CS429: Computer Organization and Architecture
Integers

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Topics of this Slideset

- Numeric Encodings: Unsigned and two’s complement
- Programming Implications: C promotion rules
- Basic operations:
  - addition, negation, multiplication
  - Consequences of overflow
  - Using shifts to perform power-of-2 multiply/divide
Assume a machine with 32-bit, two’s complement integers.

For each of the following, either:

- Argue that is true for all argument values;
- Give an example where it’s not true.

\[
\begin{align*}
&\text{x < 0} \quad \rightarrow \quad ((x*2) < 0) \\
&\text{ux >= 0} \quad \rightarrow \quad (x\ll30) < 0 \\
&(x & 7) == 7 \quad \rightarrow \quad (x\ll30) < 0 \\
&\text{ux > -1} \\
&\text{x > y} \quad \rightarrow \quad -x < -y \\
&\text{x * x >= 0} \\
&\text{x > 0 && y > 0} \quad \rightarrow \quad x + y > 0 \\
&\text{x >= 0} \quad \rightarrow \quad -x <= 0 \\
&\text{x <= 0} \quad \rightarrow \quad -x >= 0
\end{align*}
\]
Assume we have a \( w \) length bit string \( X \).

**Unsigned:** \( B2U_w(X) = \sum_{i=0}^{w-1} X_i \times 2^i \)

**Two’s complement:** \( B2T_w(X) = -X_{w-1} \times 2^{w-1} + \sum_{i=0}^{w-2} X_i \times 2^i \)

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>15213</td>
<td>3B 6D</td>
<td>00111011 01101101</td>
</tr>
<tr>
<td>-15213</td>
<td>C4 93</td>
<td>11000100 10010011</td>
</tr>
</tbody>
</table>

**Sign Bit:**
For 2’s complement, the most significant bit indicates the sign.
- 0 for nonnegative
- 1 for negative
\[ x = \begin{align*} 15213: & \quad 00111011 \quad 01101101 \\ y = \quad -15213: & \quad 11000100 \quad 10010011 \end{align*} \]

<table>
<thead>
<tr>
<th>Weight</th>
<th>15213</th>
<th>-15213</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>64</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>128</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>256</td>
<td>1</td>
<td>256</td>
</tr>
<tr>
<td>512</td>
<td>1</td>
<td>512</td>
</tr>
<tr>
<td>1024</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2048</td>
<td>1</td>
<td>2048</td>
</tr>
<tr>
<td>4096</td>
<td>1</td>
<td>4096</td>
</tr>
<tr>
<td>8192</td>
<td>1</td>
<td>8192</td>
</tr>
<tr>
<td>16384</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>-32768</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Sum**  \[ \begin{align*} 15213: & \quad 00111011 \quad 01101101 \\ -15213: & \quad 11000100 \quad 10010011 \end{align*} \]
Numeric Ranges

Unsigned Values

UMin = 0 \quad 000\ldots0
UMax = 2^w - 1 \quad 111\ldots1

Two’s Complement Values

TMin = -2^{w-1} \quad 100\ldots0
TMax = 2^{w-1} - 1 \quad 011\ldots1

Values for w = 16

<table>
<thead>
<tr>
<th></th>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMax</td>
<td>65535</td>
<td>FF FF</td>
<td>11111111 11111111</td>
</tr>
<tr>
<td>Tmax</td>
<td>32767</td>
<td>7F FF</td>
<td>01111111 11111111</td>
</tr>
<tr>
<td>Tmin</td>
<td>-32768</td>
<td>80 00</td>
<td>10000000 00000000</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>FF FF</td>
<td>11111111 11111111</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>00 00</td>
<td>00000000 00000000</td>
</tr>
</tbody>
</table>
Values for Different Word Sizes

<table>
<thead>
<tr>
<th>w</th>
<th>8</th>
<th>16</th>
<th>32</th>
<th>64</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMax</td>
<td>255</td>
<td>65,525</td>
<td>4,294,967,295</td>
<td>18,446,744,073,709,551,615</td>
</tr>
<tr>
<td>TMax</td>
<td>127</td>
<td>32,767</td>
<td>2,147,483,647</td>
<td>9,223,372,036,854,775,807</td>
</tr>
<tr>
<td>Tmin</td>
<td>-128</td>
<td>-32,768</td>
<td>-2,147,483,648</td>
<td>-9,223,372,036,854,775,808</td>
</tr>
</tbody>
</table>

