Modifying Data Sizes (Casting)

ICS312

Machine-Level and Systems Programming

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Casting

- Statically typed programming languages (C/C++, Java, Rust, Go, etc.) all provide “casting” to convert a value from one type for another
  - Other languages automatically adjust data size/type based on values, e.g., Python, which is both good and bad
- Casting has many uses and is often necessary
  - An external library produces values of some type, and you want to pass them to another external library that expects values of some other type
  - Some method returns a 4-byte integer, but from application logic you know that the value is necessarily between 61 and 80, and you want to pass it as a 1-byte ASCII code to some other method
- Casting can be problematic
  - If you need to cast values all the time in your program, perhaps your design/approach is flawed
  - Casting a lot also prevents the compiler from detecting type errors
  - If you don’t know what you’re doing you will break things because casts can lead to wrong (numerical) results

Casting Integers

- Casting can be implicit or explicit (see next slides)
- Casting can change
    - The size of a value (remove / add bits)
    - The interpretation of a value
- In these lectures notes we only consider casts of values interpreted as integers into values also interpreted as integers
    - To make values smaller / bigger
    - To make signed / unsigned values unsigned / signed
- Let’s start with making values smaller (in number of bits), which is sometimes called *type narrowing*

High-Level Type Narrowing

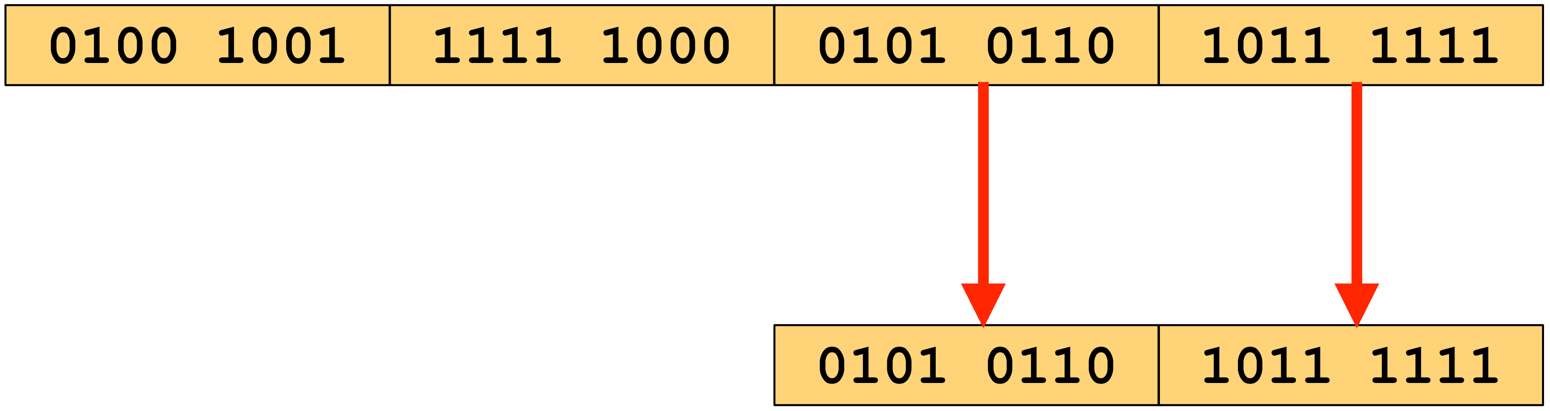
```
int a = 65535;      // 4-byte
short b = a;        // Implicit cast to a 2-byte value
                    // no compiler error/warning
printf("%d\n",b);   // prints ????

int x = -50000;
short y = x;
printf("%d\n",y);   // prints ????
```

```
int a = 65535;
short b = a; // Implicit cast
             // Compiler error: “incompatible types:
             // possible lossy conversion from int to short”

short c = (short)a;     // Explicit cast: no error/warning
System.out.println(c); // prints ???

int x = -50000;
short y = (short)x;
System.out.println(y); // prints ???
```

