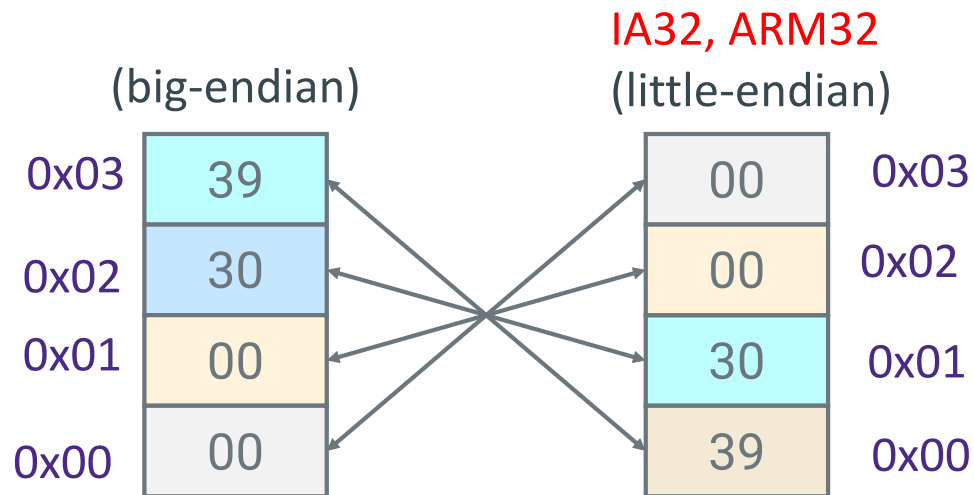
- Two different ways to place multi-byte integers in a **byte addressable** memory
- **Big-endian**: **Most** Significant Byte (“**big end**”) starts at the **lowest (starting)** address
- **Little-endian**: **Least** Significant Byte (“**little end**”) starts at the **lowest (starting)** address
- Example: 32-bit integer with 4-byte data



Byte Ordering Example

Decimal:	12345
Binary:	0011 0000 0011 1001
Hex:	3 0 3 9

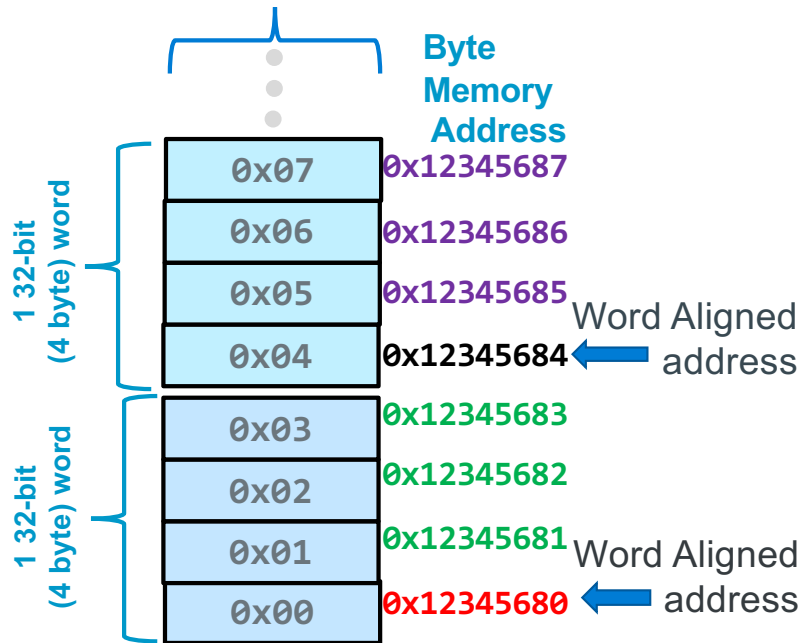
```
int x = 12345;  
// or x = 0x00003039; // show all 32 bits
```



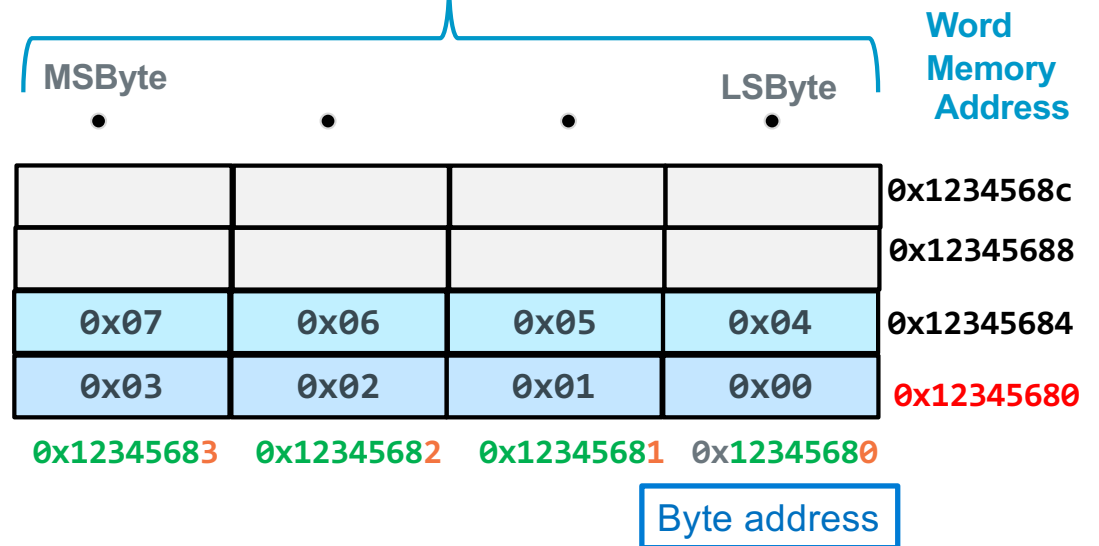
Byte Addressable Memory Shown as 32-bit words

