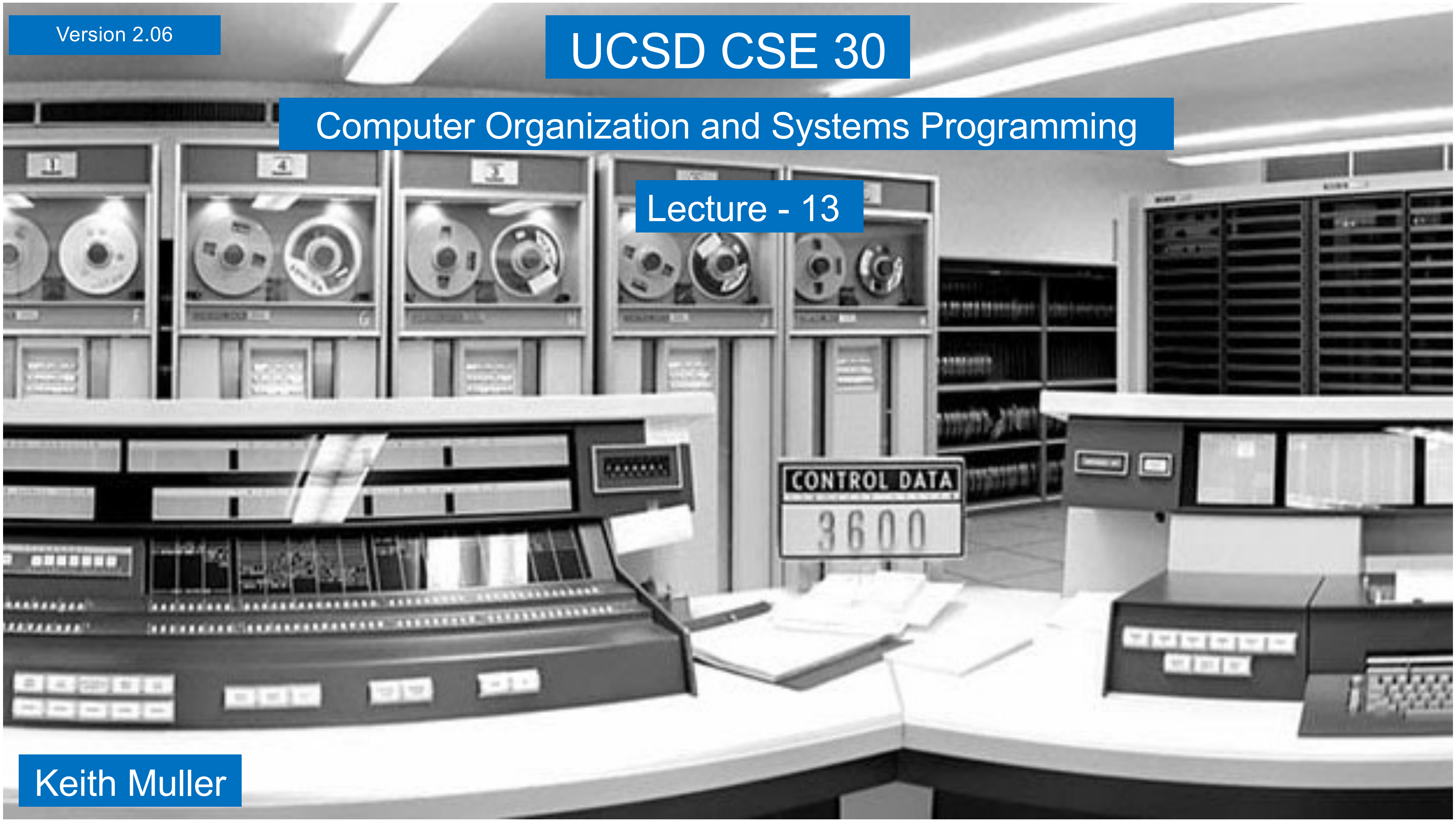
Version 2.06

UCSD CSE 30

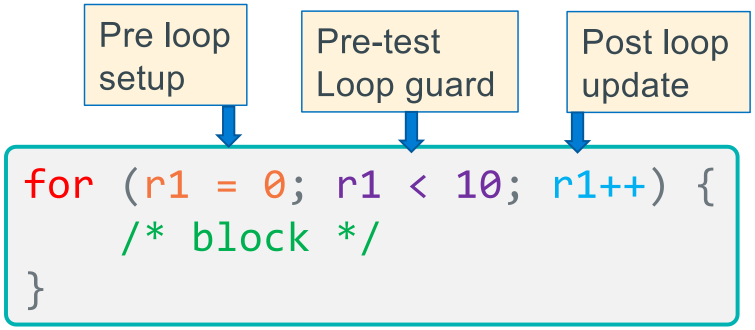
Computer Organization and Systems Programming

Lecture - 13



Keith Muller

Program Flow – Counting (For) Loop Version 1



Pre loop setup

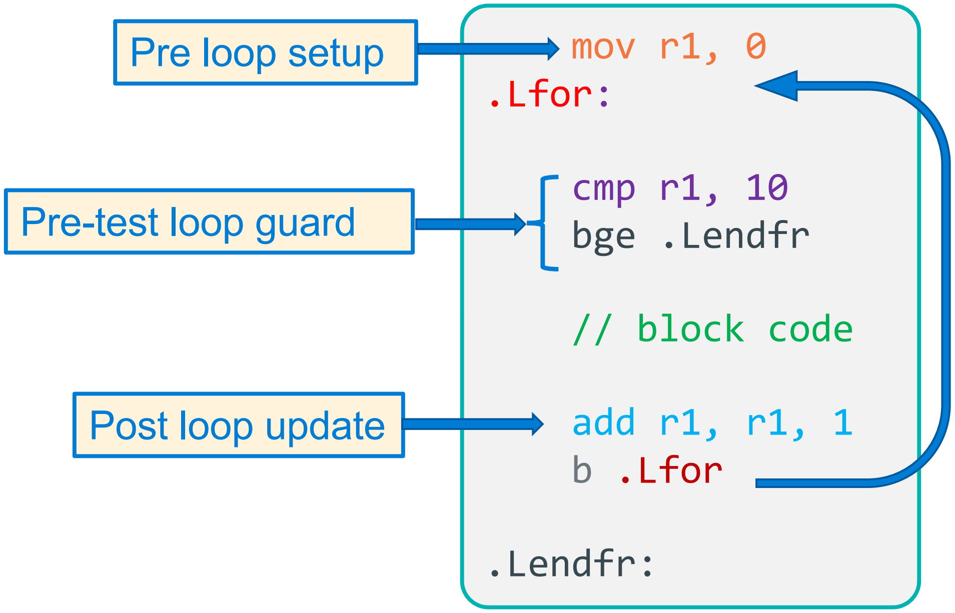
Pre-test Loop guard

Post loop update

```
for (r1 = 0; r1 < 10; r1++) {
    /* block */
}
```

A **counting loop** has three parts:

1. Pre-loop setup
2. Pre-test loop guard conditions
3. Post-loop update



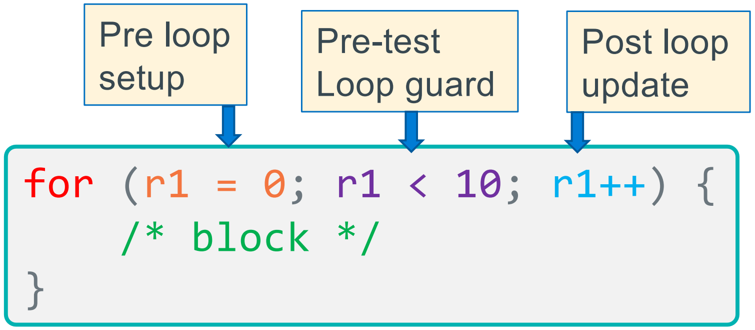
Pre loop setup

Pre-test loop guard

Post loop update

```
  mov r1, 0
.Lfor:

  cmp r1, 10
  bge .Lendfr

  // block code

  add r1, r1, 1
  b .Lfor

.Lendfr:
```

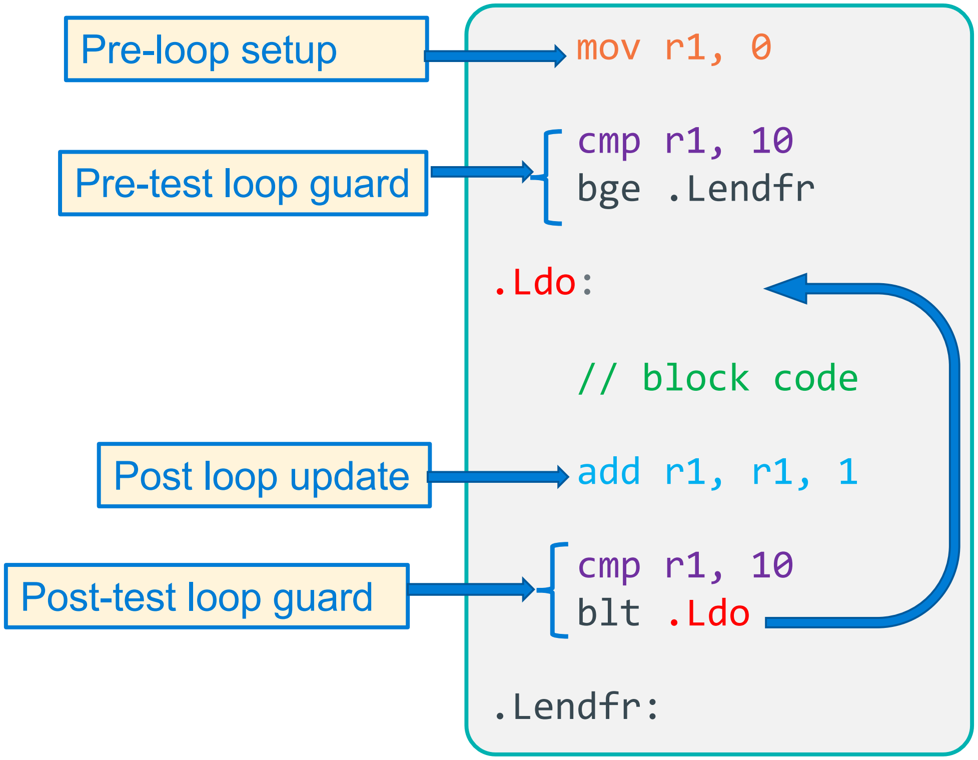
Program Flow – Counting (For) Loop – Version 2


Pre loop setup

Pre-test Loop guard

Post loop update

```
for (r1 = 0; r1 < 10; r1++) {
    /* block */
}
```


Pre-loop setup

Pre-test loop guard

Post loop update

Post-test loop guard

```
    mov r1, 0

    cmp r1, 10
    bge .Lendfr

.Ldo:

    // block code

    add r1, r1, 1

    cmp r1, 10
    blt .Ldo

.Lendfr:
```

- Alternative:
- move Pre-test loop guard before the loop
- Add post-test loop guard
    - *converts* to *do while*
    - **removes** an **unconditional branch**

Nested loops

```
for (r3 = 0; r3 < 10; r3++) {
    r0 = 0;

    do {
        r0 = r0 + r1++;
    } while (r1 < 10);

    // fall through
    r2 = r2 + r1;
}
r5 = r0;
```

- Nest loop blocks as you would in C or Java

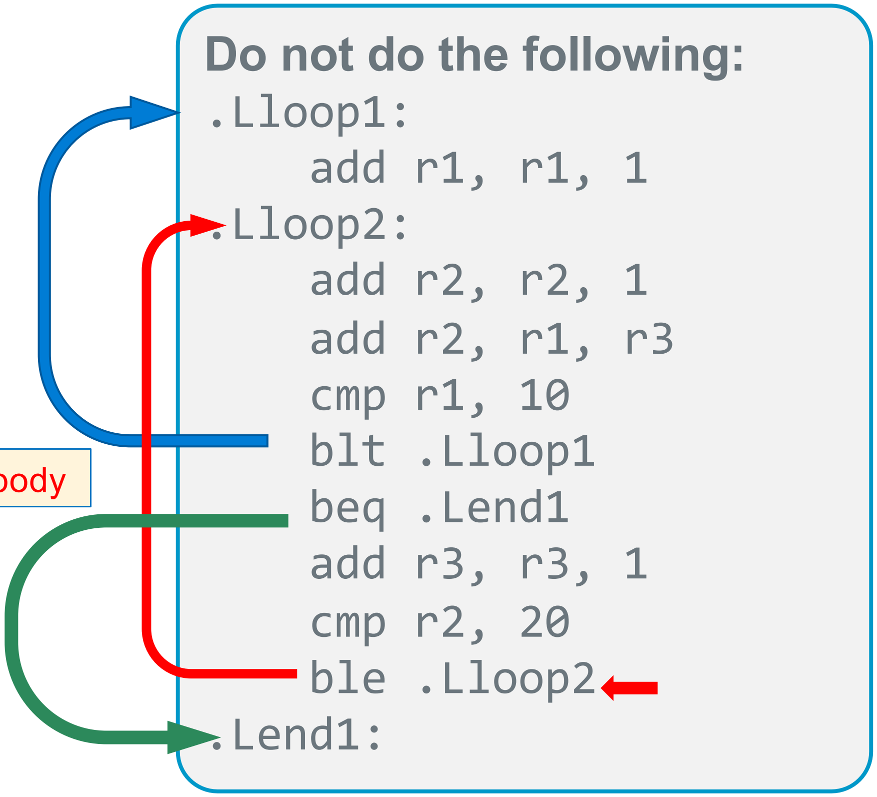
```
    mov r3, 0
.Lfor:
    cmp r3, 10      // loop guard
    bge .Lendfor

    mov r0, 0

.Ldo:
    add r0, r0, r1
    add r1, r1, 1

    cmp r1, 10   // loop guard
    blt .Ldo

    // fall through
    add r2, r2, r1

    add r3, r3, 1 // loop iteration
    b .Lfor
.Lendfor:
    mov r5, r0
```

x

Keep loops Properly Nested:
Do not branch into the middle of a loop

- It is hard to understand and debug loops when you branch into the middle of a loop
- **Keep loops proper nested**

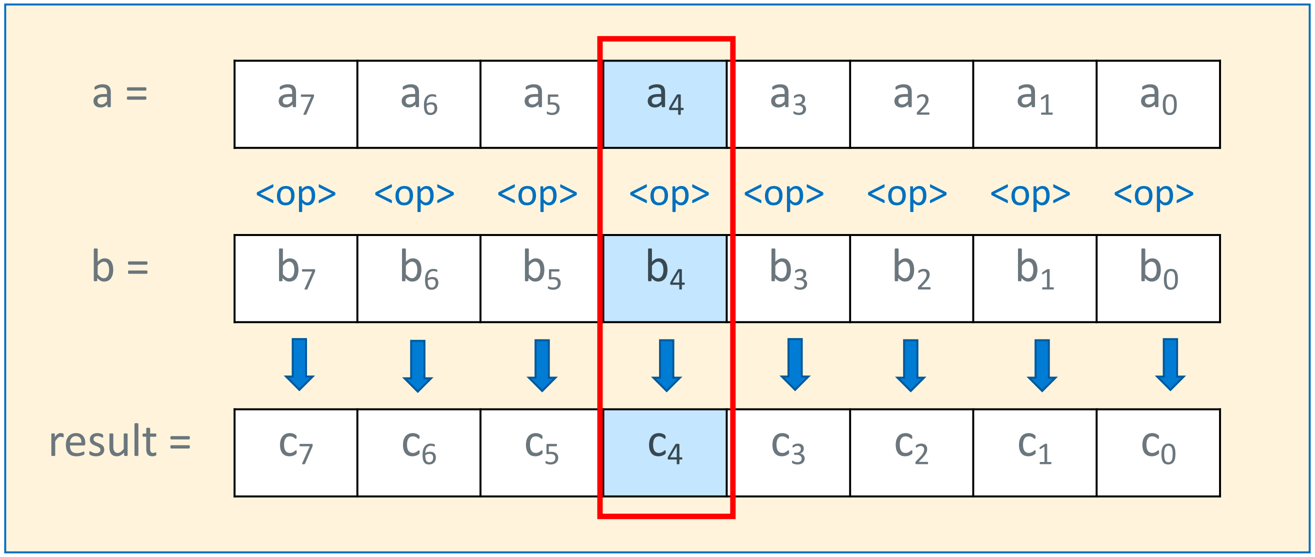
Bad practice: branch into loop body



Do not do the following:

```
.Lloop1:
    add r1, r1, 1
.Lloop2:
    add r2, r2, 1
    add r2, r1, r3
    cmp r1, 10
    blt .Lloop1
    beq .Lend1
    add r3, r3, 1
    cmp r2, 20
    ble .Lloop2
.Lend1:
```

What is a Bitwise Operation?