- The goal will be to figure out what happens here

Type Narrowing: Dropping Bits

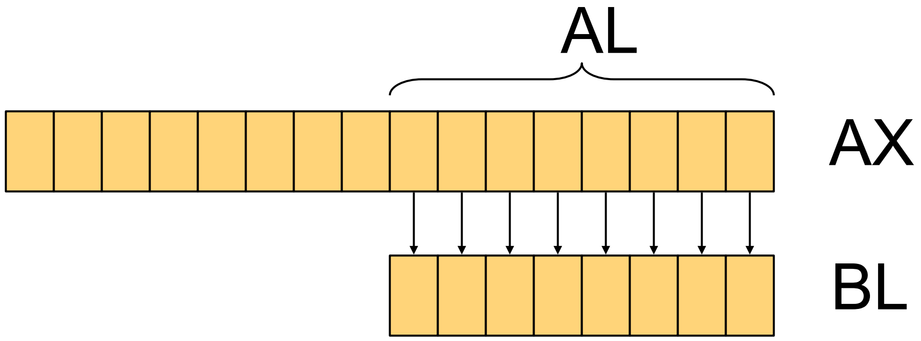
- Type narrowing: drop the most significant byte(s) and keep the least significant byte(s)
- Example: casting from a 4-byte int to a 2-byte int



- How would we do this in assembly?

Type Narrowing in Assembly

- We can use the the fact that we can access lower bits of some registers
- Example:
  - mov AX, [L] ; load 16 bits in AX
  - mov BL, AL ; take the lower 8 bits of AX and puts them in BL



- We have “cast” a 2-byte value into a 1-byte value
- If the 2-byte value is in a register like ESI or EDI, then we’d have to move the value into a register where we can access the lower bytes
- If the 2-byte value is in memory, then we could “just” read the 1-byte value into a 1-byte register (but watch out for Little Endianness!!)

Type Narrowing Correctness?

- When doing type narrowing **one loses bits**, and thus perhaps information
- Based on our signed / unsigned interpretation of the number, then we may get a result that is not equal numerically to the original number
- Let's consider the following 2-byte values, which we cast into 1-byte values:
  - $0051_{16} \Rightarrow 51_{16}$
  - $FFA2_{16} \Rightarrow A2_{16}$
  - $00B1_{16} \Rightarrow B1_{16}$
  - $FF7A_{16} \Rightarrow 7A_{16}$
- Which ones of the above make sense numerically?

Type Narrowing Correctness?

Unsigned		
2-byte	1-byte	
0051 (81_{10})	51 (81_{10})	✓
FFA2 (65442_{10})	A2 (162_{10})	✗
00B1 (177_{10})	B1 (177_{10})	✓
FF7A (65402_{10})	7A (122_{10})	✗

Signed		
2-byte	1-byte	
0051 (81_{10})	51 (81_{10})	✓
FFA2 (-95_{10})	A2 (-95_{10})	✓
00B1 (177_{10})	B1 (-79_{10})	✗
FF7A (-134_{10})	7A (122_{10})	✗

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Values are too large to be encoded with only 8 bits (we lost bits that were set to 1)

We lost mostly “useless” bits, but the remaining sign bit is wrong, so the results is wrongly positive or negative

Two “Rules” to Remember

- For unsigned numbers: size reduction leads to a numerically consistent result if all removed bits are 0

0	0	0	0	0	0	0	0	X	X	X	X	X	X	X	X

X	X	X	X	X	X	X	X

- For signed numbers: size reduction leads to a numerically consistent result if all removed bits are all 0’s or if all removed bits are all 1’s, AND if the highest bit not removed is equal to the removed bits
    - This highest remaining bit is the new sign bit, and thus must be the same as the original sign bit

a	a	a	a	a	a	a	a	a	X	X	X	X	X	X	X

a = 0 or 1

a	X	X	X	X	X	X	X

Type Narrowing in High-Level PLs

```
int a = 65535;          // 4-byte (0x0000FFFF)
short b = a;
printf("%d\n",b);   // prints ????


int x = -50000;         // 4-byte (0xFFFF3CB0)
short y = x;
printf("%d\n",y);   // prints ????
```

- Any ideas?