1 byte Memory Content

One byte per row



Contents of Memory
One 32-bit (4 byte) word per row



Observation
32-bit aligned addresses
rightmost 2 bits of the address are always 0

Using pointers to examine byte order (on pi-cluster)

```
#include <stdio.h>
#define SZ 2
int main()
{
    unsigned int foo[SZ] = {0x11223344, 0xaabbccdd};
    unsigned int *iptr = foo;
    unsigned char *chptr = (unsigned char *)foo;

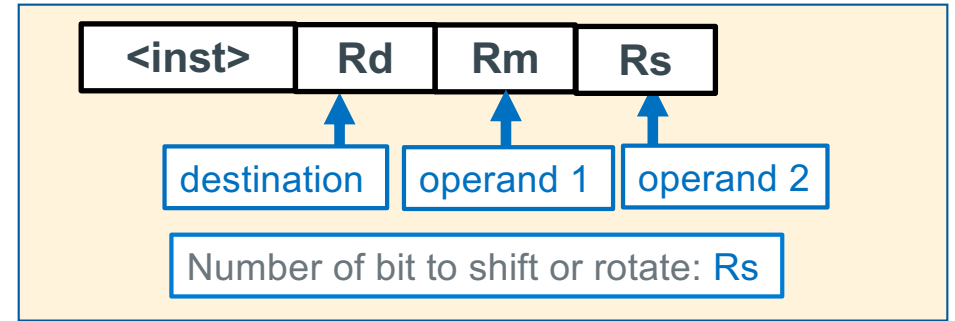
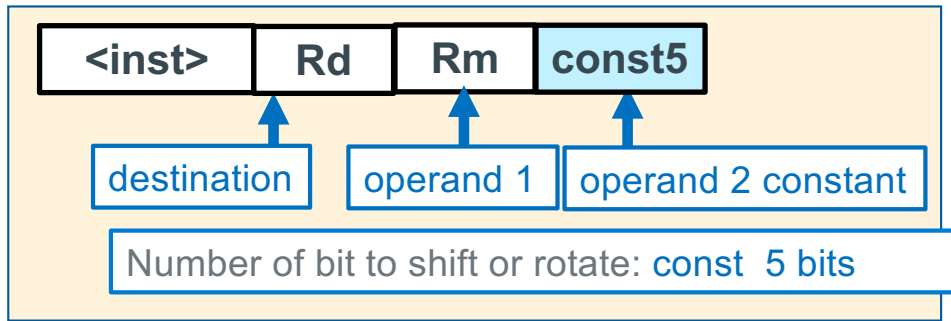
    for (int i = SZ-1; i >= 0; i--)
        printf("foo[%d]: %x\n", i, *(iptr + i));

    for (int i = sizeof(foo)-1; i >= 0; i--)
        printf("byte %d: %x\n", i, (unsigned int)*(chptr + i));
    return 0;
}
```

```
kmuller@keithm-pi4:~$ ./a.out
foo[1]: aabbccdd
foo[0]: 11223344
byte 7: aa
byte 6: bb
byte 5: cc
byte 4: dd
byte 3: 11
byte 2: 22
byte 1: 33
byte 0: 44
```

0xaa	0x12345687
0xbb	0x12345686
0xcc	0x12345685
0xdd	0x12345684
0x11	0x12345683
0x22	0x12345682
0x33	0x12345681
0x44	0x12345680