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

- 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 = ~a;
```

a	~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

```

~ 1100
  ----
  0011
```

Bitwise
AND

```
  0110
& 1100
  ----
  0100
```

Bitwise
OR

```
  0110
| 1100
  ----
  1110
```

Bitwise
EOR

```
  0110
^ 1100
  ----
  1010
```

x

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

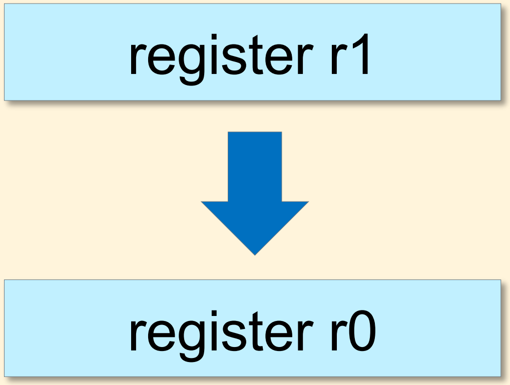
Meaning	*Operator*	*Operator*	*Meaning*
Boolean NOT	!b	~b	Bitwise NOT

Boolean operators act on the entire value not the individual bits

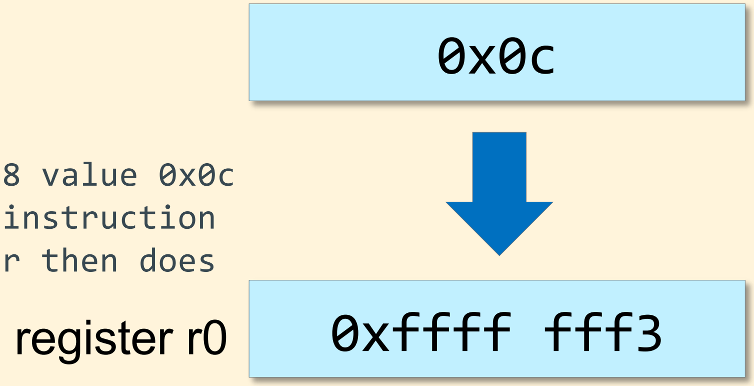
Type	*Operation*	result
bitwise	~0x01	1111 1111 1111 1111 1111 1111 1111 1110
Boolean	!0x01	0000 0000 0000 0000 0000 0000 0000 0000

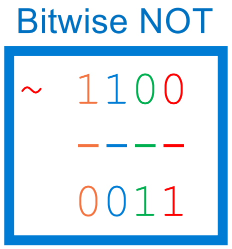
MVN (not)

```
mvn   r0, r1


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

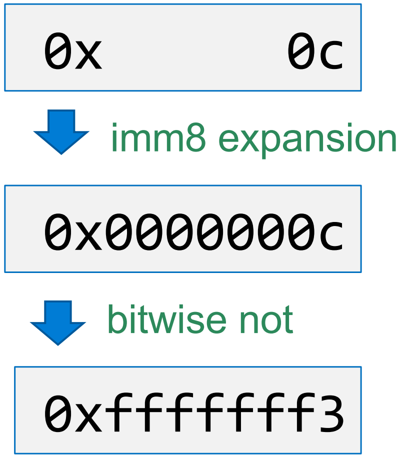


```
mvn   r0, 12


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



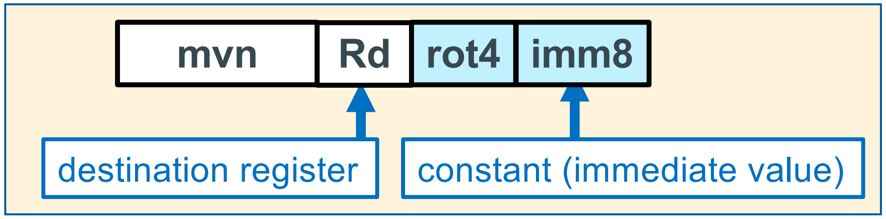


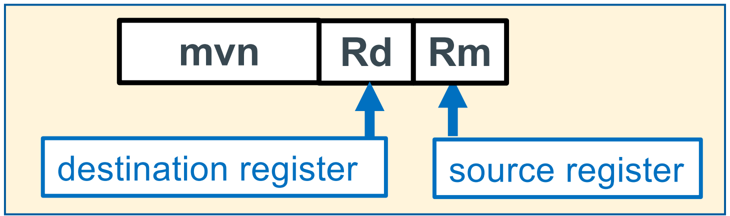
- A **bitwise NOT** operation



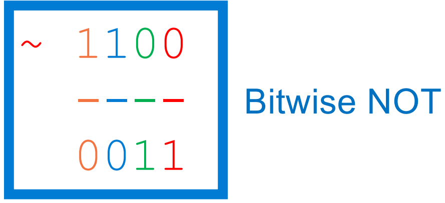
x

mvn – Copies NOT (~)





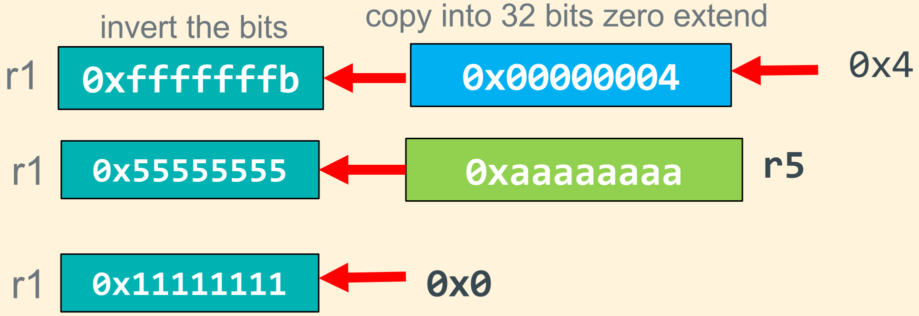
```
mvn   Rd, constant    // Rd = constant
mvn   Rd,  Rm         // Rd = Rm
```



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

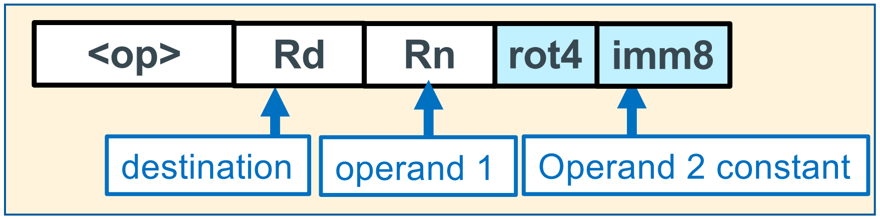
imm8	extended imm8	inverted imm8	signed base 10
0x00	0x00 00 00 00	0xff ff ff ff	-1
0xff	0x00 00 00 ff	0xff ff ff 00	-256

```
mvn    r1, 4          // x = ~4
mvn    r1, r5         // x = ~y in C


mvn    r1, 0          // x = -1
```



x

Bitwise Instructions

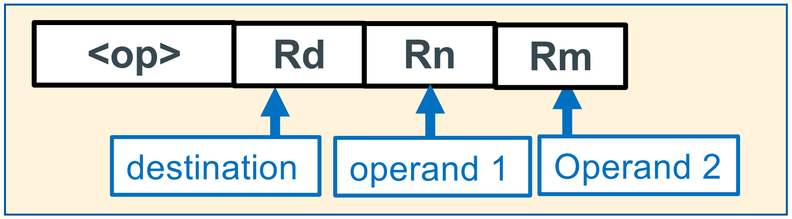


<op> Rd Rn rot4 imm8

destination

operand 1

Operand 2 constant



<op> Rd Rn Rm

destination

operand 1

Operand 2

```
<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 <= imm8 <= 255 + values from "rotating" rot 4 bits

Bitwise <op> description	C Syntax	*Arm <op> Syntax* *Op2: either register or constant value*	*Operation*
Bitwise **AND**	a & b	and R_d, R_n, Op2	R_d = R_n & Op2
Bitwise **OR**	a | b	orr R_d, R_n, Op2	R_d = R_n | Op2
Exclusive **OR**	a ^ b	eor R_d, R_n, Op2	R_d = R_n ^ Op2
Bitwise **NOT**	a = ~b	mvn R_d, R_n	R_d = ~R_n

x

Bitwise versus C Boolean Operators

Boolean Operators			Bitwise Operators	
Meaning	*Operator*		*Operator*	*Meaning*
Boolean AND	a && b		a & b	Bitwise AND
Boolean OR	a || b		a | b	Bitwise OR
Boolean NOT	!b		~b	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 = 0xfffffffe (bitwise)
!0x01 = 0x0 (Booelan)
```

x

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)`

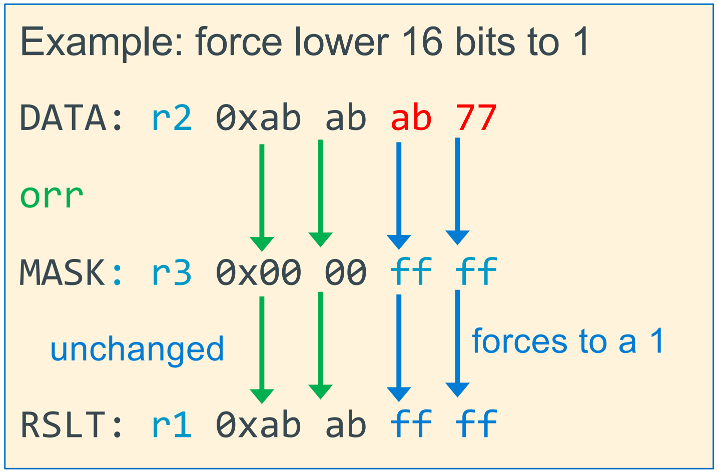
x

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

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 ab ff
```

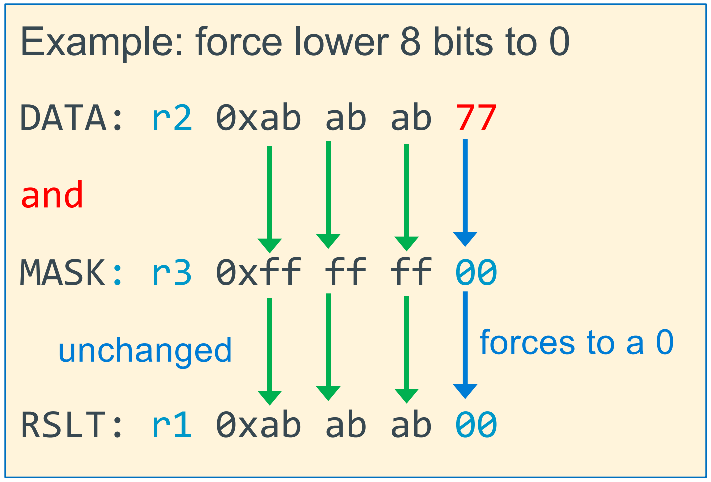
x

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, 0xffffff00

r1 = r2 & 0xffffff00; // in C

RSLT: r1 0xab ab ab 00
```

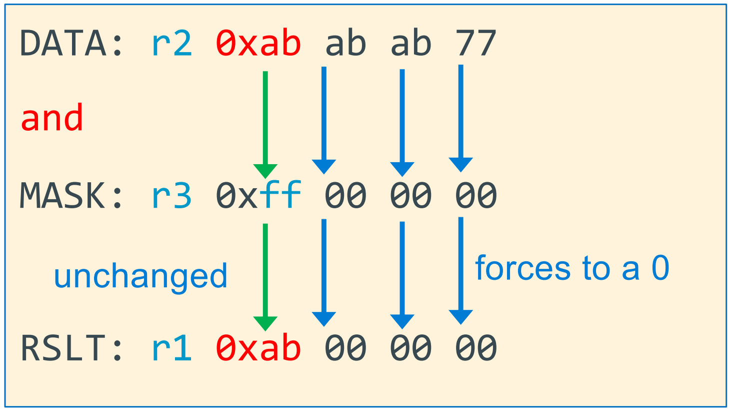
x

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
RSLT: r1 0xab 00 00 00
```

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
```

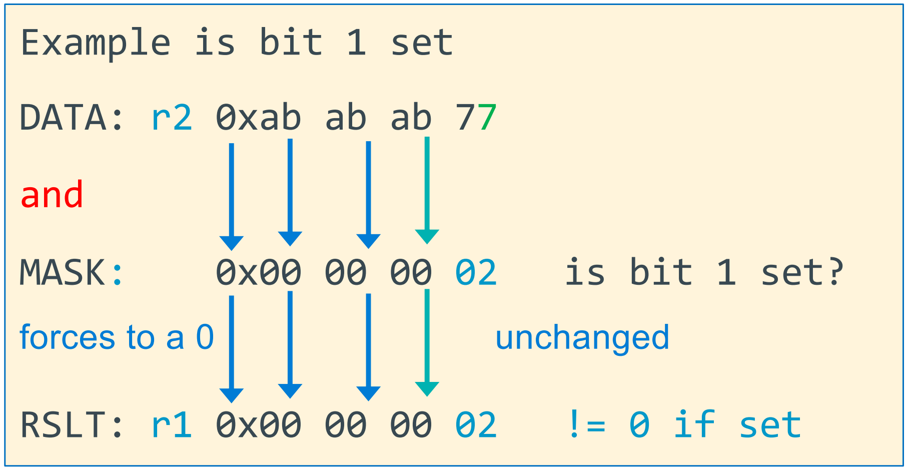
x

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:
```



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

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

x

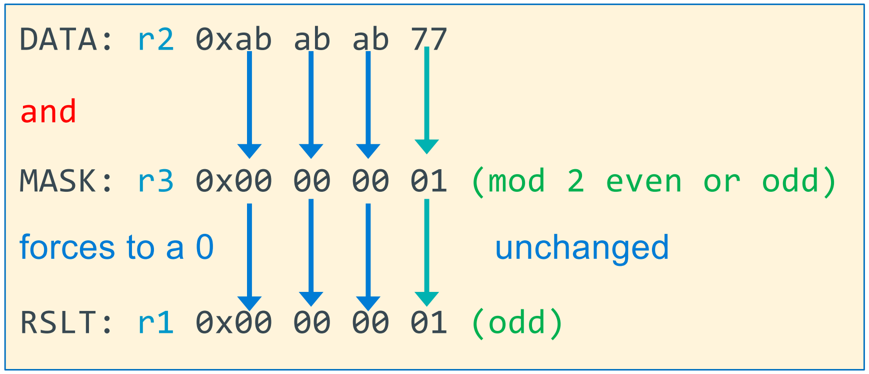
Even/Odd

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
    }
```



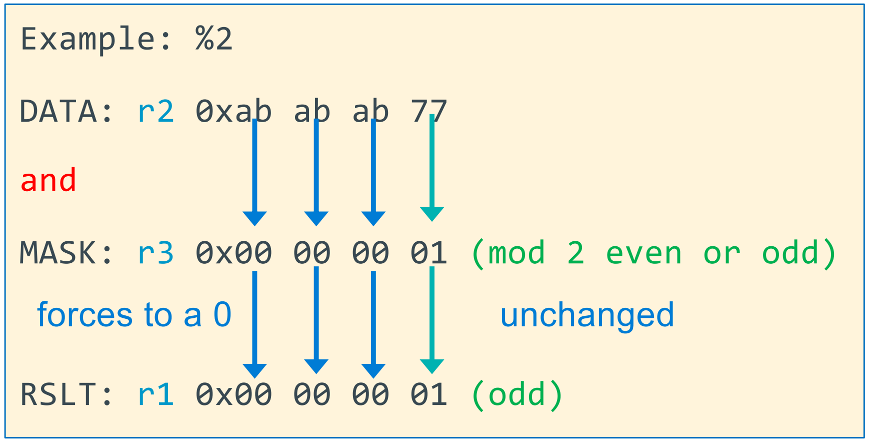
```
DATA: r2 0xab ab ab 77

and

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

forces to a 0              unchanged

RSLT: r1 0x00 00 00 01 (odd)
```

x

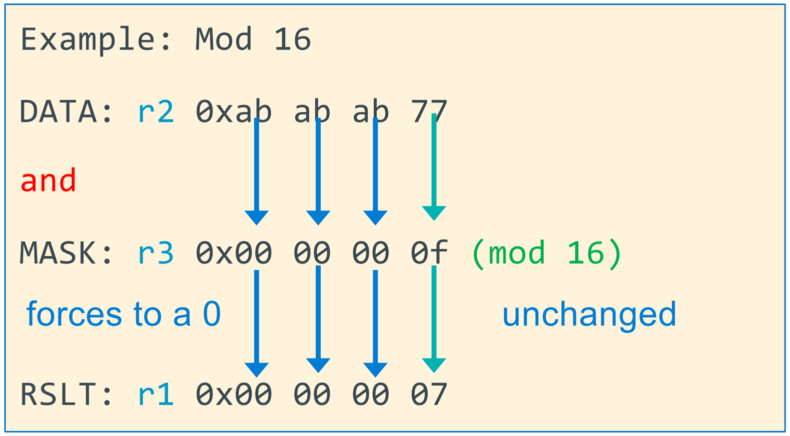
MOD %<power of 2>

remainder (mod): num % d where num ≥ 0 and d = 2^k

```
mask = 2^k -1 so for mod 16, 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
```

x

Flipping bits: bit toggle
Used in PA7/PA8

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

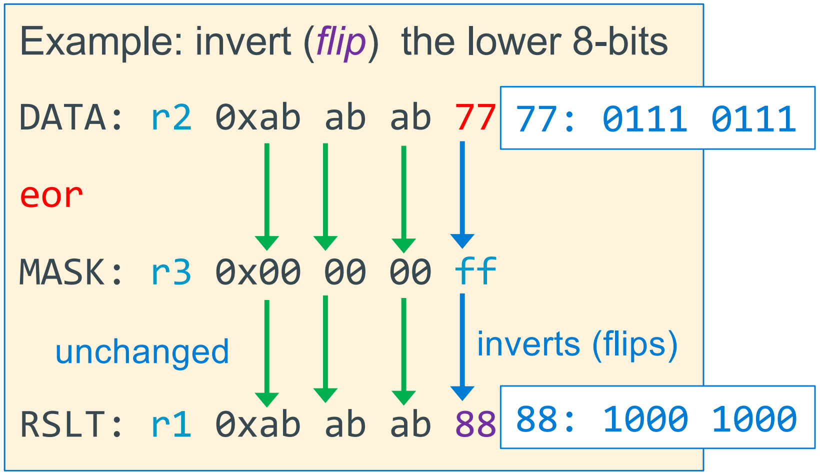
- 1 **will flip the bit**
- 0 to let a **bit through**

```
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

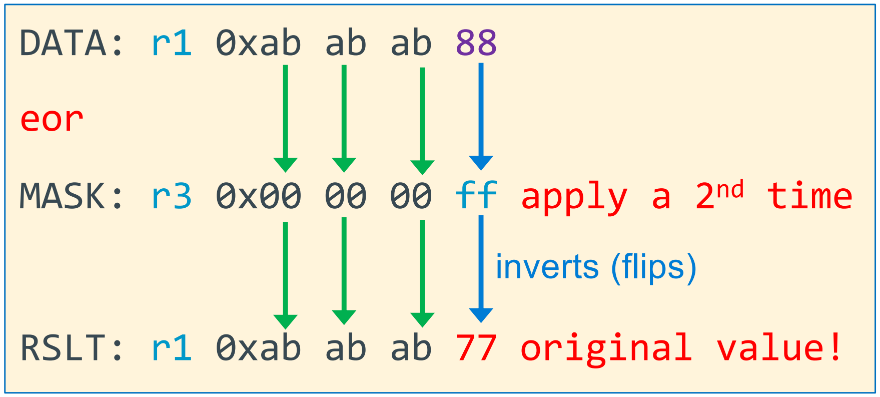
MASK: r3 0x00 00 00 ff

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!