Type Narrowing in High-Level PLs

```
int a = 65535;       // 4-byte (0x0000FFFF)
short b = a;
printf("%d\n",b);   // prints -1


int x = -50000;      // 4-byte (0xFFFF3CB0)
short y = x;
printf("%d\n",y);   // prints 15536
```

- Same outcome for the Java version (of course!)

Type Widening: Size Increase

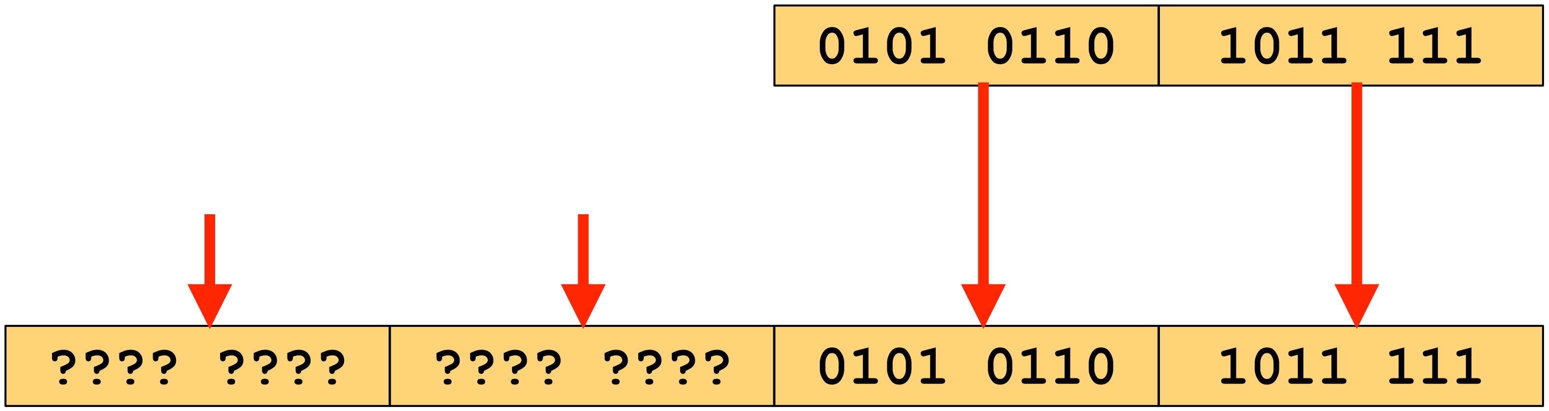
- Sometimes we need to increase the size of values using a cast
- This is called type widening

```
short a = -60;      // 2-byte, signed
int b = a;
printf("%d\n",b);   // prints ????


unsigned short x = 12;    // 2-byte, unsigned
unsigned int y = x;
printf("%d\n",y);   // prints ????
```

Type Widening: Adding Bits

- Type widening: add most significant bits
- Example: casting from a 2-byte int to a 4-byte int