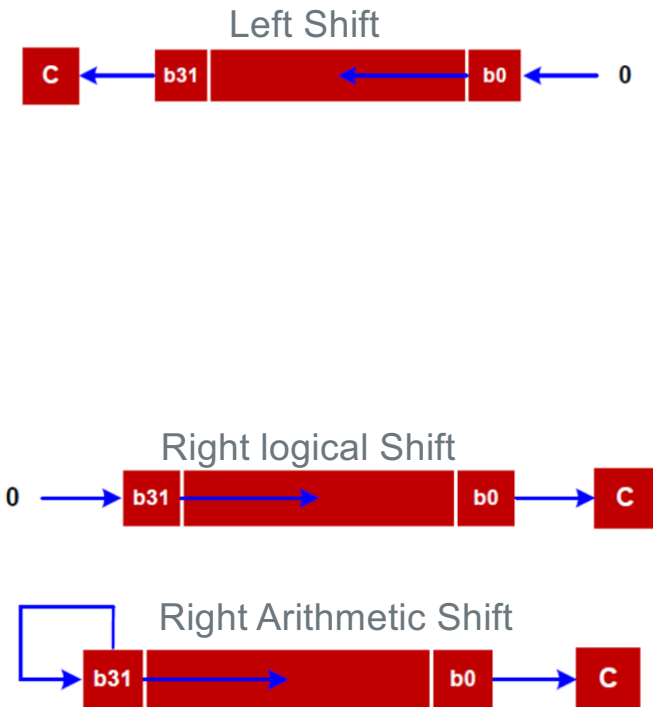
Shift and Rotate Instructions



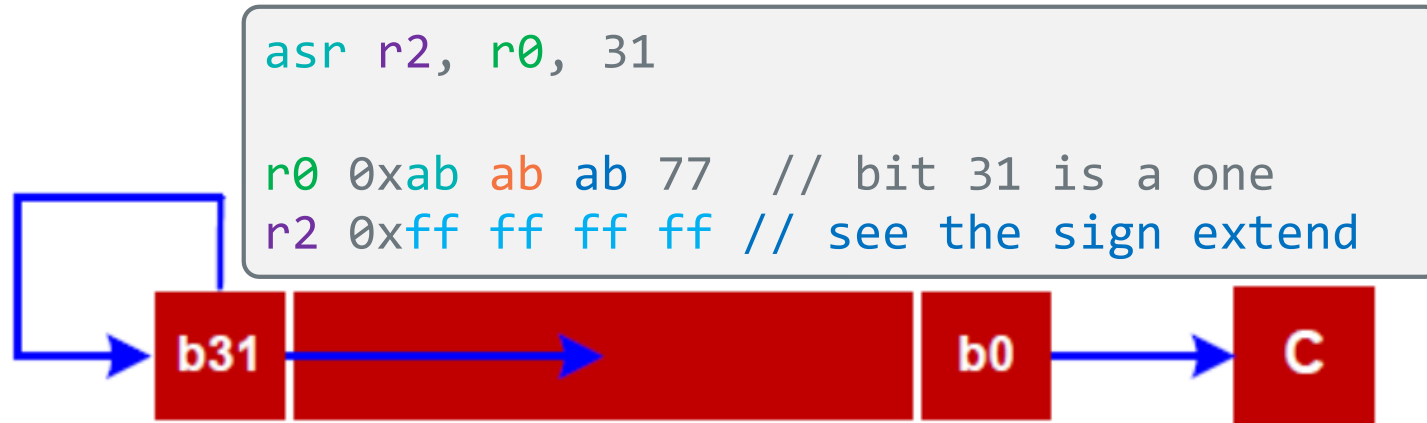
Instruction	Syntax	Operation	Notes	Diagram
Logical Shift Left <code>int x; or unsigned int x</code> <code>x << n;</code>	<code>lsl Rd, Rm, const5</code> <code>lsl Rd, Rm, Rs</code>	$R_d \leftarrow R_m \ll const5$ $R_d \leftarrow R_m \ll R_s$	Zero fills shift: 0 - 31	
Logical Shift Right <code>unsigned int x;</code> <code>x >> n;</code>	<code>lsr Rd, Rm, const5</code> <code>lsr Rd, Rm, Rs</code>	$R_d \leftarrow R_m \gg const5$ $R_d \leftarrow R_m \gg R_s$	Zero fills shift: 1 - 32	
Arithmetic Shift Right <code>int x;</code> <code>x >> n;</code>	<code>asr Rd, Rm, const5</code> <code>asr Rd, Rm, Rs</code>	$R_d \leftarrow R_m \gg const5$ $R_d \leftarrow R_m \gg R_s$	Sign extends shift: 1 - 32	
Rotate Right <code>unsigned int x;</code> <code>x = (x>>n) (x<<(32-n));</code>	<code>ror Rd, Rm, const5</code> <code>ror Rd, Rm, Rs</code>	$R_d \leftarrow R_m \text{ ror } const5$ $R_d \leftarrow R_m \text{ ror } R_s$	right rotate rot: 0 - 31	

Shift Operations in C

- n is number of bits to shift a variable x of width w bits
- Shifts by $n < 0$ or $n \geq w$ are *undefined*
- Left shift ($x \ll N$) – **Multiplies by 2^N**
 - Shift N bits left, Fill with 0s on right
- In C: behavior of \gg is determined by compiler
 - gcc: it depends on data type of x (signed/unsigned)
- Right shift ($x \gg N$) - **Divides by 2^N**
 - Logical shift (for unsigned variables)
 - Shift N bits right, Fill with 0s on left
 - Arithmetic shift (for signed variables) – Sign Extension
 - Shift N bits right while **Replicating** the most significant bit on left
 - Maintains sign of x
- In Java: logical shift is \ggg and arithmetic shift is \gg