x

Unsigned Integers (positive numbers) with Fixed # of Bits

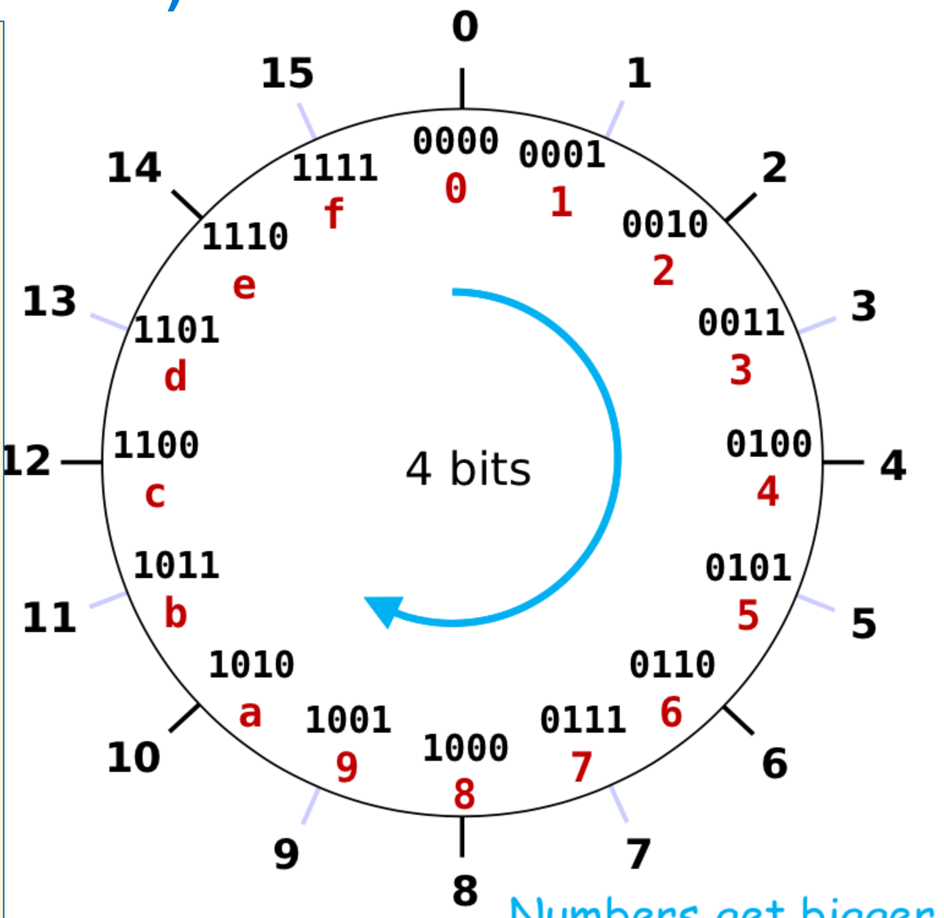
- 4 bits is 2^4 = ONLY 16 distinct values
- **Modular** (C operator: %) or clock math
  - Numbers start at 0 and “wrap around” after 15 and go back to 0
- Keep adding 1

  wraps (clockwise)

  0000 -> 0001 … -> 1111 -> 0000
- Keep subtracting 1

  wraps (counter-clockwise)

  1111 -> 1110 … -> 0000 -> 1111
- Addition and subtraction use normal "carry" and "borrow" rules, just operate in binary

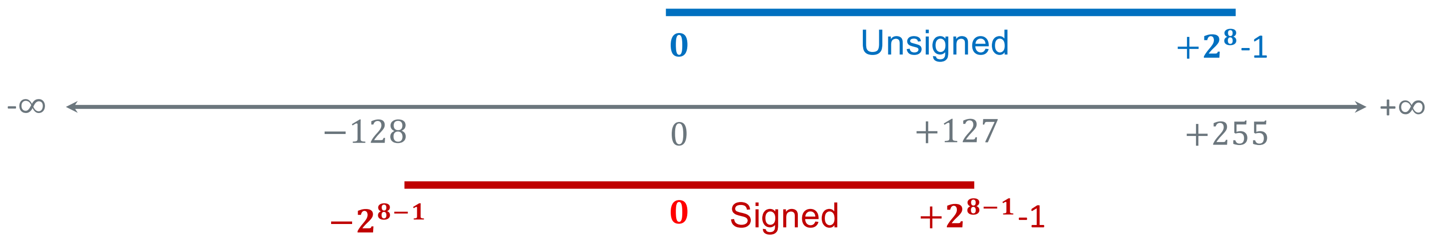


Numbers get bigger in this direction

x

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:** $0 \ldots 2^n – 1$ ← -1 comes from counting 0 as a "positive" number
- **Signed values:** $-2^{n-1} \ldots 2^{n-1} – 1$ (dividing the range in ~ half including 0)
- **On a number line (below):** 8-bit integers – signed and unsigned (*e.g.*, **`char in C`**)

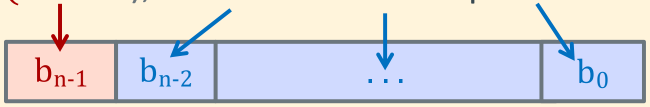


Same "width" (same number of encodings), just shifted in value

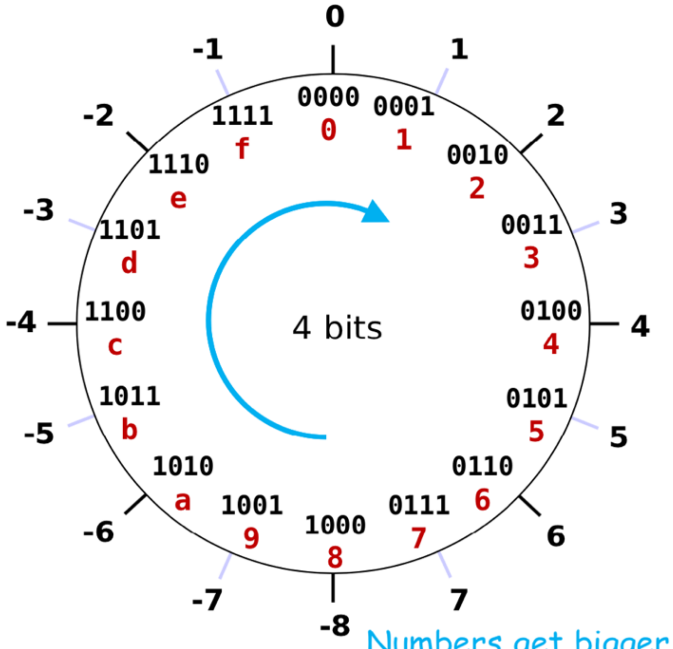
Two’s Complement: The MSB Has a *Negative Weight*

$$2's\ Comp = -b_{n-1}2^{n-1} + b_{n-2}2^{n-2} + \ldots + b_1 2^1 + b_0 2^0$$

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**:
    $1\text{x}2^3 + 0\text{x}2^2 + 1\text{x}2^1 + 0\text{x}2^0$ = **10**
  - 1010_2 **two’s complement**:
    $-1\text{x}2^3 + 0\text{x}2^2 + 1\text{x}2^1 + 0\text{x}2^0 = -8 + 2 =$ **–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**

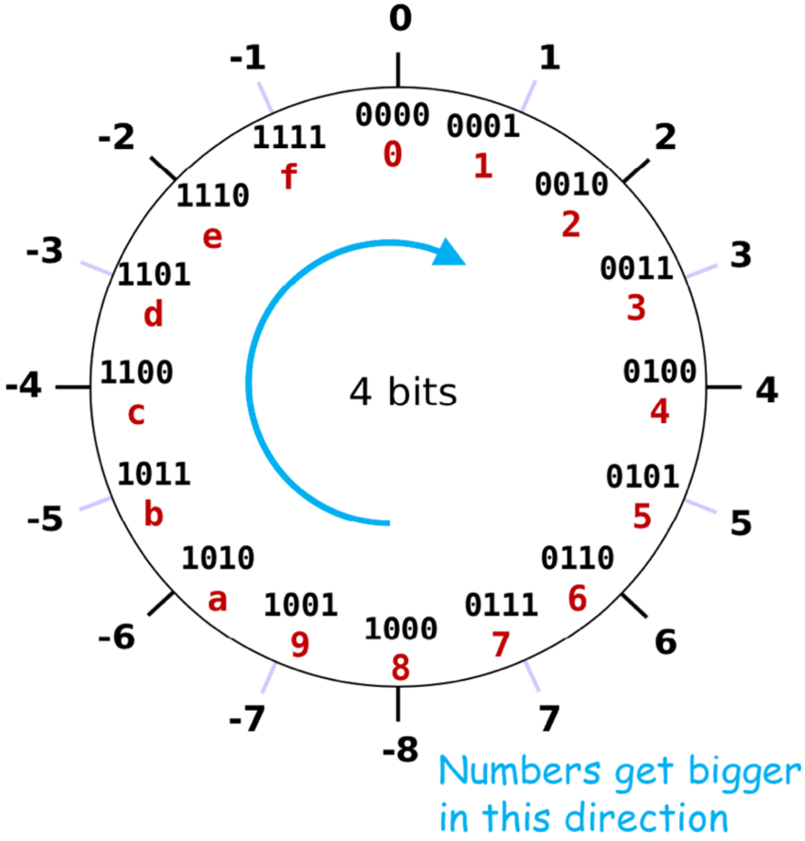


Numbers get bigger
in this direction

x

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!*



Numbers get bigger in this direction

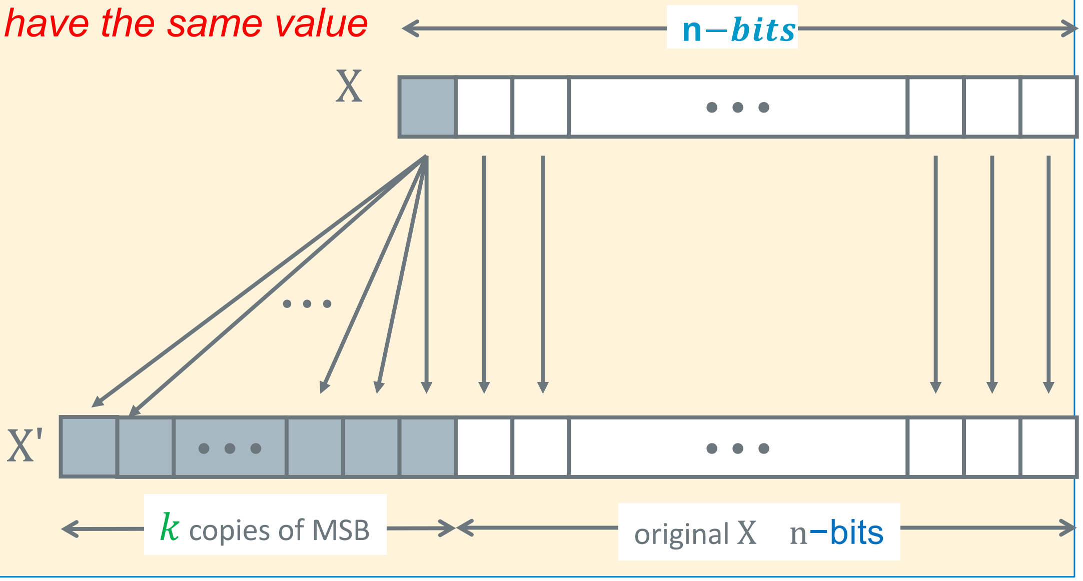
x

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

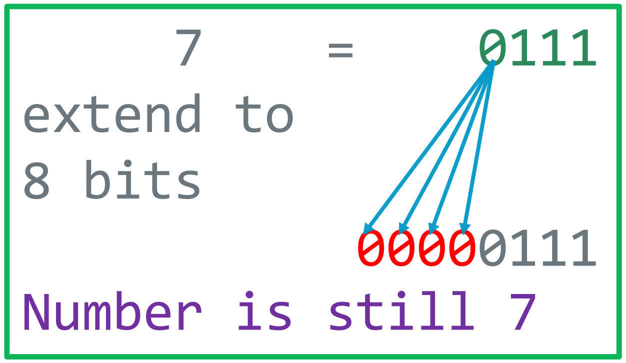
Two's Complement Signed:

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

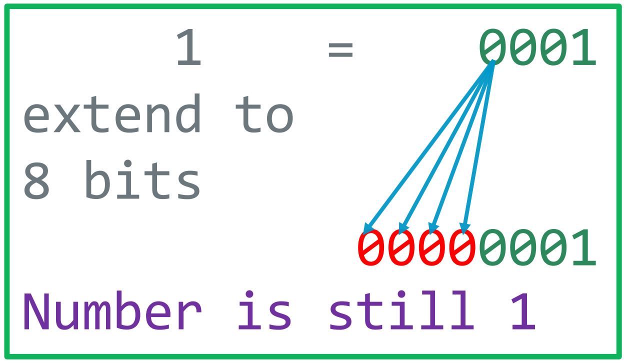
x

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

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



```
     7    =    0111
extend to
8 bits
           00000111
Number is still 7
```

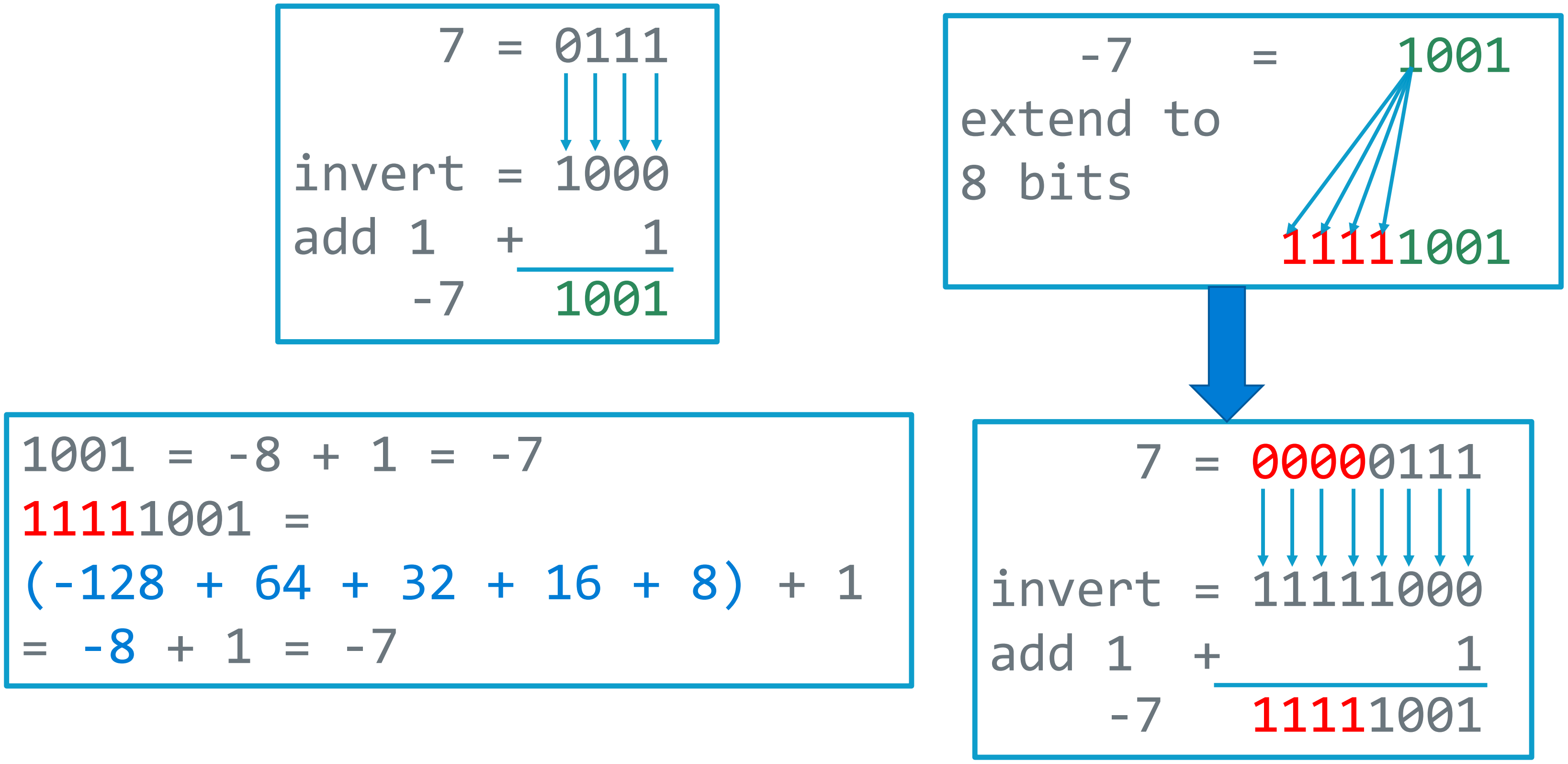


```
     1    =    0001
extend to
8 bits
           00000001
Number is still 1
```

x

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

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



```
     7 = 0111
invert = 1000
add 1  +    1
    -7   1001
```

```
   -7     =     1001
extend to
8 bits
             11111001
```

```
     7 = 00000111
invert = 11111000
add 1  +        1
    -7   11111001
```

```
1001 = -8 + 1 = -7
11111001 =
(-128 + 64 + 32 + 16 + 8) + 1
= -8 + 1 = -7
```

x

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)