Observations

- $|\text{TMin}| = \text{TMax} + 1$
- $\text{UMax} = 2 \times \text{TMax} + 1$

C Programming

```
#include <limits.h>
```

Declares various constants: `ULONG_MAX`, `LONG_MAX`, `LONG_MIN`, etc. The values are platform-specific.
**Equivalence:** Same encoding for nonnegative values

**Uniqueness:**
- Every bit pattern represents a unique integer value
- Each representable integer has unique encoding

**Can Invert Mappings:**
- inverse of $\text{B2U}(X)$ is $\text{U2B}(X)$
- inverse of $\text{B2T}(X)$ is $\text{T2B}(X)$

<table>
<thead>
<tr>
<th>X</th>
<th>B2U(X)</th>
<th>B2T(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0101</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>0111</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1000</td>
<td>8</td>
<td>-8</td>
</tr>
<tr>
<td>1001</td>
<td>9</td>
<td>-7</td>
</tr>
<tr>
<td>1010</td>
<td>10</td>
<td>-6</td>
</tr>
<tr>
<td>1011</td>
<td>11</td>
<td>-5</td>
</tr>
<tr>
<td>1100</td>
<td>12</td>
<td>-4</td>
</tr>
<tr>
<td>1101</td>
<td>13</td>
<td>-3</td>
</tr>
<tr>
<td>1110</td>
<td>14</td>
<td>-2</td>
</tr>
<tr>
<td>1111</td>
<td>15</td>
<td>-1</td>
</tr>
</tbody>
</table>
C allows conversions from signed to unsigned.

```
short int x = 15213;
unsigned short into ux = (unsigned short) x;
short int y = -15213;
unsigned short into uy = (unsigned short) y;
```

**Resulting Values:**

- *The bit representation stays the same.*
- Nonnegative values are unchanged.
- Negative values change into (large) positive values.
Signed vs Unsigned in C

**Constants**
- By default, constants are considered to be signed integers.
- They are unsigned if they have “U” as a suffix: 0U, 4294967259U.

**Casting**
- Explicit casting between signed and unsigned is the same as U2T and T2U:

```c
int tx, ty;
unsigned ux, uy;
int tx = (int) ux;
unsigned uy = (unsigned) ty;
```
- Implicit casting also occurs via assignments and procedure calls:

```c
tx = ux;
uy = ty;
```
Expression Evaluation

- If you mix unsigned and signed in a single expression, signed values implicitly cast to unsigned.
- This includes when you compare using <, >, ==, <=, >=.

<table>
<thead>
<tr>
<th>Const 1</th>
<th>Const 2</th>
<th>Rel.</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0U</td>
<td>==</td>
<td>unsigned</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>&lt;</td>
<td>signed</td>
</tr>
<tr>
<td>-1</td>
<td>0U</td>
<td>&gt;</td>
<td>unsigned</td>
</tr>
<tr>
<td>2147483647</td>
<td>-2147483648</td>
<td>&gt;</td>
<td>signed</td>
</tr>
<tr>
<td>2147483647U</td>
<td>-2147483648</td>
<td>&lt;</td>
<td>unsigned</td>
</tr>
<tr>
<td>-1</td>
<td>-2</td>
<td>&gt;</td>
<td>signed</td>
</tr>
<tr>
<td>(unsigned) 1</td>
<td>-2</td>
<td>&lt;</td>
<td>unsigned</td>
</tr>
<tr>
<td>2147483647</td>
<td>2147483648U</td>
<td>&lt;</td>
<td>unsigned</td>
</tr>
<tr>
<td>2147483647</td>
<td>(int) 2147483648U</td>
<td>&gt;</td>
<td>signed</td>
</tr>
</tbody>
</table>
**Task:** Given a w-bit signed integer $x$, convert it to a $w+k$-bit integer with the same value.

**Rule:** Make $k$ copies of the sign bit:

$$x' = x_{w-1}, \ldots, x_{w-1}, x_{w-2}, \ldots, w_0$$

Why does this work?
short int x = 15213;
int ix = (int) x;
short int y = −15213;
int iy = (int) y;

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</tr>
</thead>
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<tr>
<td>x</td>
<td>15213</td>
<td>3B 6D</td>
<td>00111011 01101101</td>
</tr>
<tr>
<td>ix</td>
<td>15213</td>
<td>00 00 3B 6D</td>
<td>00000000 00000000 00111011 01101101</td>
</tr>
<tr>
<td>y</td>
<td>-15213</td>
<td>C4 93</td>
<td>11000100 10010011</td>
</tr>
<tr>
<td>iy</td>
<td>-15213</td>
<td>FF FF C4 93</td>
<td>11111111 11111111 11000100 10010011</td>
</tr>
</tbody>
</table>

In converting from smaller to larger signed integer data types, C automatically performs sign extension.
Why Use Unsigned?