Arithmetic Shift Right Example: Testing Sign

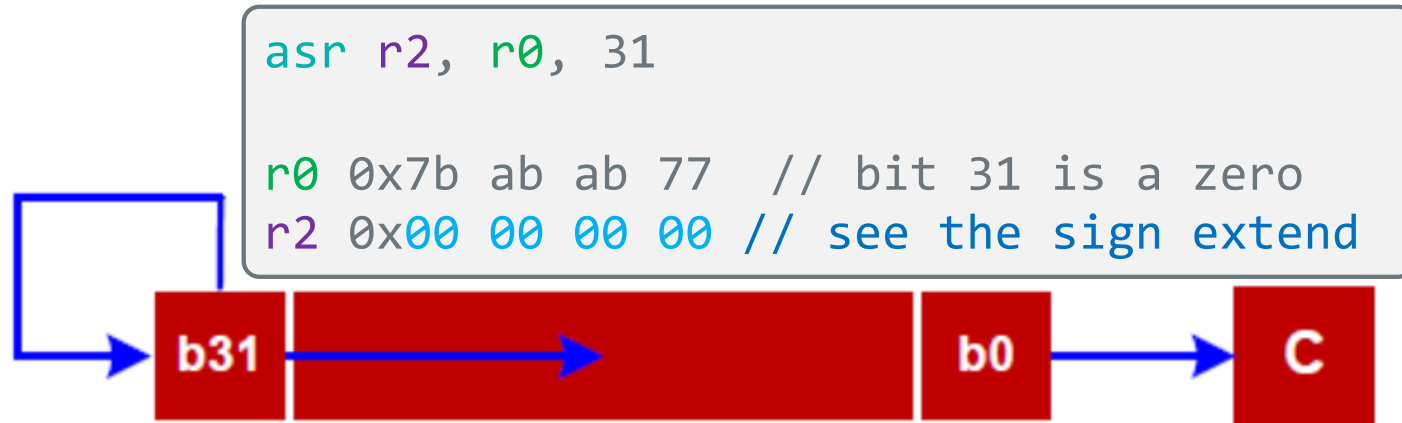


Test for sign
-1 if r0 negative

```
int i;  
//code  
if ((i>>31) == -1) {  
    // code neg #  
}
```

```
asr r2, r0, 31  
cmp r2, -1  
bne .Lendif  
//code neg #  
.Lendif:
```


Arithmetic Shift Right Example: Testing Sign



```
int i;  
//code  
if ((i>>31) == 0) {  
    // code pos #  
}
```

Test for sign
0 if r0 positive

```
asr r2, r0, 31  
cmp r2, 0  
bne .Lendif  
//code positive #  
.Lendif:
```

Logical Shift & Rotate Operations



```
lsr r2, r0, 8
```

```
r0 0xab ab ab 77
r2 0x00 ab ab ab
```



```
lsl r2, r0, 8
```

```
r0 0xab ab ab 77
r2 0xab ab 77 00
```



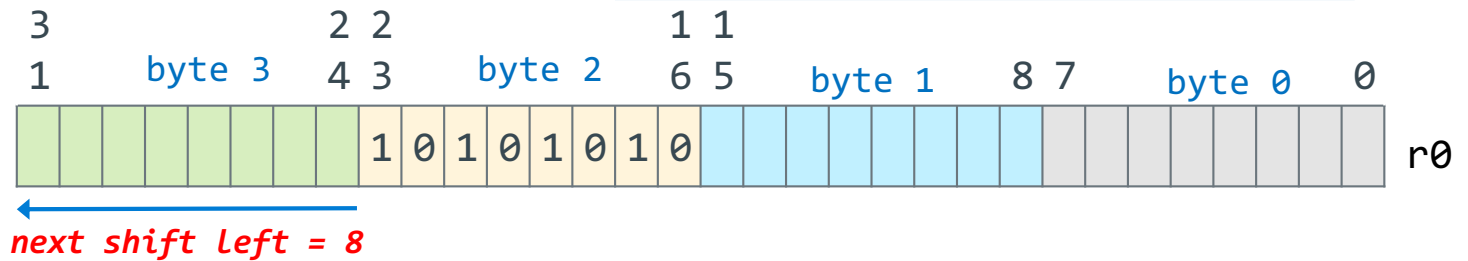
```
ror r2, r0, 8
```

```
r0 0xab ab ab 77
r2 0x77 ab ab ab
```