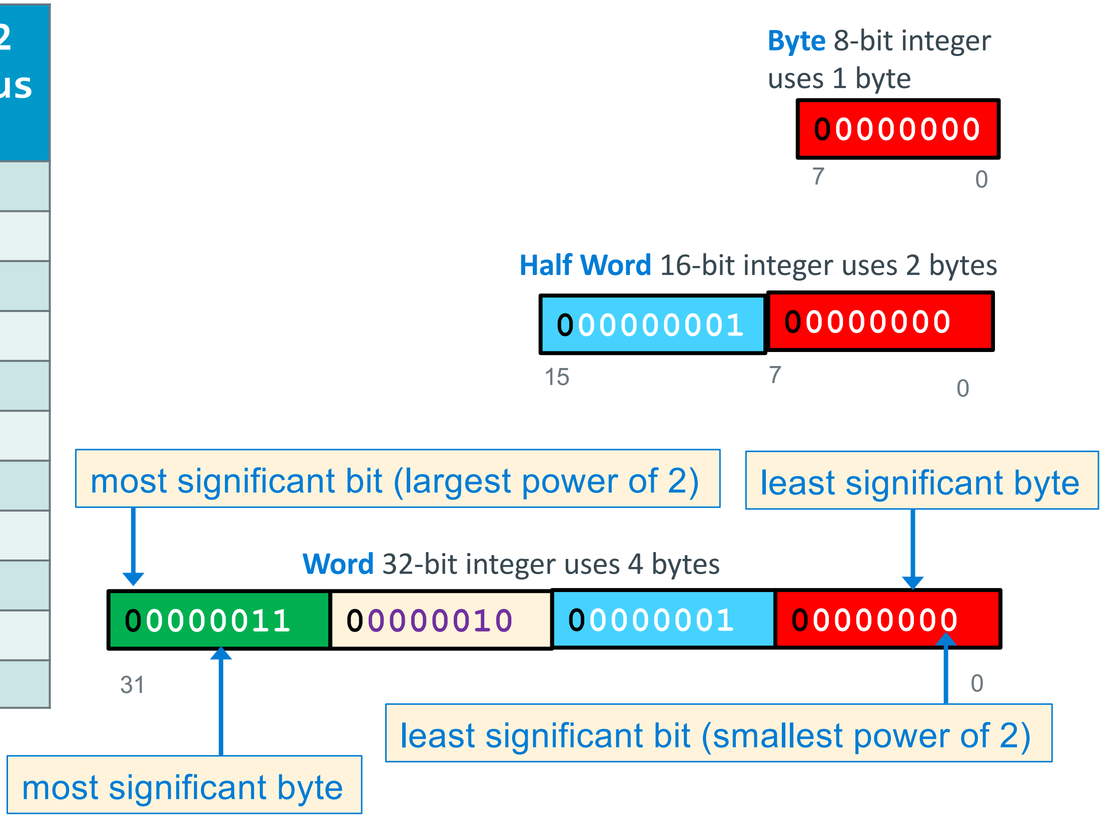
```
#include <stdlib.h>
#include <stdio.h>
int main(void)
{
    signed char c = -1;
    signed int i = c;
    unsigned char d = 1;
    unsigned int j = d;
    printf("c decimal = %hd\n", c);
    printf("c = 0x%hhx\n", c);
    printf("i decimal = %d\n", i);
    printf("i = 0x%x\n", i);
    printf("\nd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

x

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

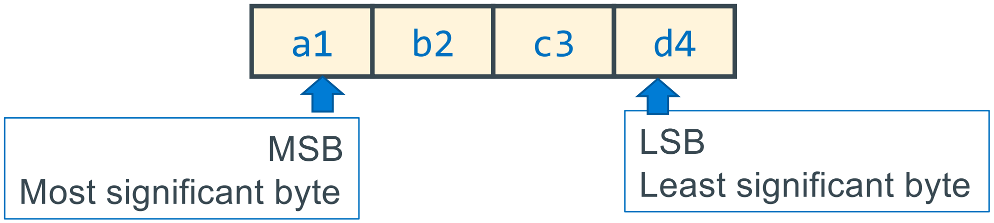
least significant bit (smallest power of 2)

most significant byte

x

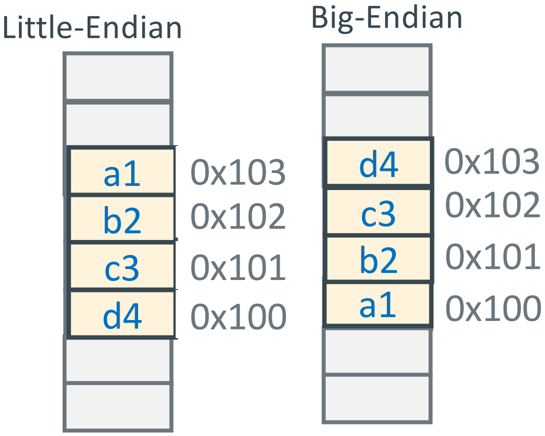
Byte Ordering of Numbers In Memory: Endianness

- 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



MSB
Most significant byte

LSB
Least significant byte



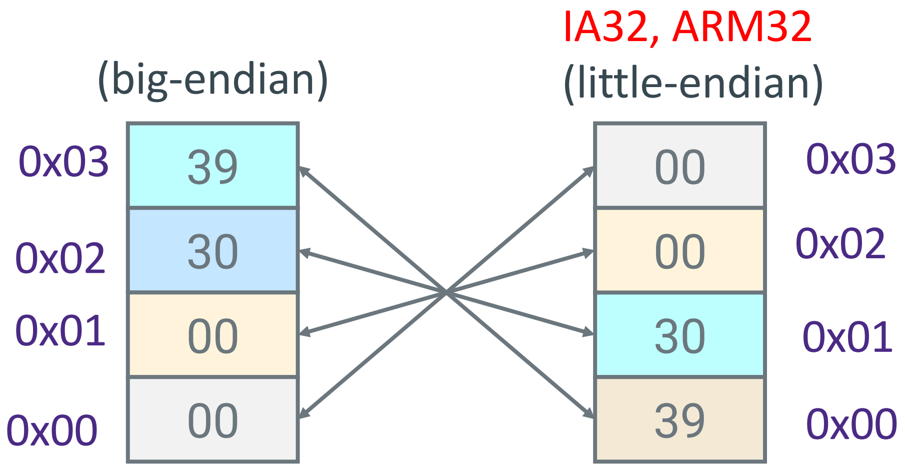
Little-Endian		Big-Endian	
a1	0x103	d4	0x103
b2	0x102	c3	0x102
c3	0x101	b2	0x101
d4	0x100	a1	0x100

x

Byte Ordering Example

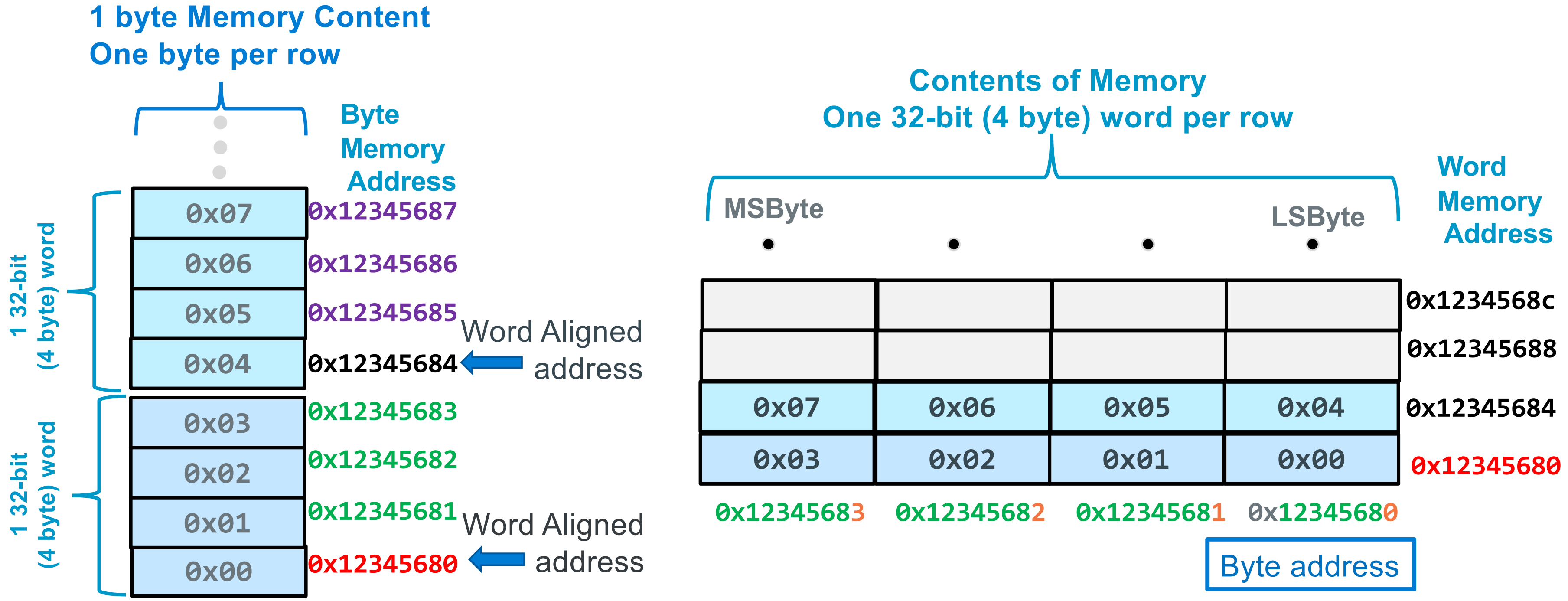
```
Decimal:   12345
Binary:     0011  0000  0011  1001
Hex:           3     0     3     9
```

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



x

Byte Addressable Memory Shown as 32-bit words



1 byte Memory Content
One byte per row

1 byte Memory Content	Byte Memory Address
0x07	0x12345687
0x06	0x12345686
0x05	0x12345685
0x04	0x12345684
0x03	0x12345683
0x02	0x12345682
0x01	0x12345681
0x00	0x12345680

1 32-bit (4 byte) word

1 32-bit (4 byte) word

Word Aligned address

Word Aligned address

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

MSByte			LSByte	Word Memory Address
				0x1234568c
				0x12345688
0x07	0x06	0x05	0x04	0x12345684
0x03	0x02	0x01	0x00	0x12345680
0x12345683	0x12345682	0x12345681	0x12345680	

Byte address

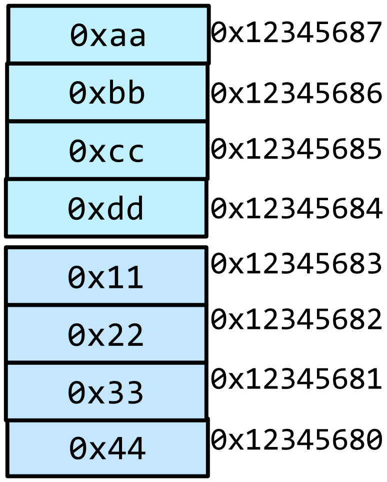
Observation
32-bit aligned addresses
rightmost 2 bits of the address are always 0

X

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;
}
```

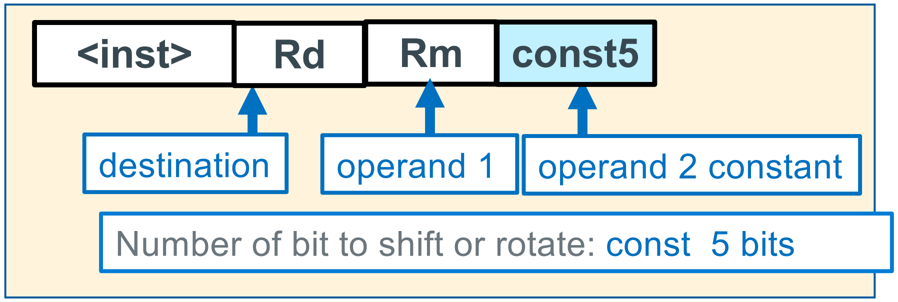
```
kmuller@keithm-pi4:~$ ./a.out
foo[1]: aabbccdd
foo[0]: 11223344
byte 7: aa
byte 6: bb
byte 5: cc
byte 4: dd
byte 3: 11
byte 2: 22
byte 1: 33
byte 0: 44
```



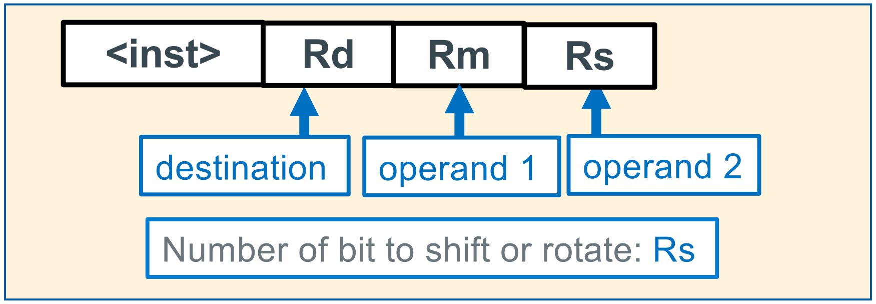
0xaa	0x12345687
0xbb	0x12345686
0xcc	0x12345685
0xdd	0x12345684
0x11	0x12345683
0x22	0x12345682
0x33	0x12345681
0x44	0x12345680

x

Shift and Rotate Instructions

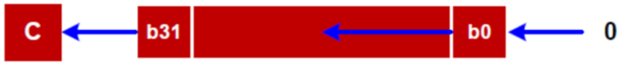


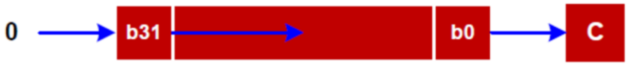
Number of bit to shift or rotate: const 5 bits

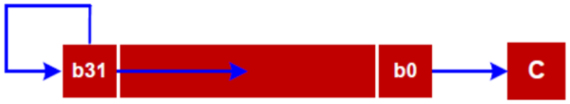


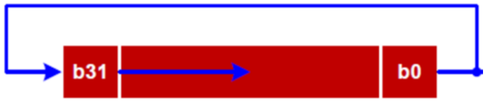
Number of bit to shift or rotate: Rs

Instruction	*Syntax*	*Operation*	*Notes*	*Diagram*

Logical Shift Left
`int x; or unsigned int x`
`x << n;`
	lsl R_d, R_m, *const5*
	lsl R_d, R_m, R_s
		$R_d \leftarrow R_m$ << *const5*
		$R_d \leftarrow R_m$ << R_s
			Zero fills
			shift: 0 - 31
				

Logical Shift Right
`unsigned int x;`
`x >> n;`
	lsr R_d, R_m, *const5*
	lsr R_d, R_m, R_s
		$R_d \leftarrow R_m$ >> *const5*
		$R_d \leftarrow R_m$ >> R_s
			Zero fills
			shift: 1 – 32
				

Arithmetic Shift Right
`int x;`
`x >> n;`
	asr R_d, R_m, *const5*
	asr R_d, R_m, R_s
		$R_d \leftarrow R_m$ >> *const5*
		$R_d \leftarrow R_m$ >> R_s
			Sign extends
			shift: 1 - 32
				

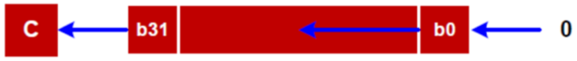
Rotate Right
`unsigned int x;`
`x = (x>>n)|(x<<(32-n));`
	ror R_d, R_m, *const5*
	ror R_d, R_m, R_s
		$R_d \leftarrow R_m$ ror *const5*
		$R_d \leftarrow R_m$ ror R_s
			right rotate
			rot: 0 - 31
				

x

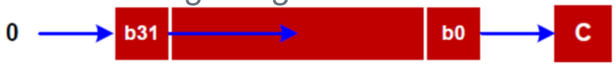
Shift Operations in C

- n is number of bits to shift a variable x of width w bits
- Shifts by `n < 0` or `n ≥ w` are *undefined*
- Left shift (`x << N`) – **Multiplies by 2^N**
  - Shift N bits left, Fill with `0`s on right
- **In C:** behavior of **>>** is determined by compiler
  - gcc: it depends on data type of **`x`** (signed/unsigned)
- Right shift (`x >> 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 **<u>Replicating</u>** the most significant bit on left
    - Maintains sign of **`x`**
- **In Java:** logical shift is **>>>** and arithmetic shift is >>

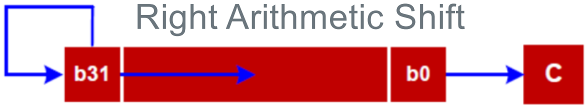
Left Shift



Right logical Shift



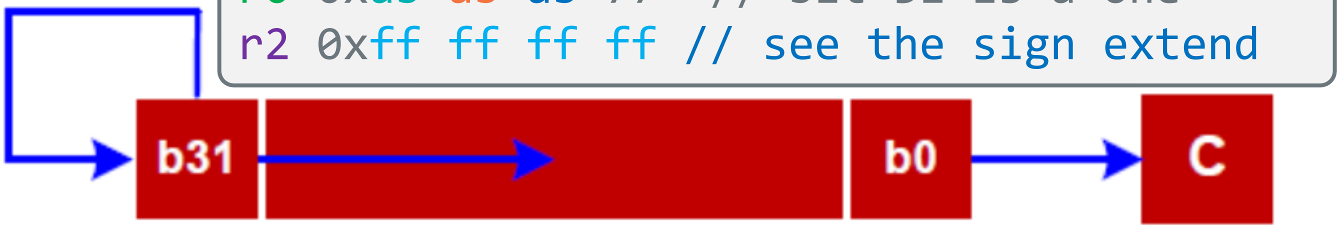
Right Arithmetic Shift



x

Arithmetic Shift Right Example: Testing Sign

```
asr r2, r0, 31

r0 0xab ab ab 77  // bit 31 is a one
r2 0xff ff ff ff // see the sign extend
```



Test for sign
-1 if r0 negative

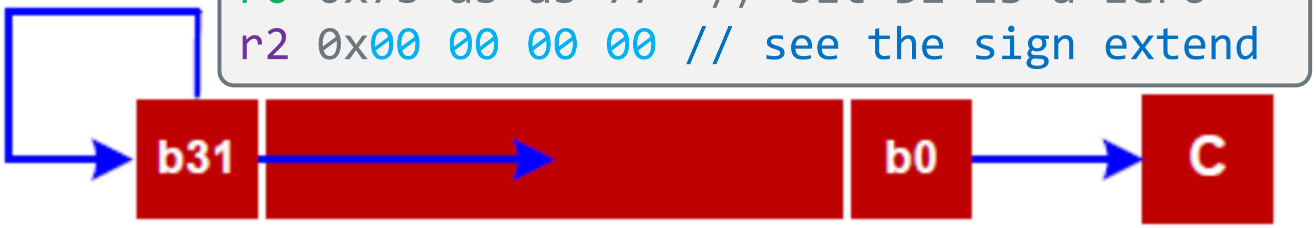
```
int i;
//code
if ((i>>31) == -1) {
  // code neg #
}
```

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

x

Arithmetic Shift Right Example: Testing SIgn

```
asr r2, r0, 31

r0 0x7b ab ab 77  // bit 31 is a zero
r2 0x00 00 00 00 // see the sign extend
```

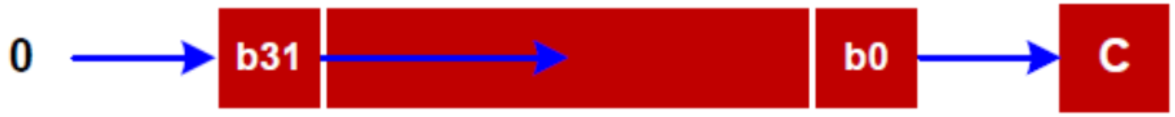


Test for sign
0 if r0 positive

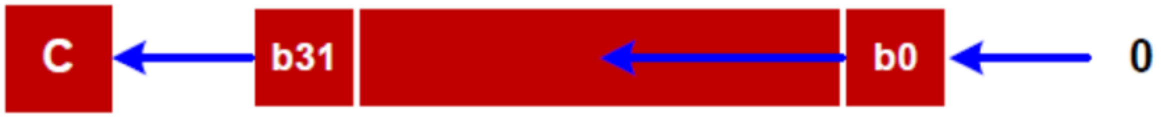
```
int i;
//code
if ((i>>31) == 0) {
  // code pos #
}
```