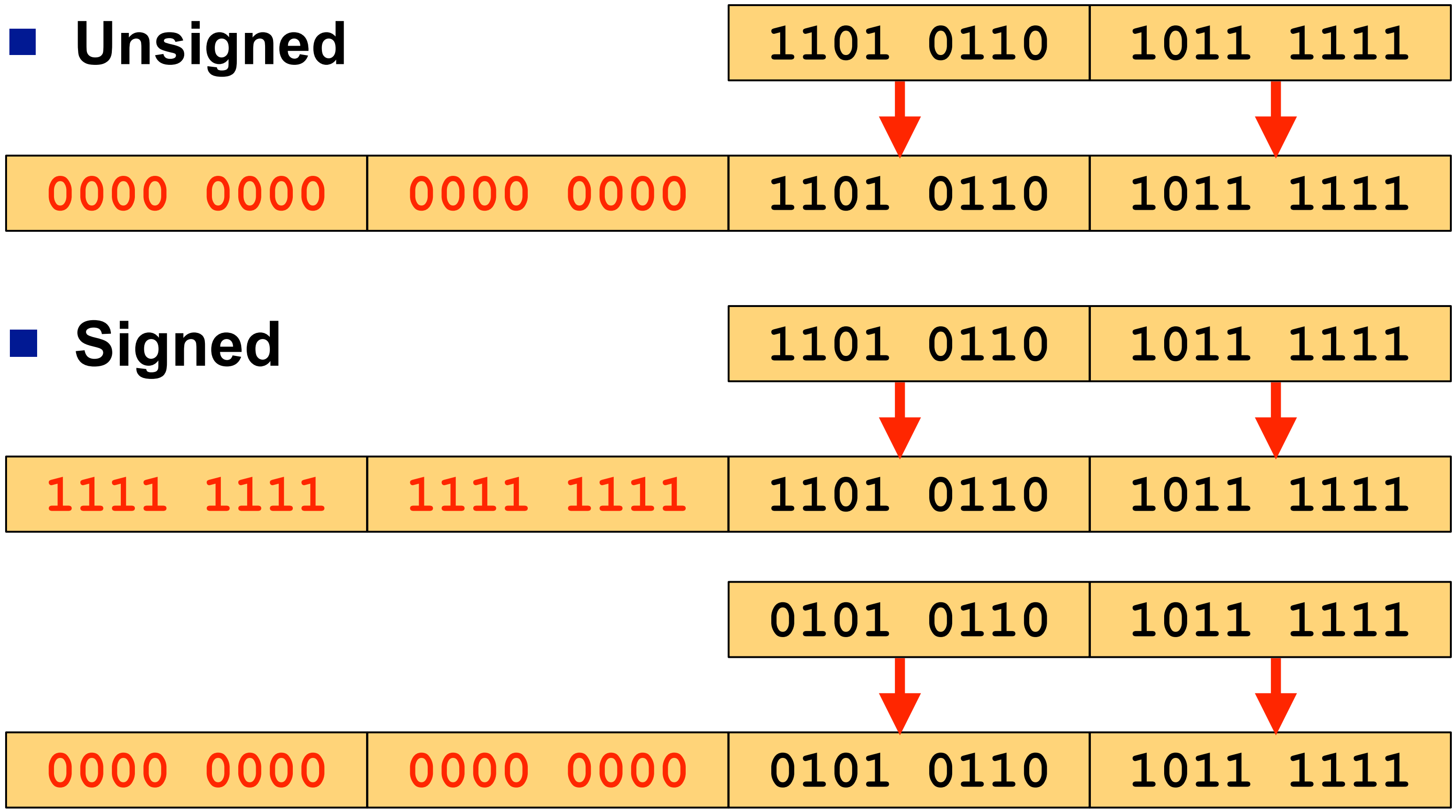


- What should the new bits be?

Unsigned/Signed Type Widening

- **Unsigned** quantities: just add a bunch of 0’s
- **Signed** quantities: perform sign extension
  - Add a bunch of replicas of the sign bit