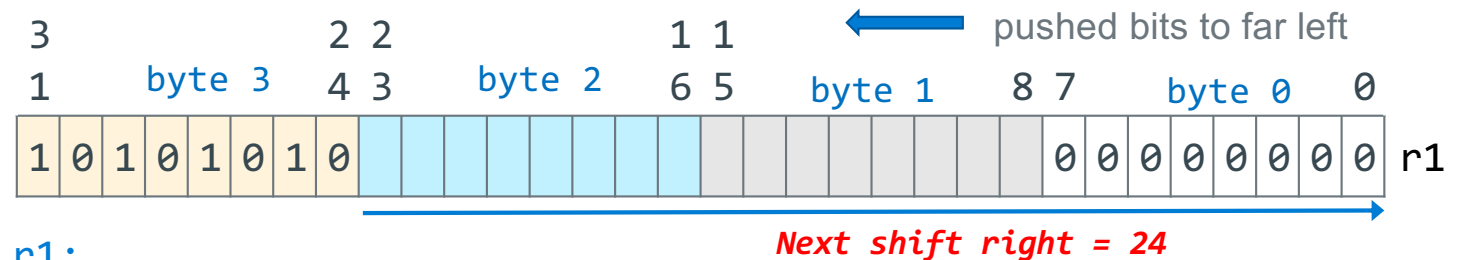
Extracting/Isolating Unsigned Bitfields

Hint: Useful for PA7

- Move byte 2 in r0 to byte 0 in r1



```
lsl r1, r0, 8
```

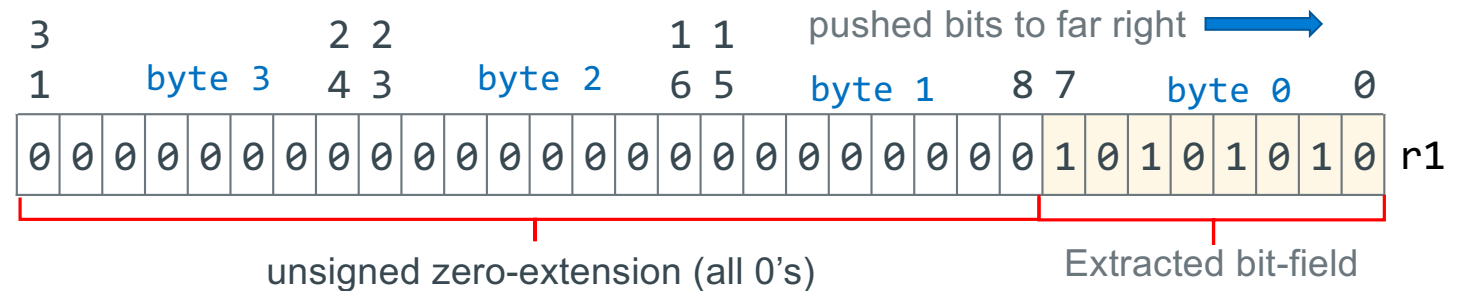


```
unsigned int r0,r1;
```

```
r1 = r0 << 8;
```

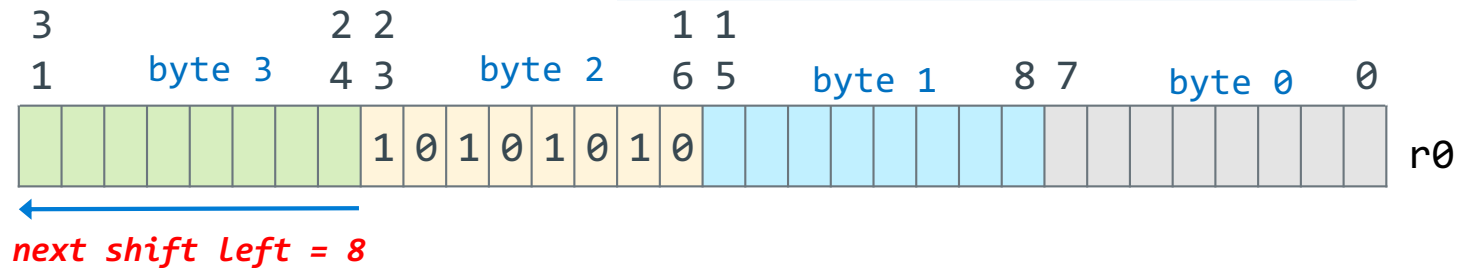
```
lsl r1, r1, 24
```

```
r1 = r1 >> 24;
```