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

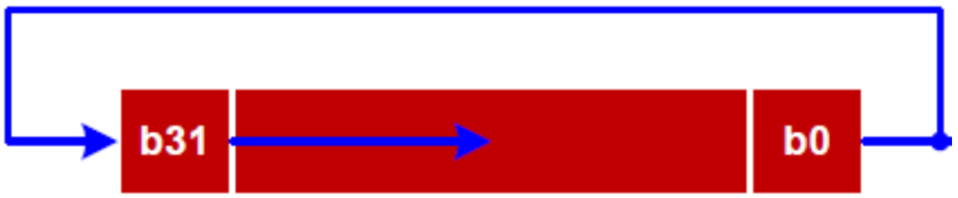
Logical Shift & Rotate Operations



```
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
```



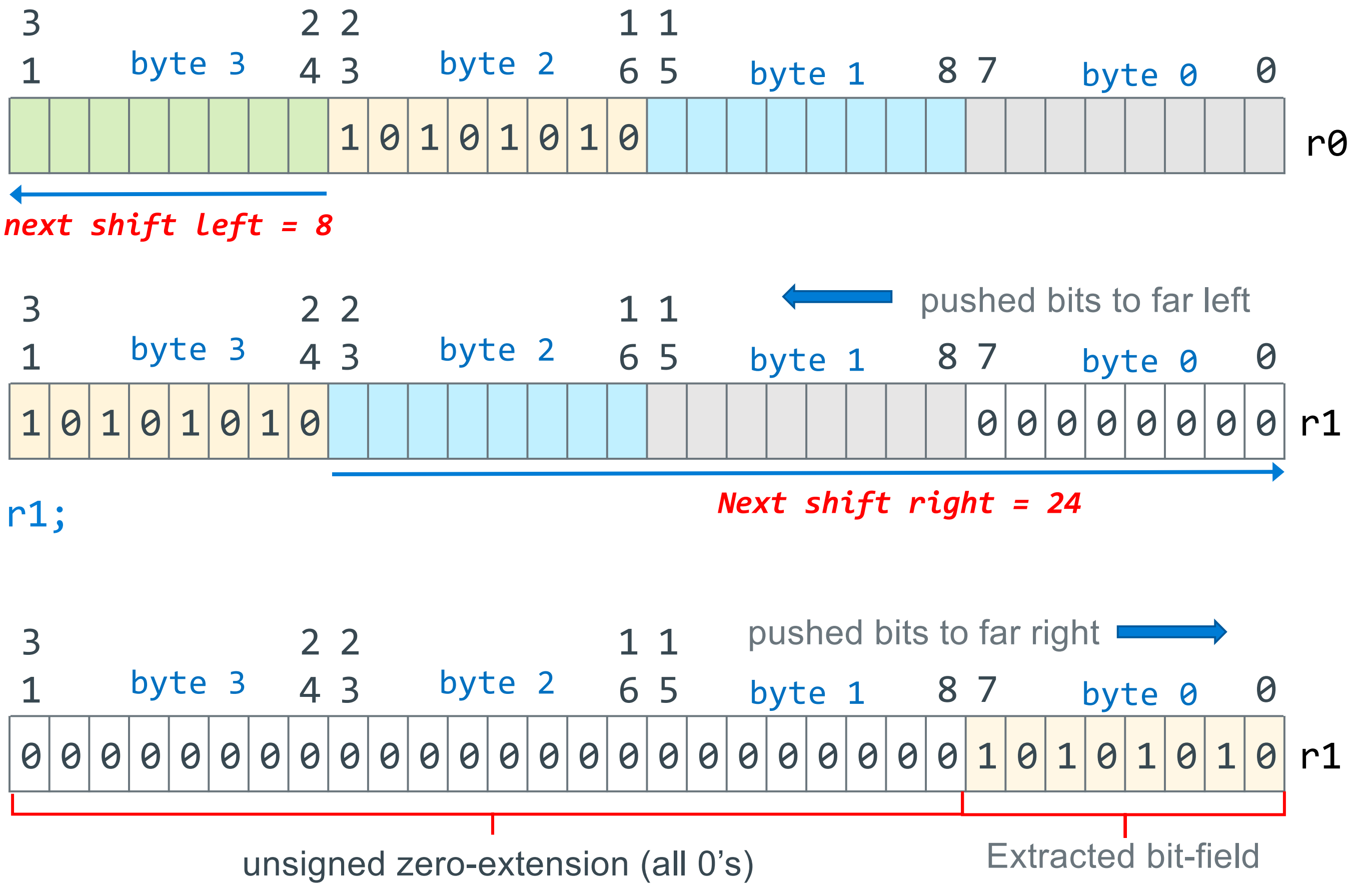
```
ror r2, r0, 8

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

x

Extracting/Isolating Unsigned Bitfields

Hint: Useful for PA7

- Move byte 2 in r0 to byte 0 in r1



31 byte 3 24	23 byte 2 16	15 byte 1 8	7 byte 0 0	
	1 0 1 0 1 0 1 0			r0

next shift left = 8

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

31 byte 3 24	23 byte 2 16	15 byte 1 8	7 byte 0 0	
1 0 1 0 1 0 1 0			0 0 0 0 0 0 0 0	r1

pushed bits to far left

Next shift right = 24

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

```
lsr   r1, r1, 24
r1 = r1 >> 24;
```

31 byte 3 24	23 byte 2 16	15 byte 1 8	7 byte 0 0	
0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	1 0 1 0 1 0 1 0	r1

pushed bits to far right

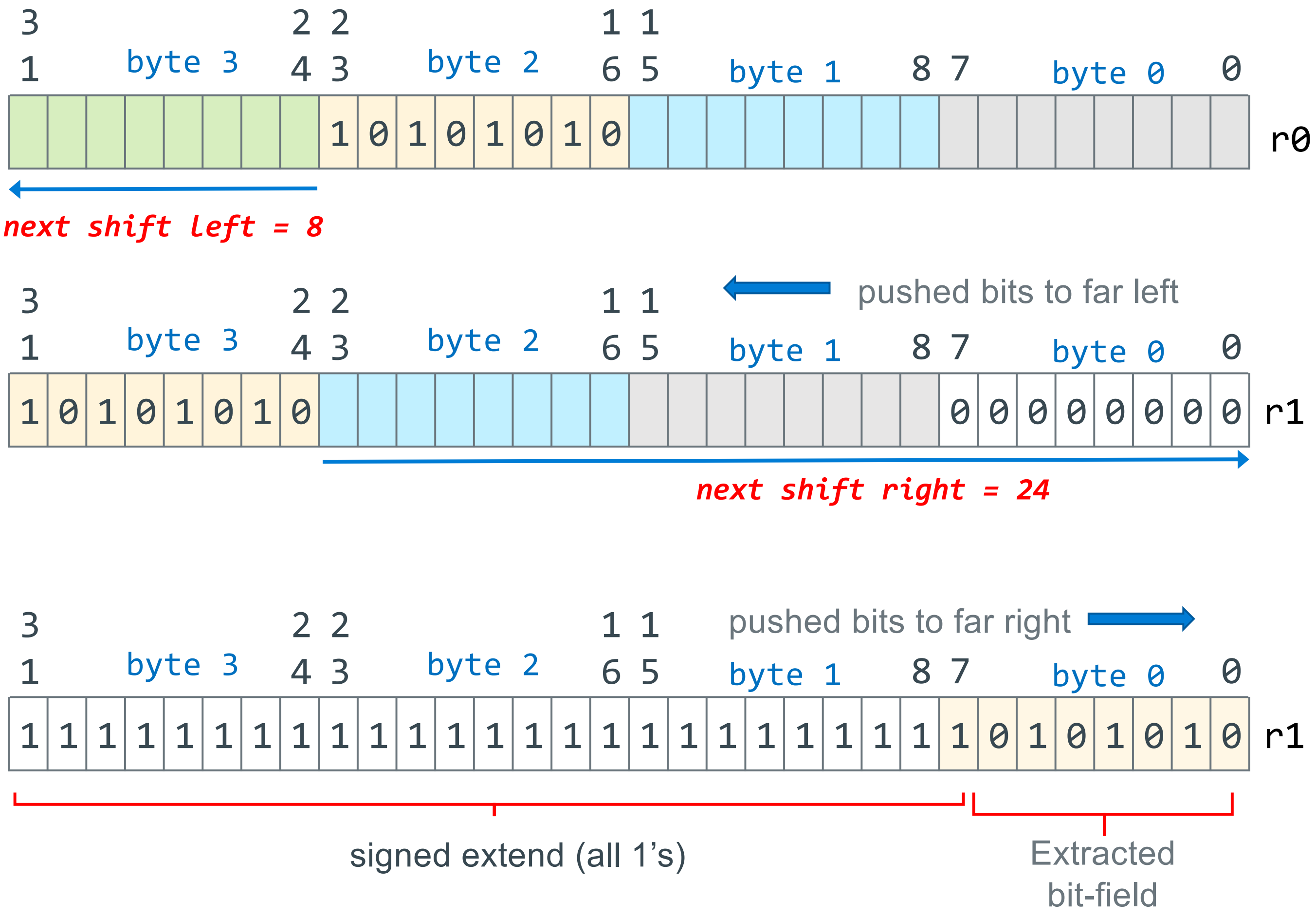
unsigned zero-extension (all 0’s)

Extracted bit-field

x

Extracting Signed Bitfields

- Move byte 2 in r0 to byte 0 in r1



```
r0: . . . . . . . . 1 0 1 0 1 0 1 0 . . . . . . . . . . . . . . . .
r1: 1 0 1 0 1 0 1 0 . . . . . . . . . . . . . . . . 0 0 0 0 0 0 0 0
r1: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 1 0 1 0
```

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

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

x

Inserting Bitfields – Inserting Source Field into Destination Field

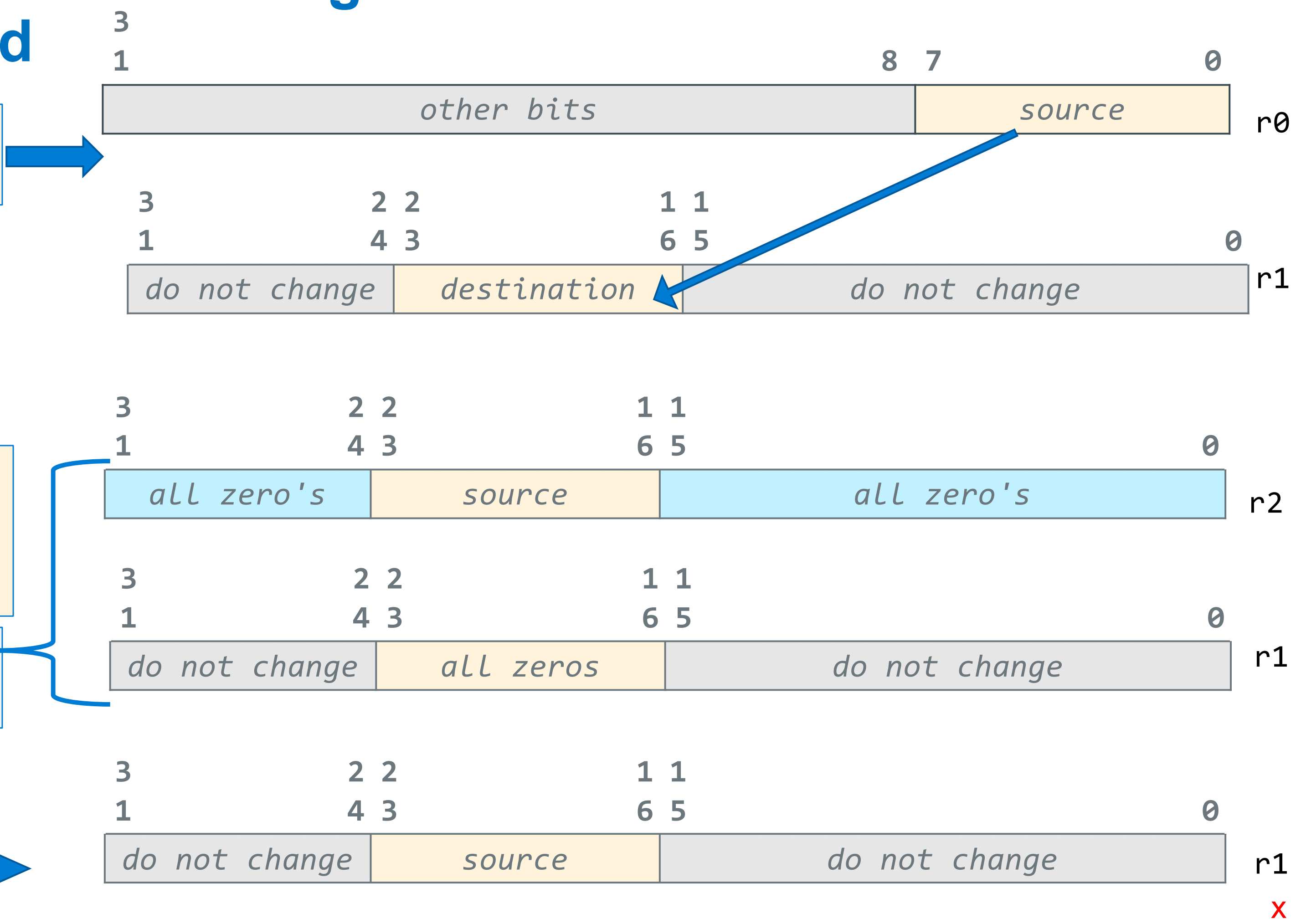
Task: Insert source into destination

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

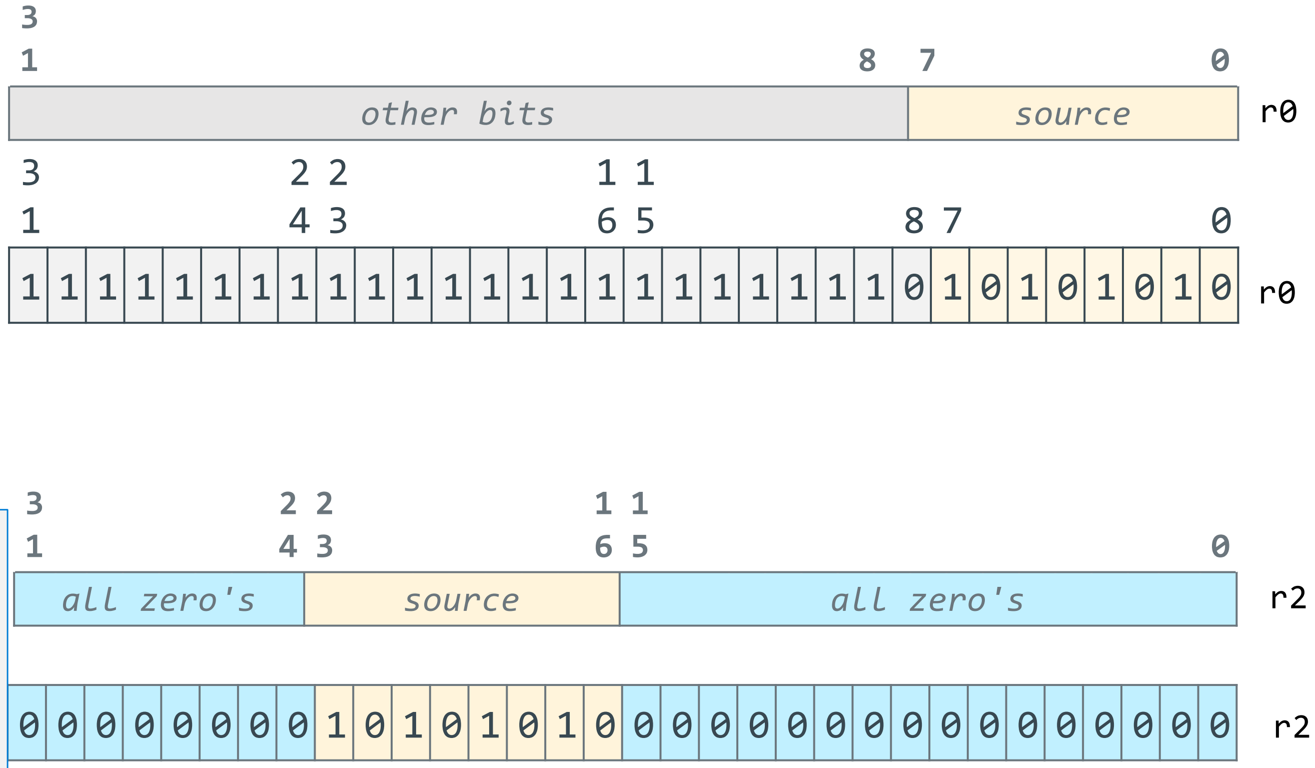
Approach
(1) isolate source field
(2) clear destination field
(3) Bitwise or together

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

results in



Inserting Bitfields – Isolating the Source Field



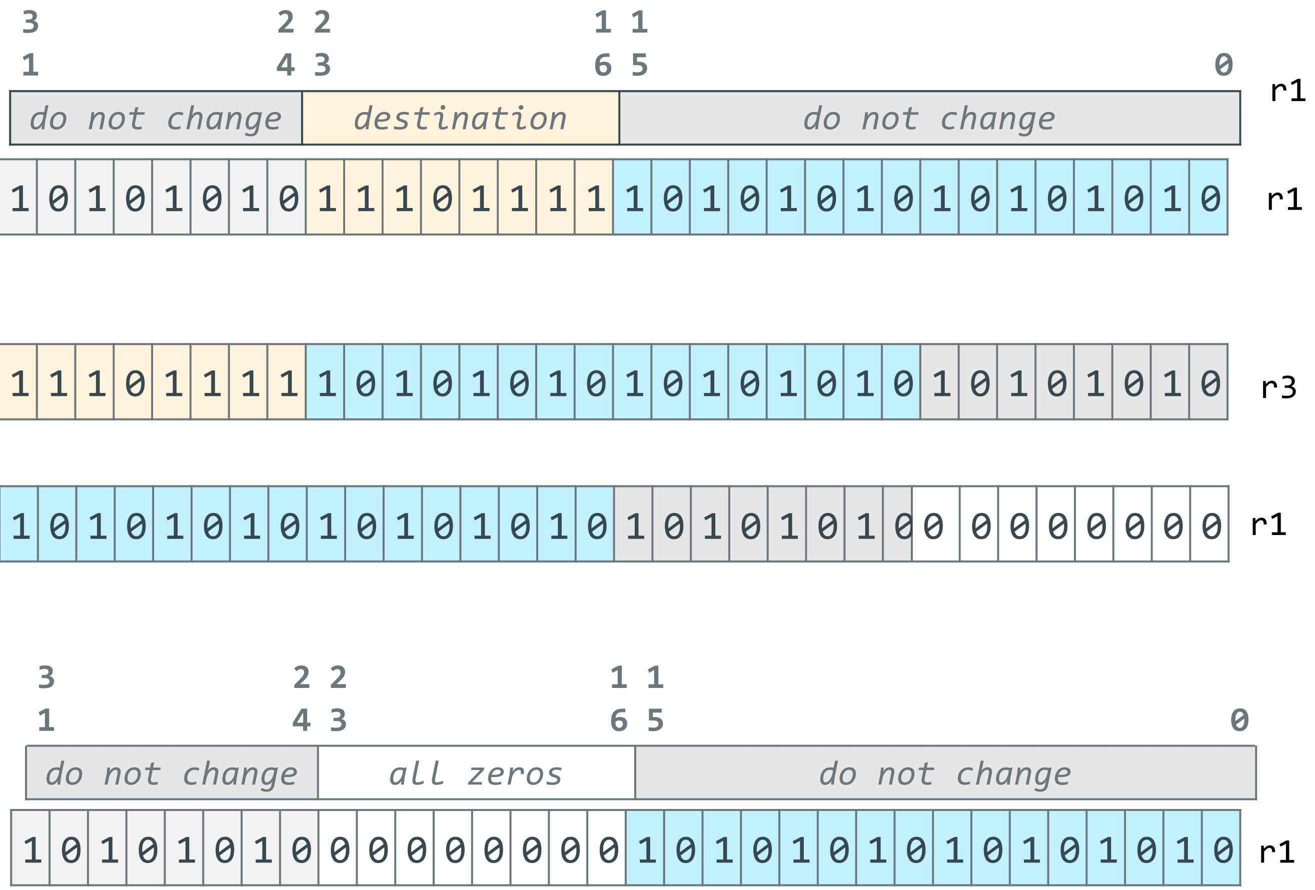
r0: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 1 0 1 0 1 0

r2: 0 0 0 0 0 0 0 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