- **Unsigned**
- **Signed**



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- **Signed** quantities: perform sign extension
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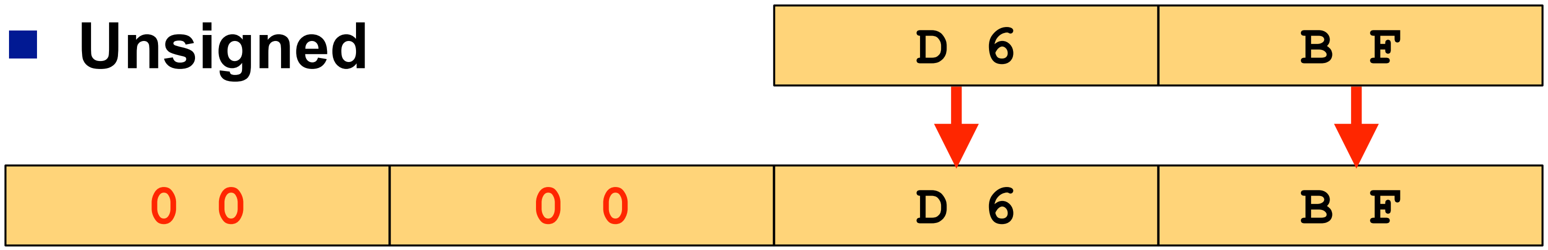
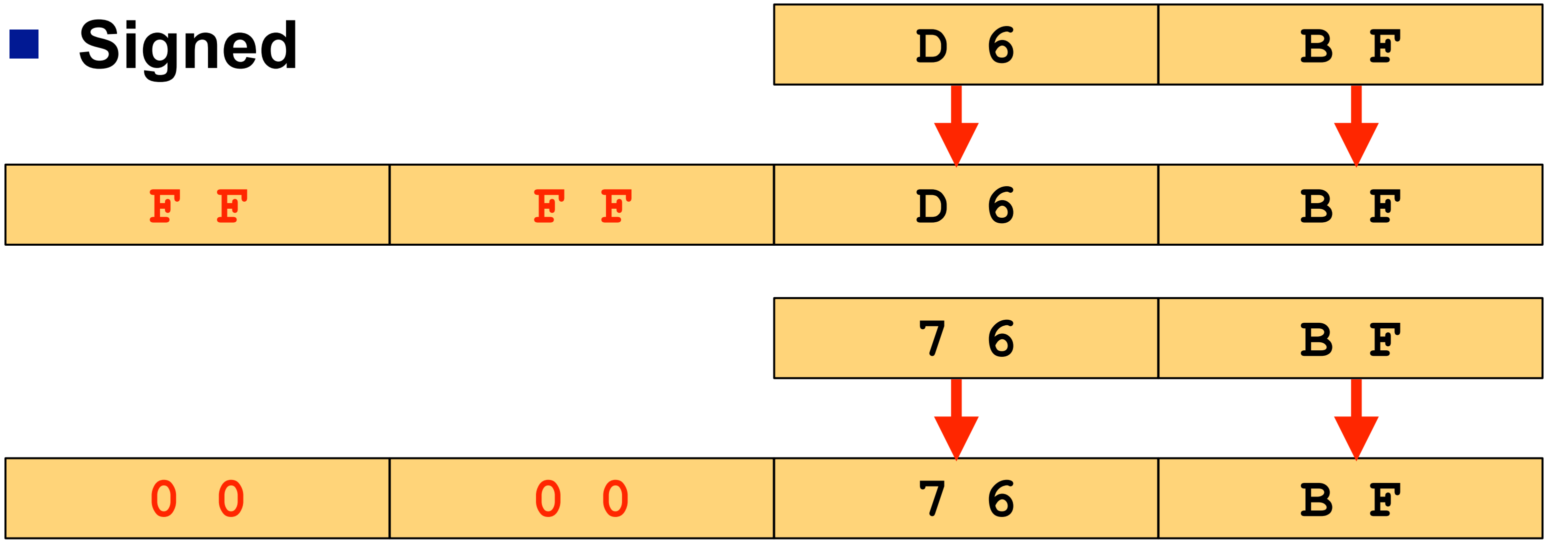
- **Unsigned**

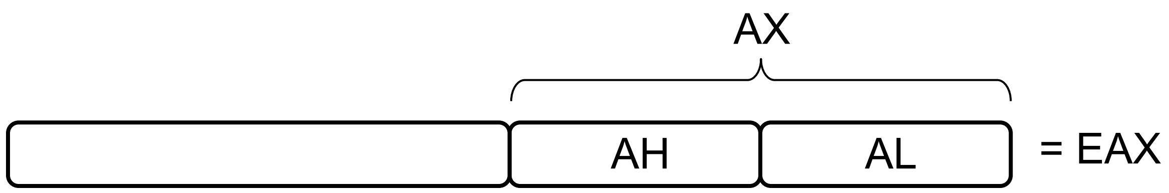


- **Signed**



Unsigned Type Widening in Assembly

- To increase a 1-byte value into a 2-byte value, one can play a trick:
  - Put the 1-byte value into AL, set AH to 0, AX now contains the 2-byte value
- But not for casting a 2-byte value into a 4-byte value: there is no way to access the 16 high bit of register eax separately!