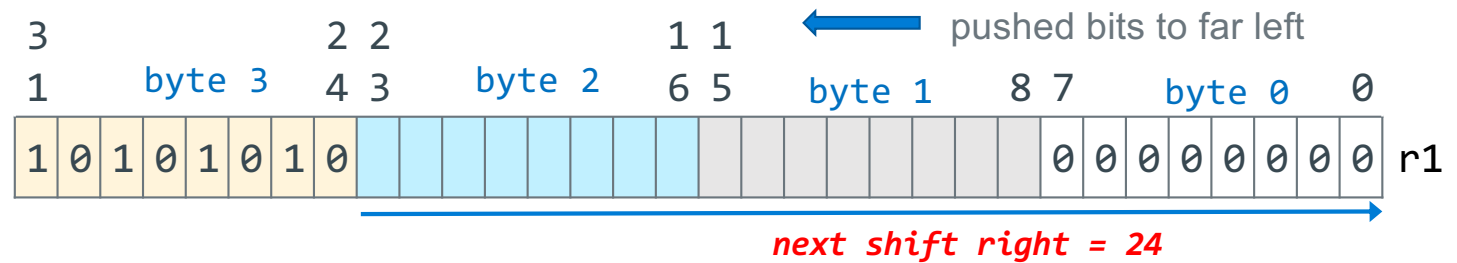


Extracting Signed Bitfields

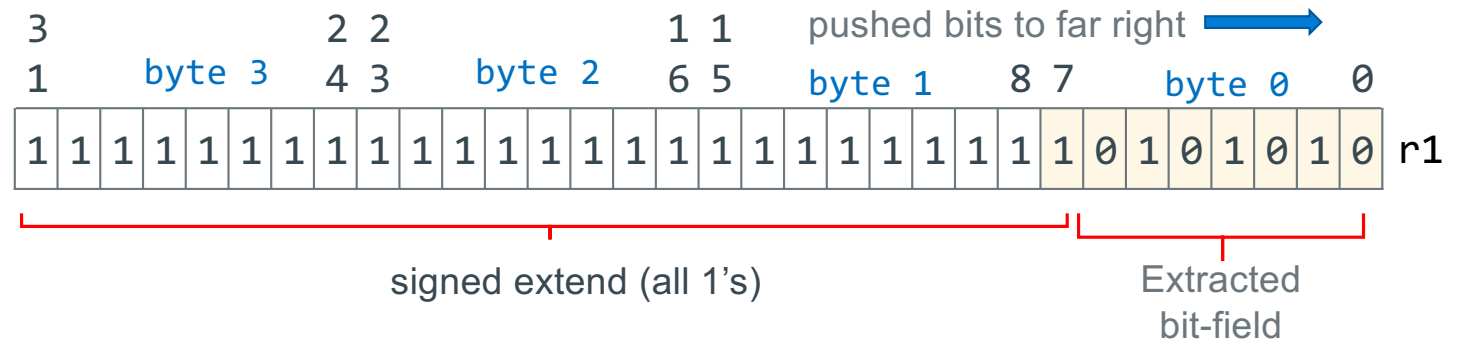
- Move byte 2 in r0 to byte 0 in r1



```
lsl r1, r0, 8
int r0,r1;
r1 = r0 << 8;
```



```
asr r1, r1, 24
r1 = r1 >> 24;
```