Don’t use just to ensure numbers are nonzero.

- Some C compilers generate less efficient code for unsigned.

  ```c
  unsigned i;
  for (i=1; i < cnt; i++)
      a[i] += a[i-1]
  ```

- It’s easy to make mistakes.

  ```c
  for (i = cnt-2; i >= 0; i--)
      a[i] += a[i+1]
  ```

Do use when performing modular arithmetic.

- multiprecision arithmetic
- other esoteric stuff

Do use when you need extra bits of range.
Negating Two’s Complement

To find the negative of a number in two’s complement form: complement the bit pattern and add 1:

$$\sim x + 1 = -x$$

**Example:**

$$10011101 = 0x9C = -99_{10}$$

complement:

$$01100010 = 0x62 = 98_{10}$$

add 1:

$$01100011 = 0x63 = 99_{10}$$

Try it with: 11111111 and 00000000.
<table>
<thead>
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<th>Binary</th>
</tr>
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<tbody>
<tr>
<td>x</td>
<td>15213</td>
<td></td>
<td>3B 6D</td>
<td></td>
<td>00111011 01101101</td>
</tr>
<tr>
<td>~x</td>
<td>-15214</td>
<td></td>
<td>C4 92</td>
<td></td>
<td>11000100 10010010</td>
</tr>
<tr>
<td>~x+1</td>
<td>-15213</td>
<td></td>
<td>C4 93</td>
<td></td>
<td>11000100 10010011</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td>00 00</td>
<td></td>
<td>00000000 00000000</td>
</tr>
<tr>
<td>~0</td>
<td>-1</td>
<td></td>
<td>FF FF</td>
<td></td>
<td>11111111 11111111</td>
</tr>
<tr>
<td>~0+1</td>
<td>0</td>
<td></td>
<td>00 00</td>
<td></td>
<td>00000000 00000000</td>
</tr>
</tbody>
</table>
Given two $w$-bit unsigned quantities $u$, $v$, the true sum may be a $w+1$-bit quantity.

Discard the carry bit and treat the result as an unsigned integer.

Thus, unsigned addition implements **modular addition**.

$$UAdd_w(u, v) = (u + v) \mod 2^w$$

$$UAdd_w(u, v) = \begin{cases} 
  u + v & u + v < 2^w \\
  u + v - 2^w & u + v \geq 2^w 
\end{cases}$$
Properties of Unsigned Addition

W-bit unsigned addition is:

- **Closed under addition:**

\[ 0 \leq \text{UAdd}_w(u, v) \leq 2^w - 1 \]

- **Commutative**

\[ \text{UAdd}_w(u, v) = \text{UAdd}_w(v, u) \]

- **Associative**

\[ \text{UAdd}_w(t, \text{UAdd}_w(u, v)) = \text{UAdd}_w(\text{UAdd}_w(t, u), v) \]

- **0 is the additive identity**

\[ \text{UAdd}_w(u, 0) = u \]

- **Every element has an additive inverse**

Let \( \text{UComp}_w(u) = 2^w - u \), then

\[ \text{UAdd}_w(u, \text{UComp}_w(u)) = 0 \]
Given two $w$-bit signed quantities $u$, $v$, the true sum may be a $w+1$-bit quantity.

**Discard the carry bit** and treat the result as a two’s complement number.

$$\text{TAdd}_w(u, v) = \begin{cases} 
    u + v + 2^{w-1} & \text{if } u + v < \text{TMin}_w \text{ (NegOver)} \\
    u + v & \text{if } \text{TMin}_w < u + v \leq \text{TMax}_w \\
    u + v - 2^{w-1} & \text{if } \text{TMax}_w < u + v \text{ (PosOver)} 
\end{cases}$$
TAdd and UAdd have identical bit-level behavior.

```c
int s, t, u, v;
s = (int) ((unsigned) u + (unsigned) v);
t = u + v
```

This will give $s == t$.
Detecting 2’s Complement Overflow

Task:
Determine if \( s = \text{TAdd}_w(u, v) = u + v \).