- There is an instruction called `movzx` (Zero eXtend), which takes two operands:
  - Destination: 16- or 32-bit register
  - Source: 8- or 16-bit register, or 1 byte in memory, or 1 word in memory
  - The destination must be larger than the source!

Using movzx

- `movzx eax, ax ; zero extends ax into eax`
- `movzx eax, al ; zero extends al into eax`
- `movzx ax, al  ; zero extends al into ax`
- `movzx ebx, ax ; zero extends ax into ebx`
- `movzx ebx, [L]; leads to a "size not specified" error`

- `movzx ebx, byte [L] ; zero extends 1-byte value at address L into ebx`
- `movzx eax, word [L] ; zero extends 2-byte value at address L into eax`

Signed Type Widening in Assembly

- There is no (easy) way to use **`mov`** or **`movzx`** instructions to increase the size of signed numbers, because of the needed sign extension
  - Sometimes we want to add 0's (like **`movzx`**), but sometimes we want to add 1's (unlike **`movzx`**)
- For this reason, we have a new instruction: **`movsx`** (Sign eXtend)
  - Works just like **`movzx`**, but does sign extension
- Let's see an example..

Example

```
mov al, 0A7h ; as a programmer, I view this
             ; as an unsigned, 1-byte
             ; quantity (decimal 167)

mov cl, 0A7h ; as a programmer, I view this
             ; as a signed 1-byte
             ; quantity (decimal -89)

movzx eax, al ; extend to a 4-byte value
              ; (000000A7)
movsx ebx, cl ; extend to a 4-byte value
              ; (FFFFFFA7)
```

In-class Exercise

- Consider the following code

```
mov      al, 0B2h
movsx    eax, al
mov      bx, ax
movzx    ebx, bx
```

- What’s the final value of eax?
- What’s the final value of ebx?

In-class Exercise Solution

		EAX				EBX			
`mov`	`al, 0B2h`	??	??	??	B2	??	??	??	??
`movsx`	`eax, al`	FF	FF	FF	B2	??	??	??	??
`mov`	`bx, ax`	FF	FF	FF	B2	??	??	FF	B2
`movzx`	`ebx, bx`	FF	FF	FF	B2	00	00	FF	B2

Type Widening in High-Level PLs

```
short a = -60;      // 0xFFC4
int b = a;
printf("%d\n",b);  // prints ????


unsigned short x = 12; // 0x000C
unsigned int y = x;
printf(“%d\n",y);  // prints ????
```

- Any ideas?

Type Widening in High-Level PLs

The compiler will generate a **movsx** instruction

```
short a = -60;     // 0xFFC4
int b = a;
printf("%d\n",b);   // prints -60 (0xFFFFFFC4)
```

The compiler will generate a **movzx** instruction

```
unsigned short x = 12; // 0x000C
unsigned int y = x;
printf(“%d\n",y);   // prints 12 (0x0000000C)
```

Another Example

```
unsigned char uchar = 0xFF;
signed char schar = 0xFF;
int a = uchar;
int b = schar;

printf("%d\n",a);   // prints ????
printf("%d\n",b);   // prints ????
```

- Any ideas?

Another Example

```
unsigned char uchar = 0xFF;
signed char schar = 0xFF;
int a = uchar;
int b = schar;

printf("%d\n",a);   // prints 255
printf("%d\n",b);   // prints -1
```

The compiler with generate a **movzx** instruction

The compiler with generate a **movsx** instruction

How `printf` works

- By declaring variables as “signed” or “unsigned” you define which of **`movsx`** or **`movzx`** will be used for type widening
  - This happens when you do an implicit or explicit cast
- It also happens with **`printf`**
- Say you pass a n-byte argument x to **`printf`**, and that you print it using some “%X” format string
- What **`printf`** does is:
  - If “%X” is for a larger data size, then printf uses **`movzx`** or **`movsx`** to cast the value to a larger size
  - Then the number is printed based on the “%X” format string, **regardless** of how it was declared
- Good luck understanding this if you have never studied assembly at all…
- Let’s see a few examples…