Inserting Bitfields – Inserting Source Field into Destination Field

Task: Insert source into destination

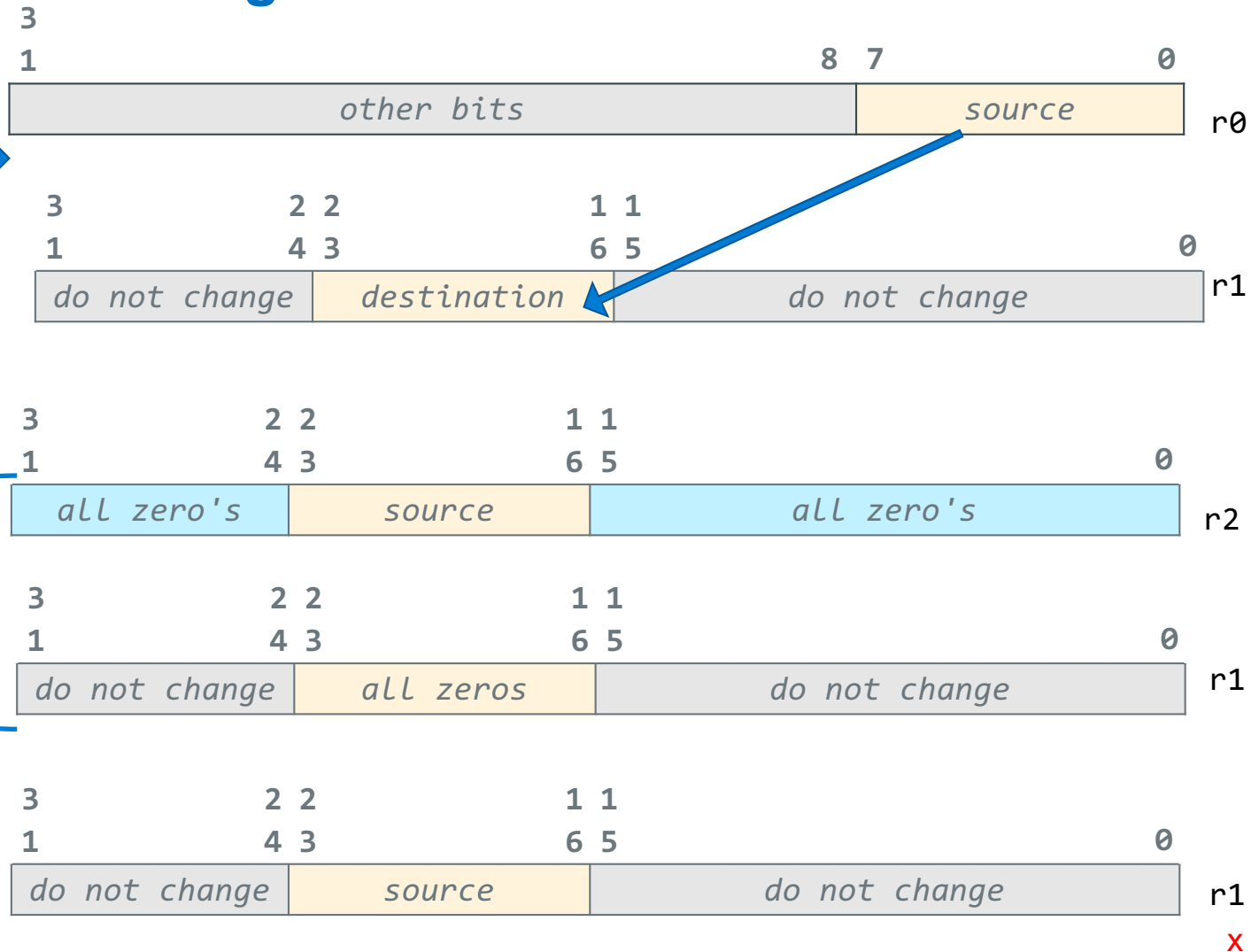
a	b	a b
0	0	0
0	1	1
1	0	1
1	1	1

Approach

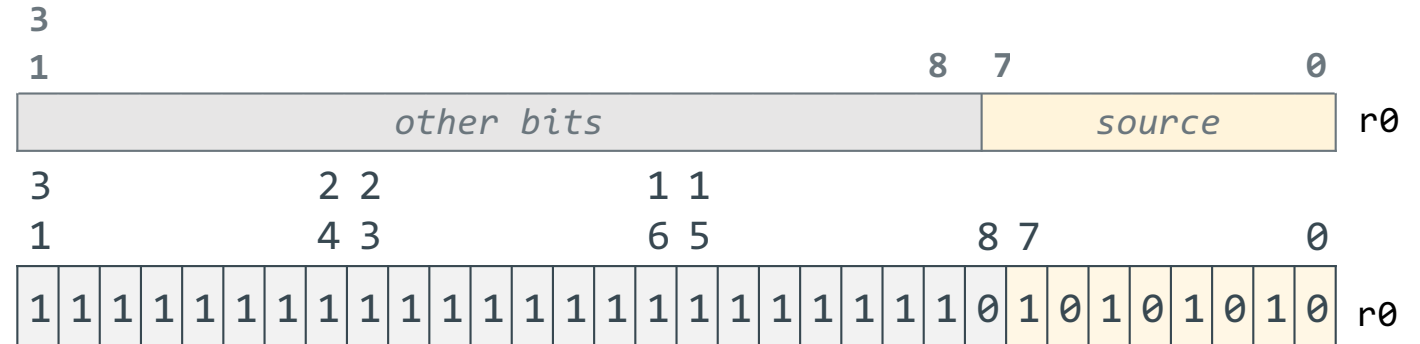
- (1) isolate source field
- (2) clear destination field
- (3) Bitwise **or** together

```
orr    r1, r1, r2
r1 =   r1 | r2;
```

results in



Inserting Bitfields – Isolating the Source Field



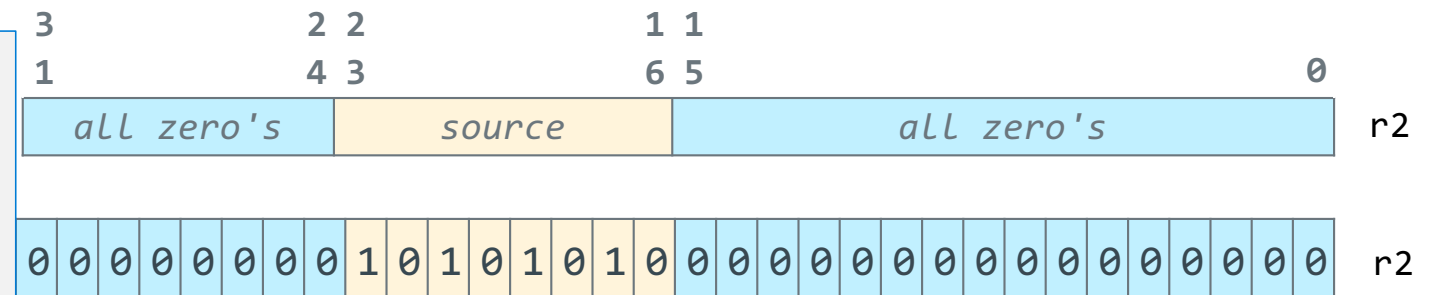
isolate source field

```
lsl    r2, r0, 24
```

```
lsr    r2, r2, 8
```

```
r2 = r0 << 24;
```

```
r2 = r2 >> 8;
```

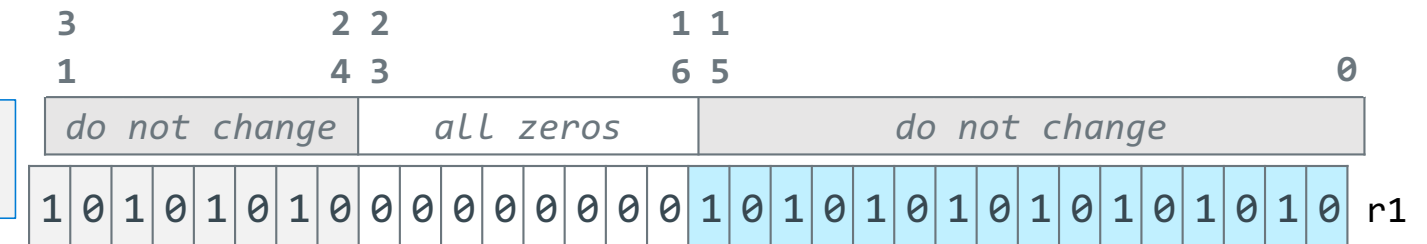
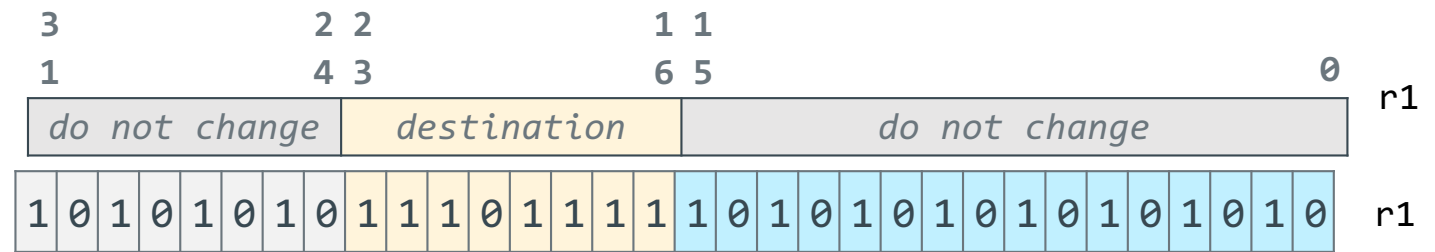