```
isolate source field

lsl    r2, r0, 24
lsr    r2, r2, 8

r2 = r0 << 24;
r2 = r2 >> 8;
```

x

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);
```

x

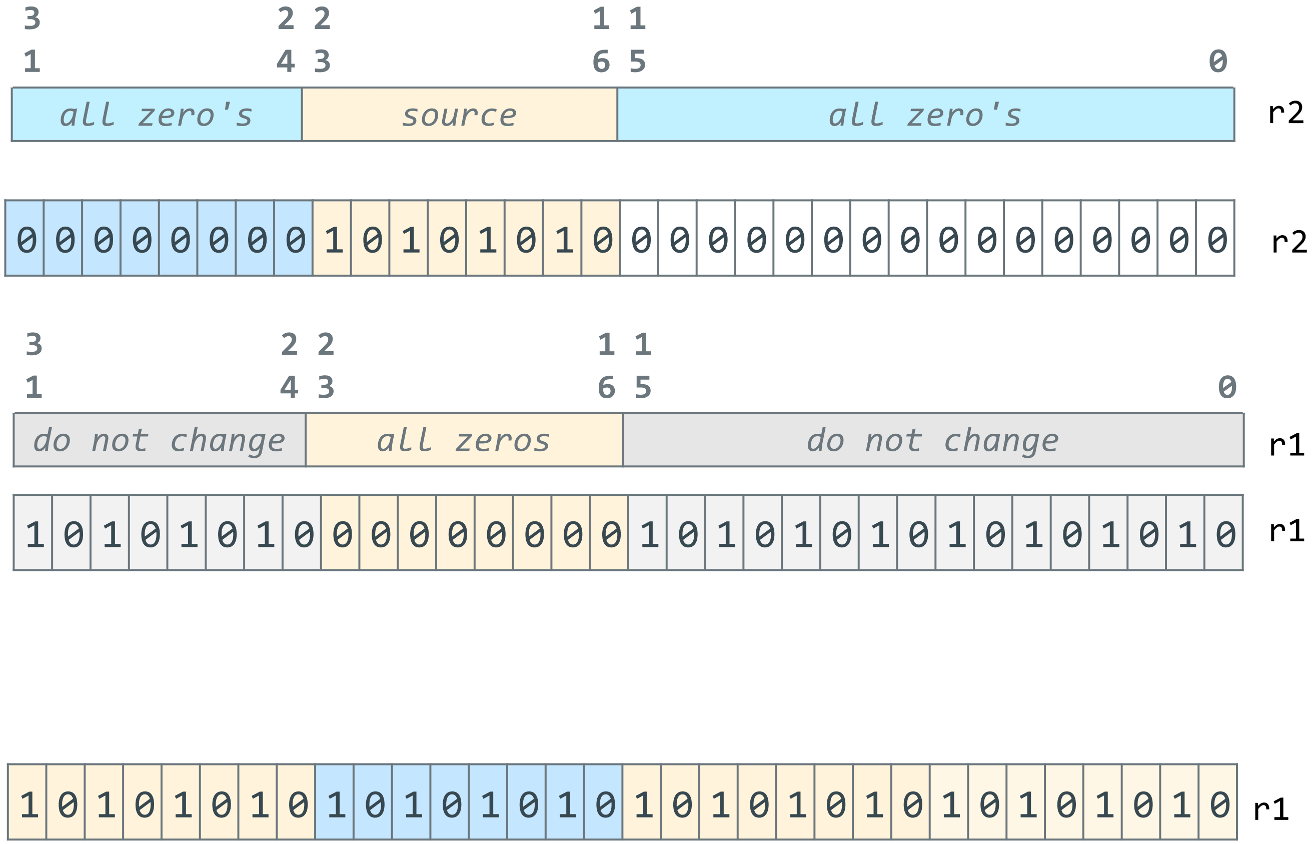
Inserting Bitfields – Combining Isolated Source and Cleared Destination

isolated source

field cleared in destination

inserted field

```
orr     r1, r1, r0
r1 = r1 | r0;
```



```
0 0 0 0 0 0 0 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   r2
```

```
1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0   r1
```

```
1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0   r1
```

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

0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0 0 0 0 0 0

selection mask

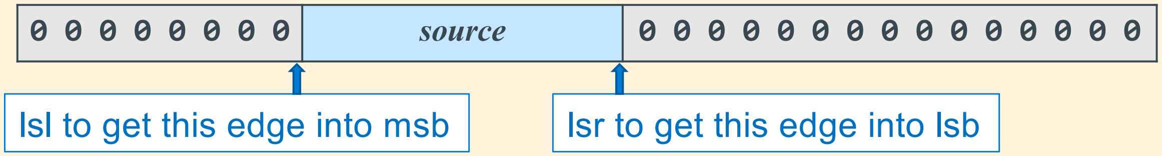
Clear a field: Use `and` with a mask of zero's surrounded by one's to select the bits that have a 1 in the mask, all other bits will be set to zero

clears this field when used with and

1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

clear a field mask

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



0 0 0 0 0 0 0 0	*source*	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

lsl to get this edge into msb

lsr to get this edge into lsb

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

0 0 0 0 0 0 0 0	*source*	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Keep these bits	0 0 0 0 0 0 0 0	Keep these bits

x

Reference For PA7/8: C Stream Functions Opening Files

```
FILE *fopen(char filename[], const char mode[]);
```

- Opens a stream to the specified file in specified file access mode
  - returns NULL on failure – always check the return value; make sure the open succeeded!
- Mode is a string that describes the actions that can be performed on the stream:

"r” Open for reading.

The stream is positioned at the beginning of the file. Fail if the file does not exist.

"w” Open for writing.

The stream is positioned at the beginning of the file. Create the file if it does not exist.

"a” Open for writing.

The stream is positioned at the end of the file. Create the file if it does not exist.

Subsequent writes to the file will always be at current end of file.

- An optional "+" following "r", "w", or "a" opens the file for both reading and writing

Reference: C Stream Functions Closing Files and Usage

```
int fclose(FILE *stream);
```

- Closes the specified stream, forcing output to complete (eventually)
  - returns EOF on failure (often ignored as no easy recovery other than a message)

- Usage template for **`fopen()`** and **`fclose()`**
  1. Open a file with **`fopen()`** **always** checking the return value
  2. do i/o – keep calling stdio io routines
  3. close the file with **`fclose()`** when done with that I/O stream

C Stream Functions Array/block read/write

- These do not process contents they simply **transfer** a fixed number of bytes to and from a buffer passed to them
- `size_t fwrite(void *ptr, size_t size, size_t count, FILE *stream);`
    - Writes an array of *count* ***elements*** of ***size*** bytes from **stream**
    - *Updates the write file pointer forward by the number of bytes written*
    - returns number of elements written
    - error is short element count or 0
- `size_t fread(void *ptr, size_t size, size_t count, FILE *stream);`
    - Reads an array of ***count elements*** of ***size*** bytes from *stream*
    - *Updates the read file pointer forward by the number of bytes read*
    - returns number of elements read, EOF is a return of 0
    - error is short element count or 0
- **I almost always set size to 1 to return bytes read/written**

x

C fread/fwrite Example - 1

```
#include <stdio.h>
#include <stdlib.h>
#include <errno.h>
#define BFSZ      8192 /* size of read */
int main(void)
{
  unsigned char fbuf[BFSZ];
  FILE *fin, *fout;
  size_t readlen;
  size_t bytes_copied = 0;
  retval = EXIT_SUCCESS;

  if (argc != 3){
    fprintf(stderr, "%s requires two args\n", argv[0]);
    return EXIT_FAILURE;
  }
  /* Open the input file for read */
  if ((fin = fopen(argv[1], "r")) == NULL) {
    fprintf(stderr,"fopen for read failed\n");
    return EXIT_FAILURE;
  }
  /*  Open the output file for write */
  if ((fout = fopen(argv[2], "w") == NULL) {
    fprintf(stderr, "fopen for write failed\n");
    fclose(fin);
    return EXIT_FAILURE;
  }
```

To handle bytes moved

```
% ls -ls ZZZ
ls: ZZZ: No such file or directory
% ./a.out cp.c ZZZ
bytes copied: 1122
% ls -ls cp.c ZZZ
8 -rw-r--r--  1 kmuller  staff  1122 Jul  2 08:51 ZZZ
8 -rw-r--r--  1 kmuller  staff  1122 Jul  2 08:49 cp.c
```

x

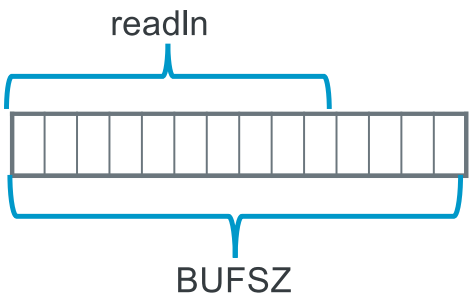
C fread/fwrite Example - 2

```
  /* Read from the file, write to fout */

  while ((readlen = fread(fbuf, 1, BUFSIZ, fin)) > 0) {

    if (fwrite(fbuf, 1, readlen, fout) != readlen) {
       fprintf(stderr, "write failed\n");
        retval =  EXIT_FAILURE;
        break;
    }
    bytes_copied += readlen; //running sum bytes copied
  }

  if (retval == EXIT_FAILURE)
    printf("Failure Copy did not complete only ");
  printf("Bytes copied: %zu\n", bytes_copied);

  fclose(fin);
  fclose(fout);

  return retval;
}
```

By using an element size of 1 with a char buffer, this is byte I/O

Capture the bytes read so you know how many bytes to write

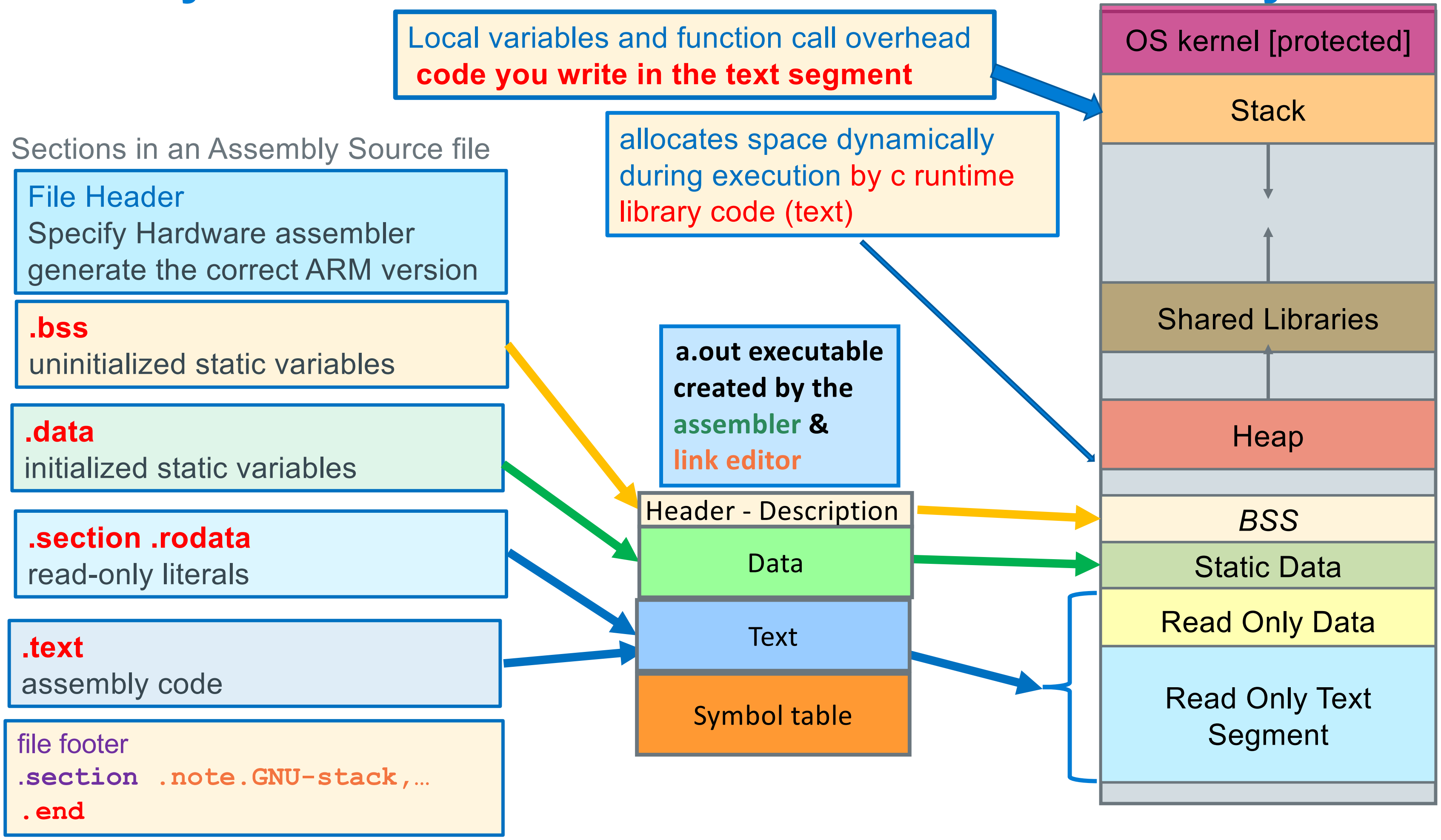
unless the input file length is an exact multiple of BUFSIZ, last fread() will always read less than BUFSIZ which is why you write readln



Jargon: the last record is often called the "runt"

x

Assembly Source File to Executable to Linux Memory



Local variables and function call overhead
code you write in the text segment

allocates space dynamically during execution by c runtime library code (text)

Sections in an Assembly Source file

File Header
Specify Hardware assembler generate the correct ARM version

.bss
uninitialized static variables

.data
initialized static variables

.section .rodata
read-only literals

.text
assembly code

file footer
```
.section .note.GNU-stack,…
.end
```

a.out executable created by the assembler & link editor

Header - Description

Data

Text

Symbol table

OS kernel [protected]

Stack

Shared Libraries

Heap

BSS

Static Data

Read Only Data

Read Only Text Segment

x

Creating Segments, Definitions In Assembly Source

- The following assembler directives indicate the ***start*** of a **memory segment specification**
  - **Remains in effect** until the next segment directive is seen

```
.bss
        // start uninitialized static segment variables definitions
        // does not consume any space in the executable file
.data
        // start initialized static segment variables definitions
.section .rodata
        // start read-only data segment variables definitions
.text
        // start read-only text segment (code)
```

Assembly Source File Template

```
// File Header
        .arch armv6                 // armv6 architecture instructions
        .arm                        // arm 32-bit instruction set
        .fpu vfp                    // floating point co-processor
        .syntax unified             // modern syntax

// BSS Segment (only when you have initialized globals)
         .bss
// Data Segment (only when you have uninitialized globals)
         .data
// Read-Only Data (only when you have literals)
         .section .rodata
// Text Segment – your code
         .text

// Function Header
        .type   main, %function     // define main to be a function
        .global main                // export function name
main:
// function prologue                // stack frame setup
                  // your code for this function here
// function epilogue                //stack frame teardown

// function footer
         .size  main, (. – main)

// File Footer
          .section .note.GNU-stack,"",%progbits // stack/data non-exec
.end
```

- assembly programs end in .S
  - That is a **capital** .S
  - example: test.S
- Always use gcc to assemble
  - _start() and C runtime
- File has a complete program

  `gcc file.S`
- File has a partial program

  `gcc –c file.S`
- Link files together

  `gcc file.o cprog.o`

x

Preview: Return Value and Passing Parameters to Functions

(Four parameters or less)

Register	Function Call Use
r0	1st parameter
r1	2nd parameter
r2	3rd parameter
r3	4th parameter

Register	Function Return Value Use
r0	8, 16 or 32-bit result, 32-bit address or least-significant half of a 64-bit result
r1	most-significant half of a 64-bit result

- Where `r0, r1, r2, r3` are arm registers, the function declaration is (first four arguments):

```
r0 = function(r0, r1, r2, r3)          // 32-bit return
r0, r1 = function(r0, r1, r2, r3)      // 64-bit return – long long
```

- Each **parameter and return value is limited to data that can fit in 4 bytes or less**
- You receive up to the first four parameters in these four registers
- You copy up to the first four parameters into these four registers before calling a function
- For parameter values using more than 4 bytes, a pointer to the parameter is passed (we will cover this later)
- **You MUST ALWAYS assume** that the called function will **alter the contents of all four registers: r0-r3**
  - **In terms of C runtime support, these registers contain the copies given to the called function**
  - **C allows the copies to be changed in any way by the called function**