Understanding `printf`

```
unsigned char uc = 0xA0; // hex
printf(“%d\n”, uc); // prints 160
```

- The argument to **`printf`** is a 1-byte value
- The format string “%d” is for a 4-byte value
- So **`printf`** will increase the size to a 4-byte value
- Variable **`uc`** is declared as an unsigned value
- So the size increase will be done using **`movzx`**
- So the hex value will be 00 00 00 A0
- **`printf`** then interprets this value as a signed value (since the format string is “%d” and not “%u”)
- So so, the above prints 160

Understanding `printf`

```
signed char sc = 0xA0; // hex
printf("%u\n", sc); // prints a large >0 number
```

- The argument to **`printf`** is a 1-byte value
- The format string "%u" is for a 4-byte value
- So **`printf`** will increase the size to a 4-byte value
- Variable **`uc`** is declared as a signed value
- So the size increase will be done using **`movsx`**
- So the hex value will be FF FF FF A0
- **`printf`** then interprets this value as an unsigned value (since the format string is "%u" and not "%d")
- So the above prints some huge number (4294967200)

In-Class Exercise

```
unsigned short us = 259; // 0x0103
signed short ss = -45; // 0xFFD3

printf("%d %d\n", us, ss);  // prints ????
printf("%u %u\n", us, ss);  // prints ????
```

- What does the above print?

Solution

```
unsigned short us = 259; // 0x0103
signed short ss = -45; // 0xFFD3

printf(“%d %d\n”, us, ss);  // 259 -45
printf(“%u %u\n”, us, ss);  // 259 4294967251
```

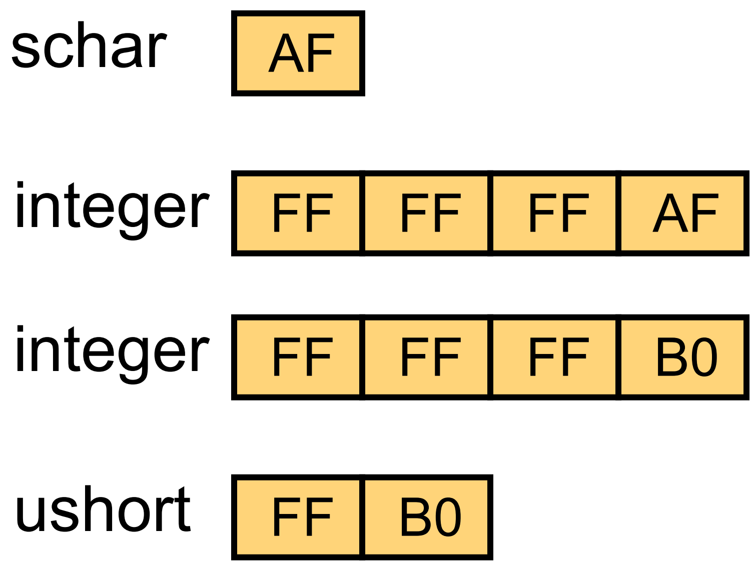
A “kitchen sink” example

```
unsigned short ushort; // 2-byte quantity
signed char schar;     // 1-byte quantity
int integer;           // 4-byte quantity

schar = 0xAF;
integer = (int) schar;
integer++;
ushort = integer;

printf(“%d\n”, ushort);  // prints ????
```

- What does this code print?
  - Or what’s the hex value of the value it prints?
- Let’s do this together…

A “kitchen sink” example

```
unsigned short ushort;
signed char schar;
int integer;

schar = 0xAF;

integer = (int) schar;

integer++;

ushort = integer;

printf(“%d\n”, ushort);
```



Because **`printf`** doesn’t specify “h” ushort is size augmented to 4-bytes using **`movzx`** (because declared as unsigned): 00 00 FF B0
The number is then printed as a signed integer (“%d”): 65456

More Signed/Unsigned in C

- On page 32 of the textbook there is an interesting example about the use of the fgetc() function
  - fgetc reads a 1-byte character from a file but returns it as a 4-byte quantity!
- This is a good example of how understanding low-level details can be necessary to understand high-level constructs
- Let’s go through the example...