Claim: We have overflow iff either:
- \( u, v < 0 \) but \( s \geq 0 \) (NegOver)
- \( u, v \geq 0 \) but \( s < 0 \) (PosOver)

Can compute this as:
\[
\text{ovf} = (u<0 == v<0) && (u<0 != s<0);
\]

Why don’t we have to worry about the case where one input is positive and one negative?
TAdd is Isomorphic to UAdd.
This is clear since they have identical bit patterns.

\[ \text{Tadd}_w(u, v) = \text{U2T(UAdd}_w(\text{T2U}(u), \text{T2U}(v))) \]

Two’s Complement under TAdd forms a group.
- Closed, commutative, associative, 0 is additive identity.
- Every element has an additive inverse:
  
  Let \( \text{TComp}_w(u) = \text{U2T(UComp}_w(\text{T2U}(u)) \), then
  
  \[ \text{TAdd}_w(u, \text{UComp}_w(u)) = 0 \]

\[ \text{TComp}_w(u) = \begin{cases} 
  -u & u \neq \text{TMin}_w \\
  \text{TMin}_w & u = \text{TMin}_w 
\end{cases} \]
Computing the exact product of two $w$-bit numbers $x, y$. This is the same for both signed and unsigned.

Ranges:
- Unsigned: $0 \leq x \times y \leq (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$, requires up to $2w$ bits.
- Two’s comp. min: $x \times y \geq (-2^{w-1}) \times (2^{w-1} - 1) = -2^{2w-2} + 2^{w-1}$, requires up to $2w - 1$ bits.
- Two’s comp. max: $x \times y \leq (-2^{w-1})^2 = 2^{2w-2}$, requires up to $2w$ (but only for $TMin_w^2$).

Maintaining the exact result
- Would need to keep expanding the word size with each product computed.
- Can be done in software with “arbitrary precision” arithmetic packages.
Given two $w$-bit unsigned quantities $u$, $v$, the true sum may be a $2w$-bit quantity.

We just discard the most significant $w$ bits, treat the result as an unsigned number.

Thus, unsigned multiplication implements modular multiplication.

$$\text{UMult}_w(u, v) = (u \times v) \mod 2^w$$
Unsigned vs. Signed Multiplication

### Unsigned Multiplication

```c
unsigned ux = (unsigned) x;
unsigned uy = (unsigned) y;
unsigned up = ux * uy;
```

- Truncates product to w-bit number: \( up = \text{UMult}_w(ux, uy) \)
- Modular arithmetic: \( up = (ux \cdot uy) \mod 2^w \)

### Two’s Complement Multiplication

```c
int x, y;
int p = x * y;
```

- Compute exact product of two w-bit numbers \( x, y \).
- Truncate result to w-bit number: \( p = \text{TMult}_w(x, y) \)
Unsigned Multiplication

```c
unsigned ux = (unsigned) x;
unsigned uy = (unsigned) y;
unsigned up = ux * uy;
```

Two’s Complement Multiplication

```c
int x, y;
int p = x * y;
```

Relation

- Signed multiplication gives same bit-level result as unsigned.
- `up == (unsigned) p`
A left shift by \( k \), is equivalent to multiplying by \( 2^k \). This is true for both signed and unsigned values.

\[
\begin{align*}
&u \ll 1 \rightarrow u \times 2 \\
&u \ll 2 \rightarrow u \times 4 \\
&u \ll 3 \rightarrow u \times 8 \\
&u \ll 4 \rightarrow u \times 16 \\
&u \ll 5 \rightarrow u \times 32 \\
&u \ll 6 \rightarrow u \times 64
\end{align*}
\]

Compilers often use shifting for multiplication, since shift and add is much faster than multiply (on most machines).

\[
u \ll 5 - u \ll 3 = u \times 24
\]
Aside: Floor and Ceiling Functions

Two useful functions on real numbers are the *floor* and *ceiling* functions.

**Definition:** The floor function \([r]\), is the greatest integer less than or equal to \(r\).

\[
[3.14] = 3 \\
[-3.14] = -4 \\
[7] = 7
\]

**Definition:** The ceiling function \([r]\), is the smallest integer greater than or equal to \(r\).

\[
[3.14] = 4 \\
[-3.14] = -3 \\
[7] = 7
\]
A right shift by $k$, is (approximately) equivalent to dividing by $2^k$, but the effects are different for the unsigned and signed cases. **Quotient of unsigned value by power of 2.**

\[ u \gg k \equiv \lfloor x/2^k \rfloor \]

Uses logical shift.