Preview: Writing an ARM32 function

```
#include <stdlib.h>
#include <stdio.h>
int sum4(int, int, int, int);
int main()
{
    int reslt;

    reslt = sum4(1,2,3,4);

    printf("%d\n", reslt);
    return EXIT_SUCCESS;
}
```

```
#ifndef SUM4_H
#define SUM4_H

#ifndef __ASSEMBLER__
int sum4(int, int, int, int);
#else
.extern sum4
#endif

#endif
```

two _

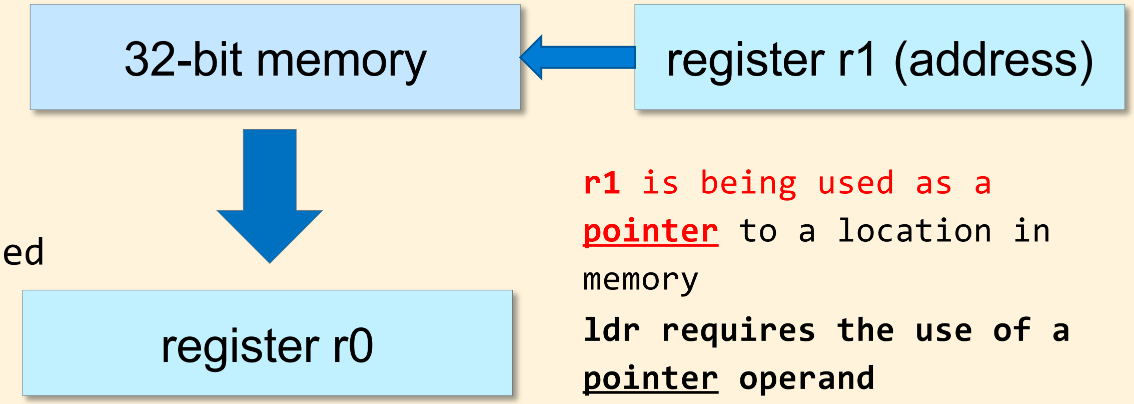
```
#include "sum4.h"
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .global sum4
    .type   sum4, %function
    .equ    FP_OFF, 28
    // r0 = sum4(r0, r1, r2, r3)
sum4:
    push    {r4-r9, fp, lr}
    add     fp, sp, FP_OFF

    add     r0, r0, r1
    add     r0, r0, r2
    add     r0, r0, r3

    sub     sp, fp, FP_OFF
    pop     {r4-r9, fp, lr}
    bx      lr

    .size sum4, (. - sum4)
    .section .note.GNU-stack,"",%progbits
.end
```

```
$ gcc -Wall -Wextra -c main.c
$ gcc -c sum4.S
$ gcc sum4.o main.o
$ ./a.out
10
```

Load/Store: Register Base Addressing

```
ldr r0, [r1]
```

Copies a 32-bit word from the memory location whose address is contained in r1 (r1 is a pointer) into register r0

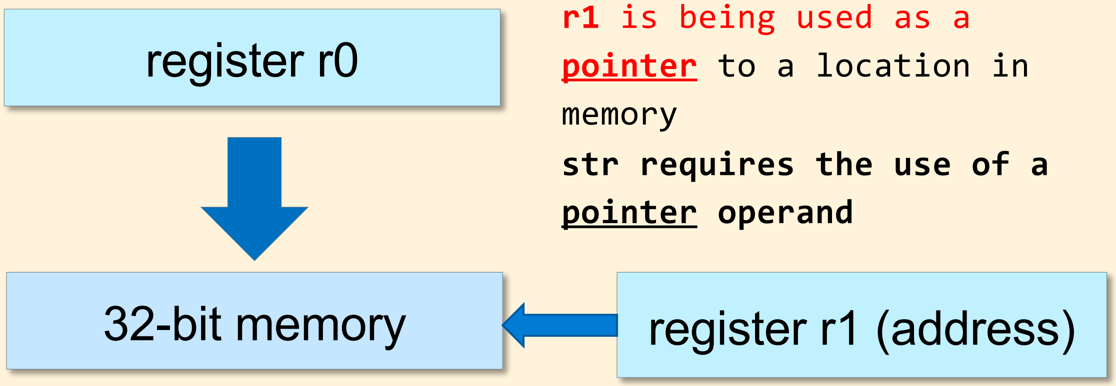


r1 is being used as a **pointer** to a location in memory

ldr requires the use of a pointer operand

```
str  r0, [r1]
```

Copies all 32 bits of the value held in register r0 to the 32-bit memory location contained in register r1 (r1 pointer)

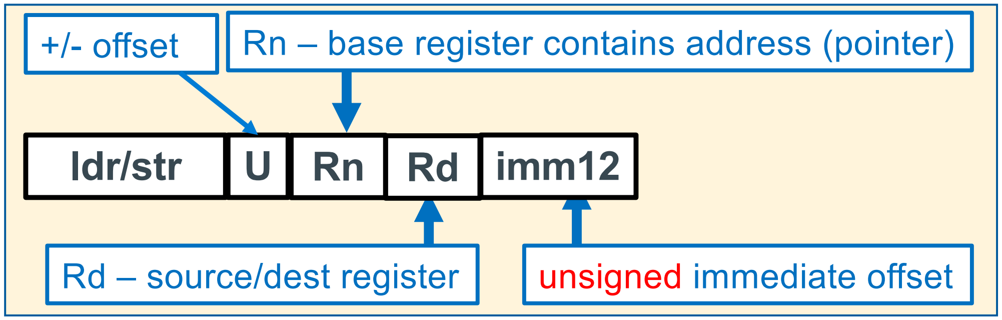


r1 is being used as a **pointer** to a location in memory

str requires the use of a pointer operand

x

LDR/STR – Base Register + Immediate Offset Addressing

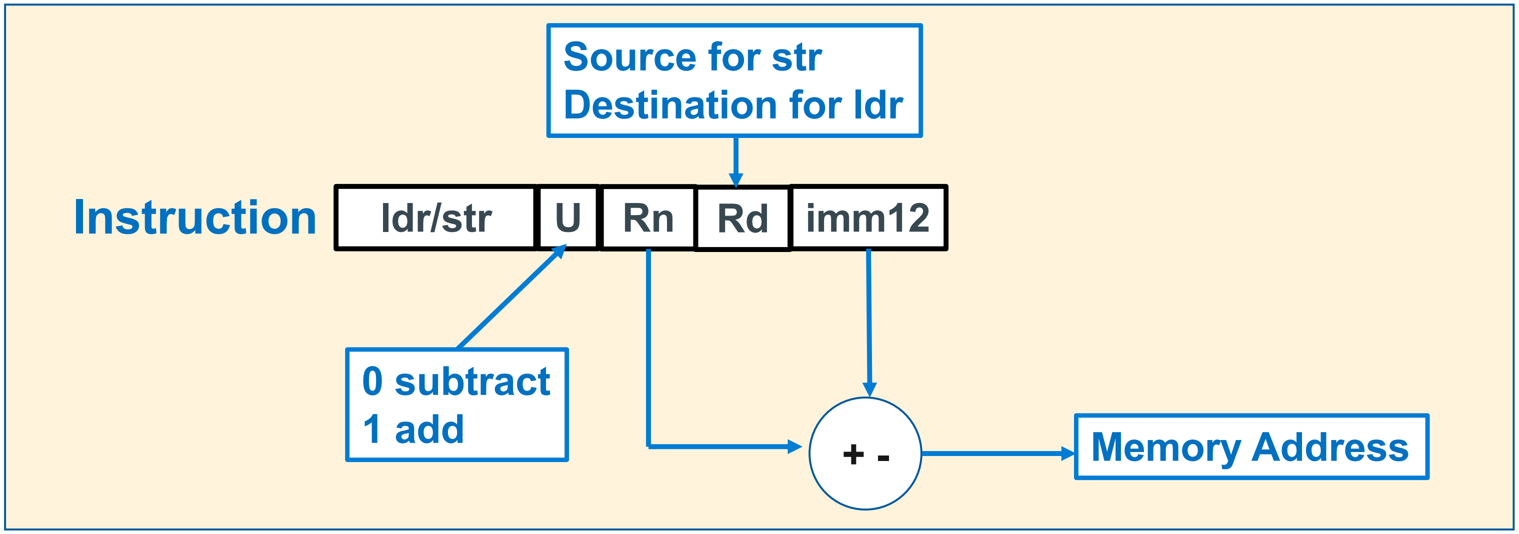

+/- offset
Rn – base register contains address (pointer)
ldr/str
U
Rn
Rd
imm12
Rd – source/dest register
unsigned immediate offset

- **Register Base Addressing**:
  - Pointer Address: Rn; source/destination data: Rd
  - **Unsigned pointer address** in stored in the base register
- **Register Base + immediate offset Addressing:**
  - Pointer Address = register content + immediate offset
  - Unsigned offset integer immediate value (bytes) is added or subtracted (U bit above says to add or subtract) from the pointer address in the base register

```
ldr/str  Rd,  [Rn, +- imm12] // base register pointer + offset  imm12 in bytes
                             -4095 <= imm12 <= 4095 (bytes)
ldr/str  Rd,  [Rn]           // base register pointer + 0 offset (imm12 is 0)
```

x

ldr/str Register Base and Register + Immediate Offset Addressing



Source for str
Destination for ldr

Instruction

ldr/str	U	Rn	Rd	imm12

0 subtract
1 add

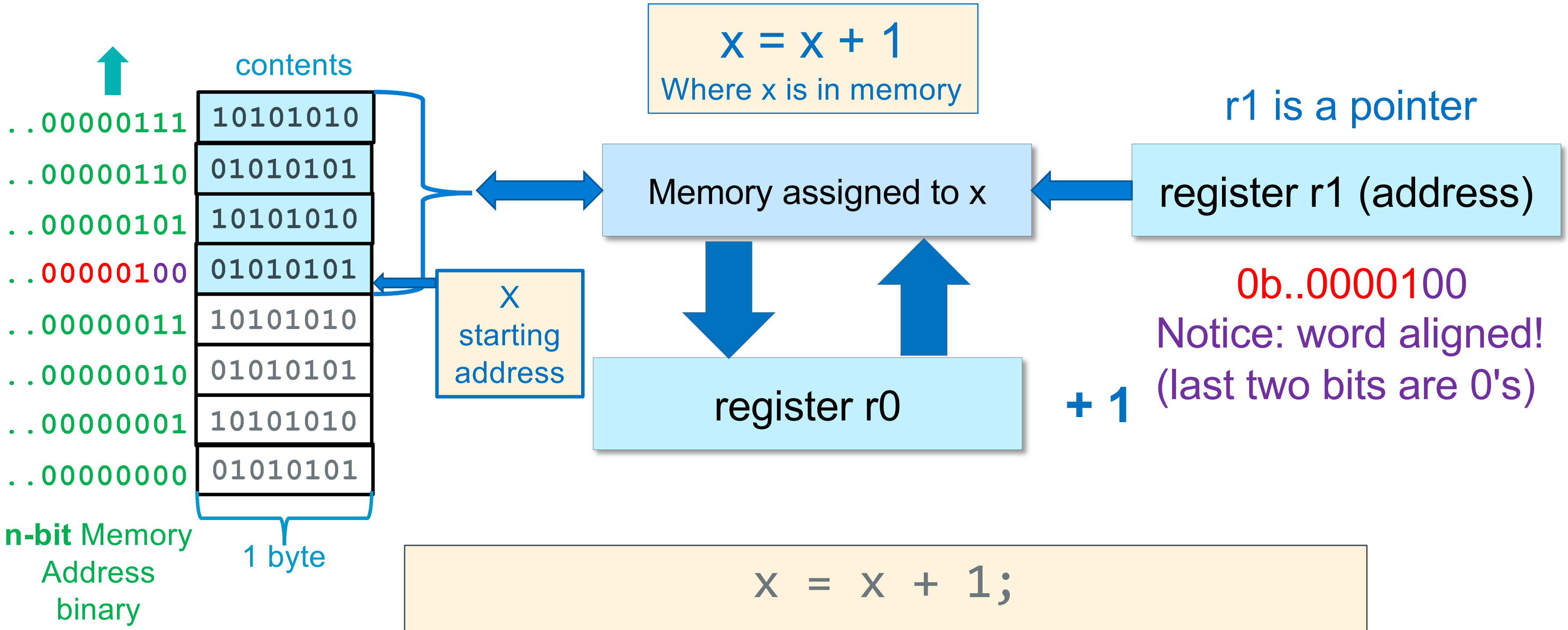
+ -

Memory Address

Syntax	Address	Examples
ldr/str Rd, [Rn +/- constant]	Rn + or – constant	ldr r0, [r5,100]
constant is in bytes	same →	str r1, [r5, 0]
		str r1, [r5]

x

Example Base Register Addressing Load – Modify – Store



x = x + 1
Where x is in memory

r1 is a pointer

n-bit Memory Address binary	contents
..00000111	10101010
..00000110	01010101
..00000101	10101010
..00000100	01010101
..00000011	10101010
..00000010	01010101
..00000001	10101010
..00000000	01010101

1 byte

x starting address

Memory assigned to x

register r1 (address)

register r0

+ 1

0b..0000100
Notice: word aligned!
(last two bits are 0's)

```
              x = x + 1;
ldr r0, [r1]          // r0 = *r1 (read x)
add r0, r0, 1         // r0 = r0 + 1 (x++)
str r0, [r1]          // *r1 = r0 write x
```

x

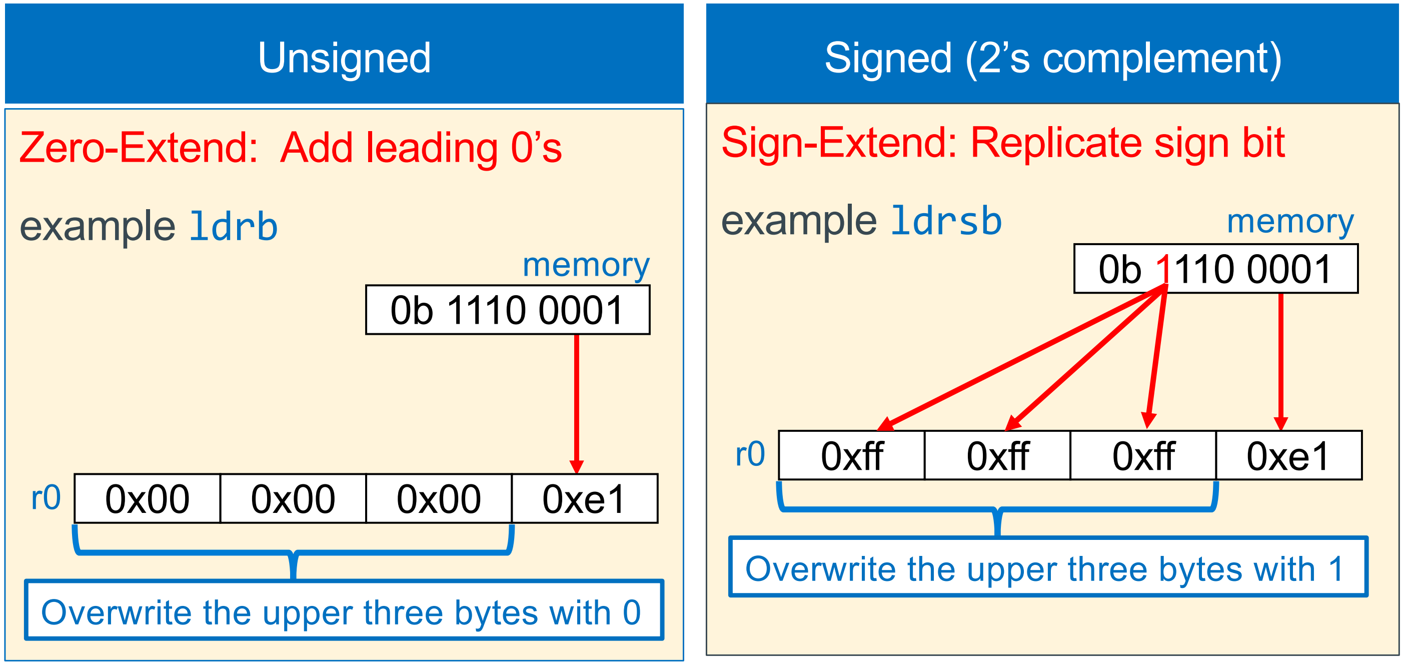
Loading and Storing: Variations List

- Load and store have variations that move 8-bits, 16-bits and 32-bits
- Load into a register with less than 32-bits will set the upper bits not filled from memory differently depending on which variation of the load instruction is used
- Store will only select the lower 8-bit, lower 16-bits or all 32-bits of the register to copy to memory, register contents are not altered

Instruction	Meaning	Sign Extension	Memory Address Requirement
`ldrsb`	load signed byte	sign extension	none (any byte)
`ldrb`	load unsigned byte	zero fill (extension)	none (any byte)
`ldrsh`	load signed halfword	sign extension	halfword (2-byte aligned)
`ldrh`	load unsigned halfword	zero fill (extension)	halfword (2-byte aligned)
`ldr`	load word	---	word (4-byte aligned)
`strb`	store low byte (bits 0-7)	---	none (any byte)
`strh`	store halfword (bits 0-15)	---	halfword (2-byte aligned)
`str`	store word (bits 0-31)	---	word (4-byte aligned)

x

Loading 32-bit Registers From Memory Variables < 32-Bits Wide



Unsigned

Zero-Extend: Add leading 0's

example `ldrb`

Overwrite the upper three bytes with 0

Signed (2's complement)