The Trouble with `fgetc`

- The `fgetc` function in the standard C I/O library takes as argument a file opened for reading, and returns a character, i.e., an ASCII code
- This function is often used to read in all characters of the file
- The prototype of the function is:

```
int fgetc(FILE *)
```

- One may have expected for `fgetc` to return a char rather than an int, since it's used to "get a character"
- But if the end of the file is reached, `fgetc` returns a special value called `EOF` (End Of File)
    - Typically defined to be -1 (`#define EOF -1`)
- So `fgetc` returns either
    - A character zero-extended into a 4-byte int (i.e., 000000xx), or
    - Integer -1 (i.e., FFFFFFFF)

The Trouble with `fgetc`

- Buggy code to compute the sum of ASCII codes in a text file:

```
char c;
while ((c = fgetc(file)) != EOF) {
        sum += c;
}
```

- In this code we have mistakenly declared c as a char
- C being C (and not Java), it thinks we know what we're doing and does a type narrowing of a 4-byte int into a 1-byte char when doing the assignment into **`c`**
- Let's say we just read in a character with ASCII code FF (decimal 255, "ÿ")
- **`fgetc`** returned 000000FF, but it was truncated into 1-byte integer **`c=0xFF`**
  - FF is -1 in decimal
- So we then compare 1-byte value FF to 4-byte value FFFFFFFF
  - C allows comparing signed integer values of different byte sizes, for convenience, by internally sign-extending the shorter value
    - **`int x=-1; char y=-1;  // (x == y) returns TRUE`**
  - So FF is sign-extended into FFFFFFFF
- Therefore, the above code will "miss" all characters after ASCII code FF and mistake them for an end of file
- Solution: declare **`c`** as an **`int`** (which may seem counter-intuitive)

Example: Type Widening Bug

- If you search around, you'll find bug reports about type widening pretty frequently
- For instance, https://unspecified.wordpress.com/2011/08/08/integer-conversions-in-c/
- Last paragraph is particularly illuminating
  - There's an implicit type widening of a signed char, that then can add a bunch of 1's when the intent was to always add a bunch of 0's
- This bug was for a popular password encryption library, which weakens its security
  - "This can result in passwords being even easier to crack than expected. This is due to a char signedness bug in crypt_blowfish."
- There are many more recent examples out there
  - https://sourceforge.net/p/perfmon2/bugs/11/
  - "I was able to squelch the error by adding a cast everywhere: = (unsigned long) -1;"

Should you care?

- It all depends of what kind of work you do and what kind of software you deal with
  - Some codes will have stuff like that all over with signed/ unsigned declarations and casts galore
  - Some codes will have none of that ever
- If all you do is JavaScript Web app development, you likely will rarely care
- If you do lower-level development, you may care every single day
  - Or rather, if you don’t know all this, your life will be very difficult for understanding, debugging, etc.
- Overall, it’s pretty rare to completely avoid it for your entire life
  - In part due to binary data formats used all over the place

Important Takeaways

- Casting is often needed but is a bit “sketchy” and shouldn’t be overly used
- It can be used for decreasing data size (type narrowing)
  - Just drop bits
  - For unsigned values, correct if dropping only zeros
  - For signed values, correct if dropping only all zeros or all ones, without changing the sign of the value
- It can be used for increasing data size (type widening)
  - Implemented via **`movzx`** or **`movsx`** instructions for unsigned or signed values
  - The compilers of high-level languages translate explicit/ implement tasks into **`movzx`** and **`movsx`** instructions
- Printf is more complicated than you think :)

Conclusion

- Being aware of data sizes and of data size extension/reduction behaviors is important when doing lower-level development
- Unfortunately, almost every developer at some point is confronted with data size issues and having studied a bit of assembly is the only way to resolve mysteries
  - Important to know that a cast isn’t magical, and can do the "wrong” thing
- Let’s look at some of the practice problems…