<table>
<thead>
<tr>
<th></th>
<th>Division</th>
<th>Computed</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y$</td>
<td>15213</td>
<td>15213</td>
<td>3B 6D</td>
<td>00111011 01101101</td>
</tr>
<tr>
<td>$y \gg 1$</td>
<td>7606.5</td>
<td>7606</td>
<td>1D B6</td>
<td>00011101 10110110</td>
</tr>
<tr>
<td>$y \gg 4$</td>
<td>950.8125</td>
<td>950</td>
<td>03 B6</td>
<td>00000011 10110110</td>
</tr>
<tr>
<td>$y \gg 8$</td>
<td>59.4257813</td>
<td>59</td>
<td>00 3B</td>
<td>00000000 00111011</td>
</tr>
</tbody>
</table>
Signed Divide by Shift

Quotient of signed value by power of 2.

\[ u \gg k = \lfloor x/2^k \rfloor \]

- Uses arithmetic shift. What does that mean?
- Rounds in wrong direction when \( u < 0 \).

<table>
<thead>
<tr>
<th>Division</th>
<th>Computed</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>-15213</td>
<td>-15213</td>
<td>C4 93 11000100 10010011</td>
</tr>
<tr>
<td>y &gt;&gt; 1</td>
<td>-7606.5</td>
<td>-7607</td>
<td>E2 49 11100010 01001001</td>
</tr>
<tr>
<td>y &gt;&gt; 4</td>
<td>-950.8125</td>
<td>-951</td>
<td>FC 49 11111100 01001001</td>
</tr>
<tr>
<td>y &gt;&gt; 8</td>
<td>-59.4257813</td>
<td>-60</td>
<td>FF C4 11111111 11000100</td>
</tr>
</tbody>
</table>
We’ve seen that right shifting a negative number gives the wrong answer because it rounds away from 0.

\[ x \gg k = \lfloor x/2^k \rfloor \]

We’d really like \( \lceil x/2^k \rceil \) instead.

You can compute this as: \( \lfloor (x + 2^k - 1)/2^k \rfloor \). In C, that’s:

\[
(x + (1<<k) - 1) >> k
\]

This biases the dividend toward 0.
Properties of Unsigned Arithmetic

Unsigned multiplication with addition forms a **Commutative Ring**.

- Addition is commutative
- Closed under multiplication
  \[ 0 \leq \text{UMult}_w(u, v) \leq 2^w - 1 \]
- Multiplication is commutative
  \[ \text{UMult}_w(u, v) = \text{UMult}_w(v, u) \]
- Multiplication is associative
  \[ \text{UMult}_w(t, \text{UMult}_w(u, v)) = \text{UMult}_w(\text{UMult}_w(t, u), v) \]
- 1 is the multiplicative identity
  \[ \text{UMult}_w(u, 1) = u \]
- Multiplication distributes over addition
  \[ \text{UMult}_w(t, \text{UAdd}_w(u, v)) = \text{UAdd}_w(\text{UMult}_w(t, u), \text{UMult}_w(t, v)) \]
Properties of Two’s Complement Arithmetic

Isomorphic Algebras

- Unsigned multiplication and addition: truncate to $w$ bits
- Two’s complement multiplication and addition: truncate to $w$ bits

Both form rings isomorphic to ring of integers mod $2^w$

Comparison to Integer Arithmetic

- Both are rings
- Integers obey ordering properties, e.g.
  \[ u > 0 \implies u + v > v \]
  \[ u > 0, v > 0 \implies u \cdot v > 0 \]
- These properties are not obeyed by two’s complement arithmetic.
  \[ T_{\text{Max}} + 1 == T_{\text{Min}} \]
  \[ 15213 \times 30426 == -10030 \] (for 16-bit words)
Assume a machine with 32-bit word size, two’s complement integers.

```c
int x = foo();
int y = bar();
unsigned ux = x;
unsigned uy = y;
```

$x < 0$ → $(x*2) < 0$

- False: TMin
- True: $0 = UMin$

$(x & 7) == 7$ → $(x<<30) < 0$

- True: $x1 = 1$
- False: 0

$ux >= 0$ → $-x < -y$

- False: $-1$, TMin
- True: $xMax$, TMax

$x > y$ → $x + y > 0$

- False: TMax, TMax

$x * x >= 0$ → $-x <= 0$

- False: 30426
- True: -TMax < 0

$x > 0$ && $y > 0$ → $-x >= 0$

- False: TMin

$x >= 0$ → $-x > 0$

- True: -TMax < 0

$x <= 0$ → $-x > 0$

- False: TMin