Sign-Extend: Replicate sign bit

example `ldrsb`

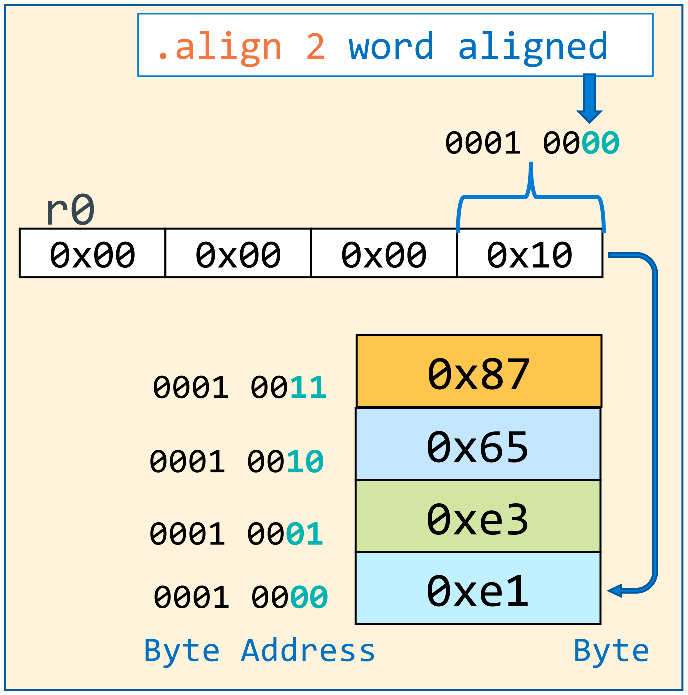
Overwrite the upper three bytes with 1

Instructions that zero-extend:
ldrb, ldrh

Instructions that sign-extend:
ldrsb, ldrsh

x

Load a Byte, Half-word, Word



.align 2 word aligned

0001 0000

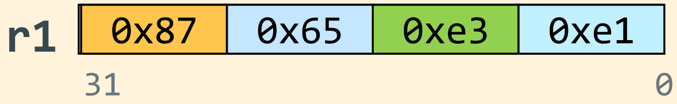
r0

0x00	0x00	0x00	0x10

Byte Address	Byte
0001 0011	0x87
0001 0010	0x65
0001 0001	0xe3
0001 0000	0xe1

Load a word

```
ldr  r1, [r0]
```

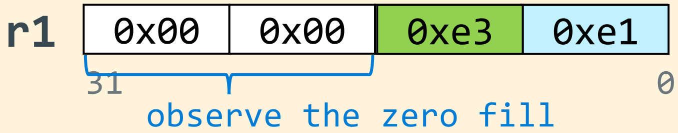


r1

0x87	0x65	0xe3	0xe1

Load a halfword

```
ldrh  r1, [r0]
```



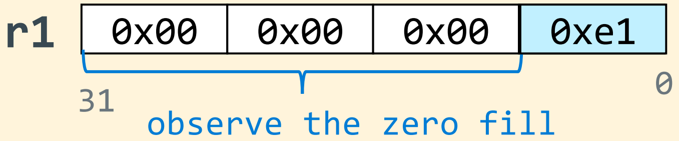
r1

0x00	0x00	0xe3	0xe1

observe the zero fill

Load a byte

```
ldrb  r1, [r0]
```

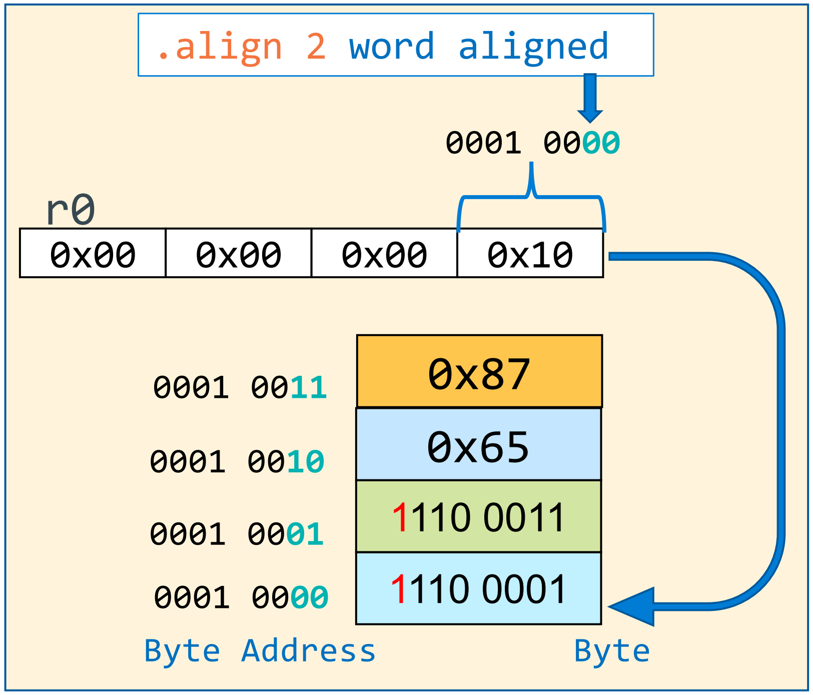


r1

0x00	0x00	0x00	0xe1

observe the zero fill

Signed Load a Byte, Half-word, Word



.align 2 word aligned

0001 0000

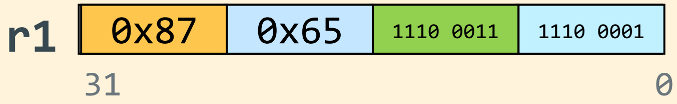
r0

0x00 0x00 0x00 0x10

Byte Address	Byte
0001 0011	0x87
0001 0010	0x65
0001 0001	1110 0011
0001 0000	1110 0001

Load a word (no change)

```
ldr  r1, [r0]
```

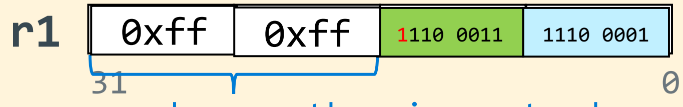


r1 0x87 0x65 1110 0011 1110 0001

31 0

Load a halfword

```
ldrsh  r1, [r0]
```



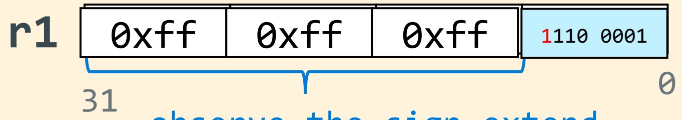
r1 0xff 0xff 1110 0011 1110 0001

31 0

observe the sign extend

Load a byte

```
ldrsb  r1, [r0]
```



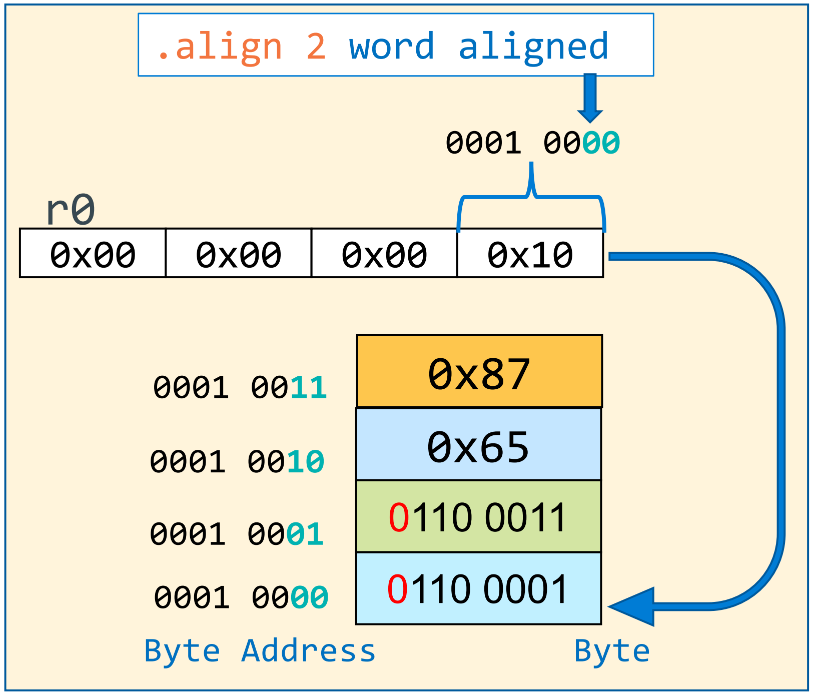
r1 0xff 0xff 0xff 1110 0001

31 0

observe the sign extend

x

Signed Load a Byte, Half-word, Word



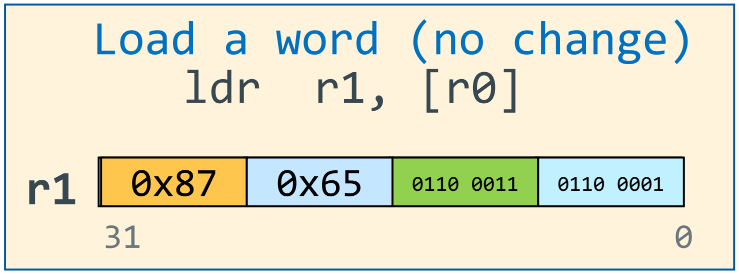
.align 2 word aligned

0001 0000

r0

0x00	0x00	0x00	0x10

Byte Address	Byte
0001 0011	0x87
0001 0010	0x65
0001 0001	0110 0011
0001 0000	0110 0001



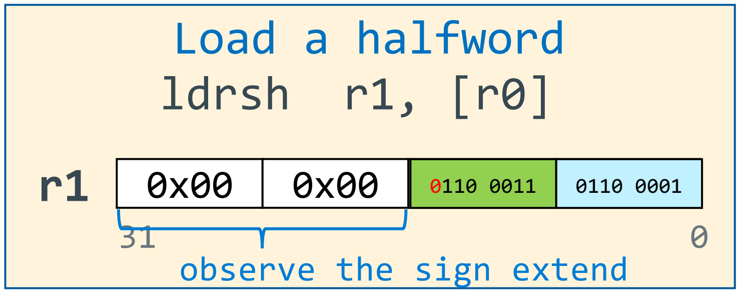
Load a word (no change)

```
ldr  r1, [r0]
```

r1

0x87	0x65	0110 0011	0110 0001

31 0



Load a halfword

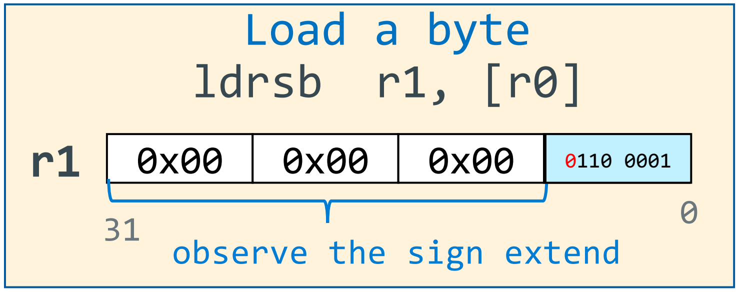
```
ldrsh  r1, [r0]
```

r1

0x00	0x00	0110 0011	0110 0001

31 0

observe the sign extend



Load a byte

```
ldrsb  r1, [r0]
```

r1

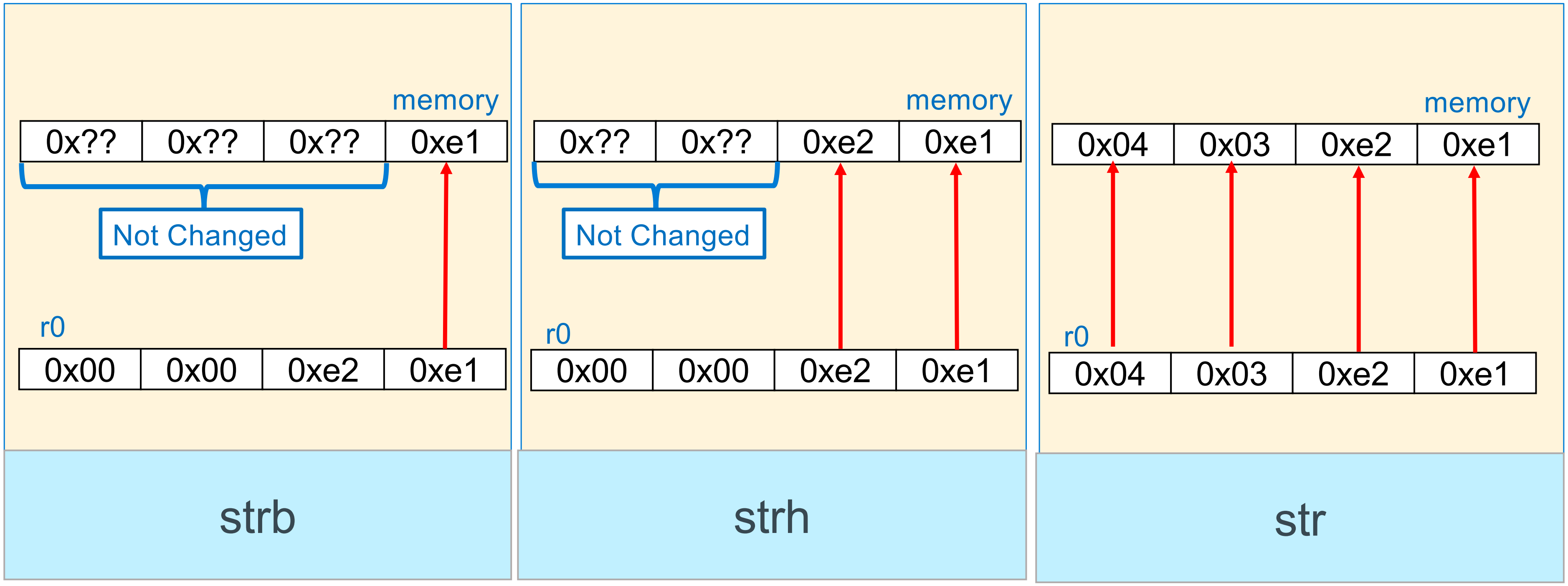
0x00	0x00	0x00	0110 0001

31 0

observe the sign extend

x

Storing 32-bit Registers To Memory 8-bit, 16-bit, 32-bit



memory

0x?? | 0x?? | 0x?? | 0xe1

Not Changed

r0

0x00 | 0x00 | 0xe2 | 0xe1

strb

memory

0x?? | 0x?? | 0xe2 | 0xe1

Not Changed

r0

0x00 | 0x00 | 0xe2 | 0xe1

strh

memory

0x04 | 0x03 | 0xe2 | 0xe1

r0

0x04 | 0x03 | 0xe2 | 0xe1

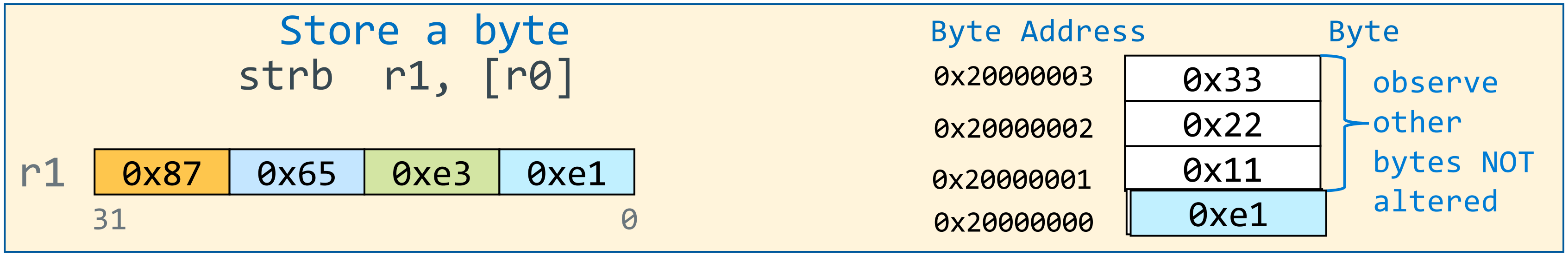
str

x

Store a Byte, Half-word, Word

initial value in r0

0x20	0x00	0x00	0x00



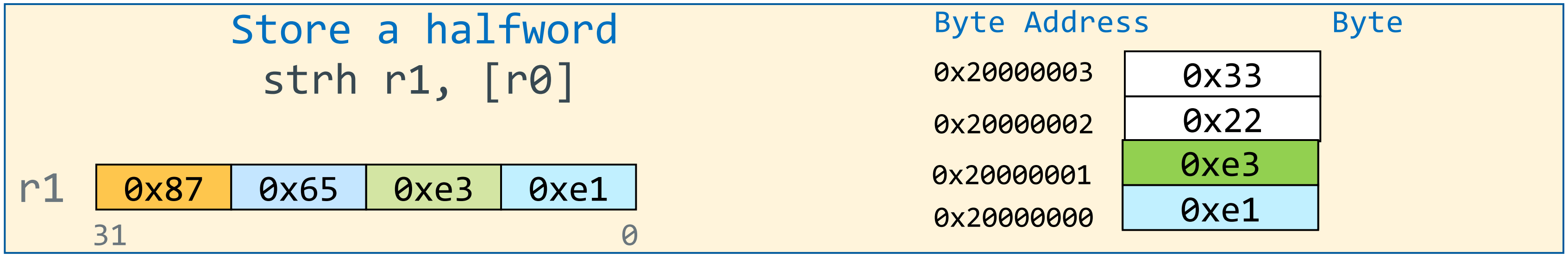
Store a byte

```
strb  r1, [r0]
```

r1	0x87	0x65	0xe3	0xe1
	31			0

Byte Address	Byte
0x20000003	0x33
0x20000002	0x22
0x20000001	0x11
0x20000000	0xe1

observe other bytes NOT altered

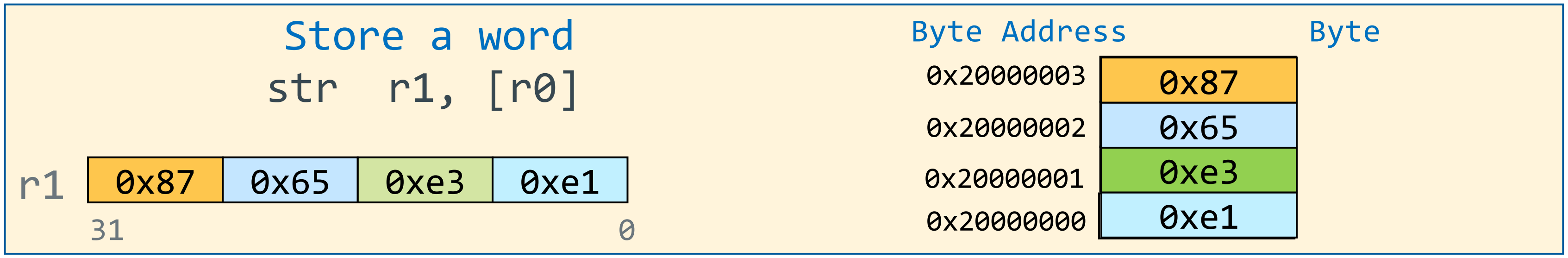


Store a halfword

```
strh r1, [r0]
```

r1	0x87	0x65	0xe3	0xe1
	31			0

Byte Address	Byte
0x20000003	0x33
0x20000002	0x22
0x20000001	0xe3
0x20000000	0xe1



Store a word

```
str  r1, [r0]
```

r1	0x87	0x65	0xe3	0xe1
	31			0

Byte Address	Byte
0x20000003	0x87
0x20000002	0x65
0x20000001	0xe3
0x20000000	0xe1

x