Inserting Bitfields – Clearing the Destination Field

```
clear the
destination field
ror    r1, r1, 24
r1=(r1>>24)|(r1<<8);
```

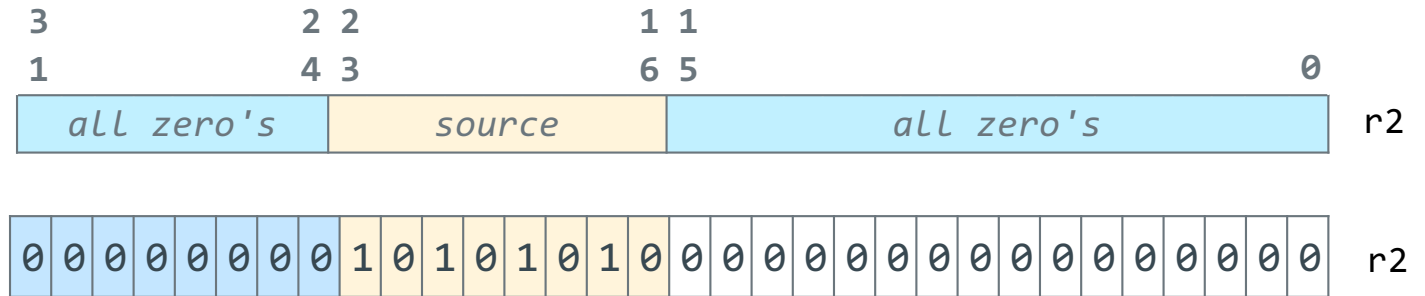
```
lsl    r1, r1, 8
r1 = r1 << 8;
```

```
ror    r1, r1, 16
r1= (r1>>16)|(r1<<16);
```

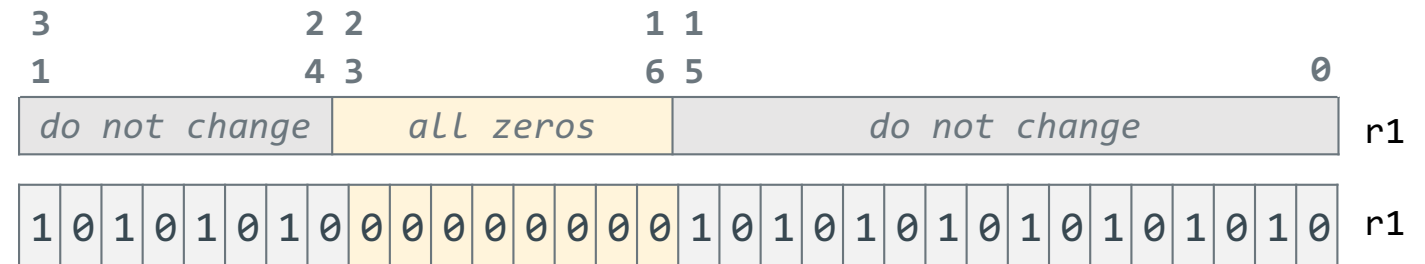


Inserting Bitfields – Combining Isolated Source and Cleared Destination

isolated source



field cleared in
destination



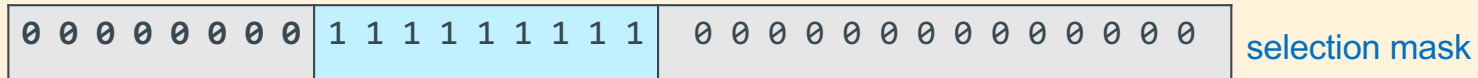
inserted field
orr r1, r1, r0
r1 = r1 | r0;



Masking Summary

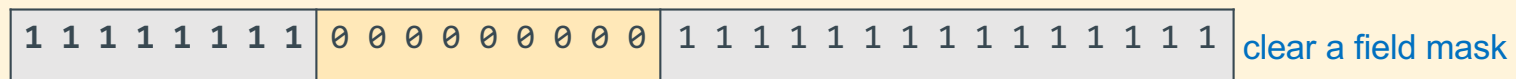
Select a field: Use **and** with a **mask** of one's surrounded by zero's to select the bits that have a 1 in the mask, all other bits will be set to zero

selects this field when used with and



Clear a field: Use **and** with a mask of zero's surrounded by one's to select the bits that have a 1 in the mask, all other bits will be set to zero

clears this field when used with and



Isolate a field: Use **lsl**, **lsl**, **rot** to get a field surrounded by zeros



lsl to get this edge into msb

lsl to get this edge into lsb

Insert a field: Use **orr** with fields surrounded by zeros

