15-213

"The course that gives CMU its Zip!"

Integer Arithmetic Operations
Jan. 27, 2000

Topics

- **Basic operations**
  - Addition, negation, multiplication
- **Programming Implications**
  - Consequences of overflow
  - Using shifts to perform power-of-2 multiply/divide

C Puzzles

- **Taken from Exam #2, CS 347, Spring '97**
- **Assume machine with 32 bit word size, two's complement integers**
- **For each of the following C expressions, either:**
  - Argue that is true for all argument values
  - Give example where not true

Initialization

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

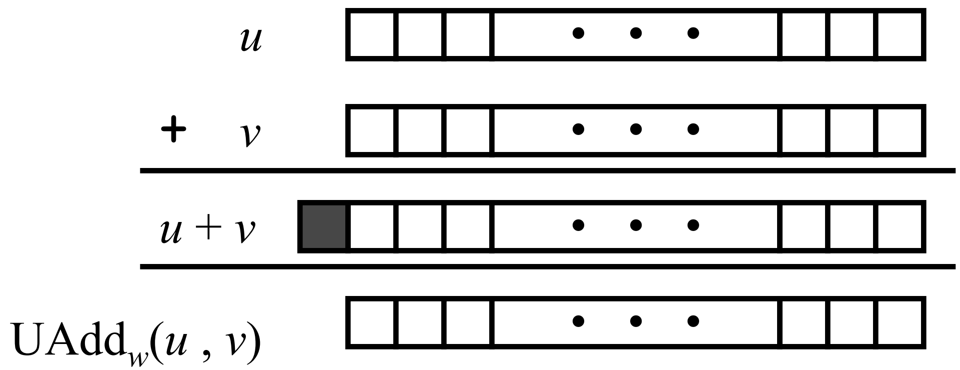
- `x < 0` ⇒ `((x*2) < 0)`
- `ux >= 0`
- `x & 7 == 7` ⇒ `(x<<30) < 0`
- `ux > -1`
- `x > y` ⇒ `-x < -y`
- `x * x >= 0`
- `x > 0 && y > 0` ⇒ `x + y > 0`
- `x >= 0` ⇒ `-x <= 0`
- `x <= 0` ⇒ `-x >= 0`

Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



Standard Addition Function

- **Ignores carry output**

Implements Modular Arithmetic

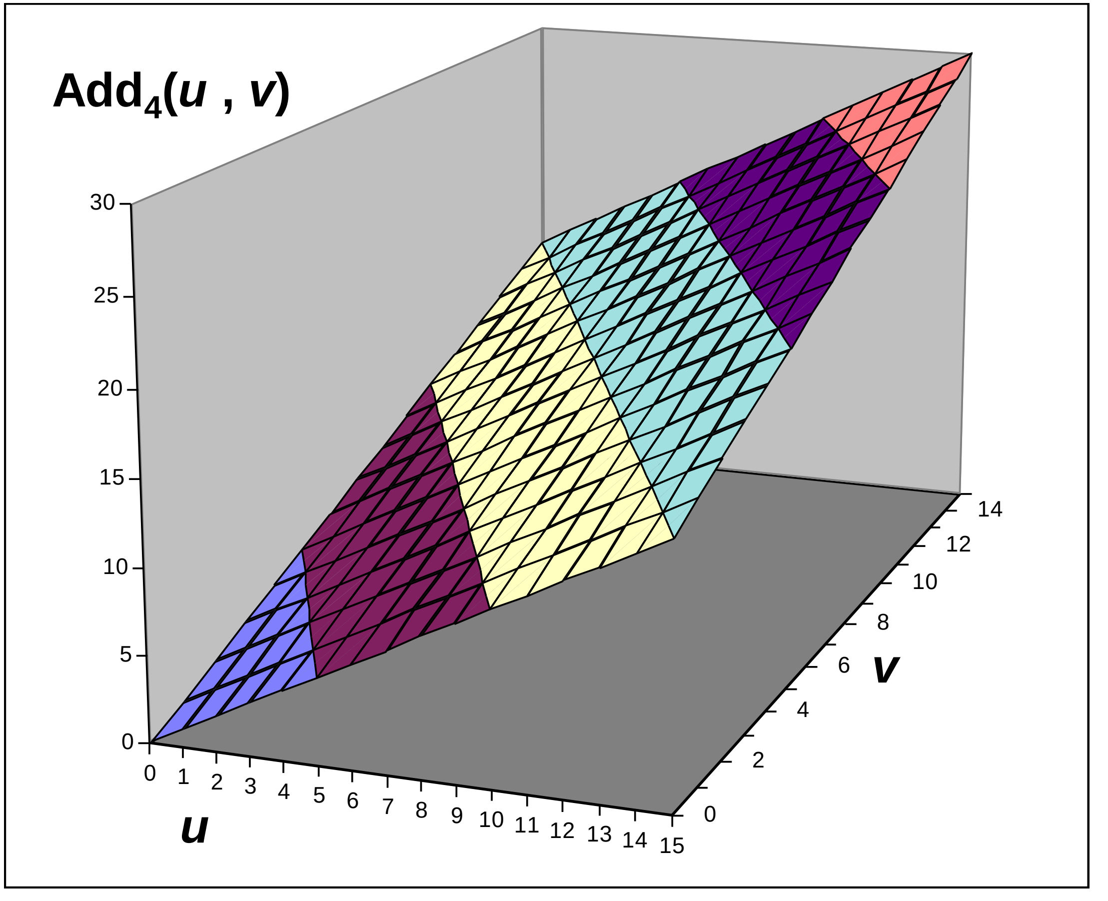
$s \quad = \quad \mathrm{UAdd}_w(u , v) \quad = \quad u + v \mod 2^w$

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

Visualizing Integer Addition

Integer Addition

- **4-bit integers *u* and *v***
- **Compute true sum Add$_4$(*u* , *v*)**
- **Values increase linearly with *u* and *v***
- **Forms planar surface**

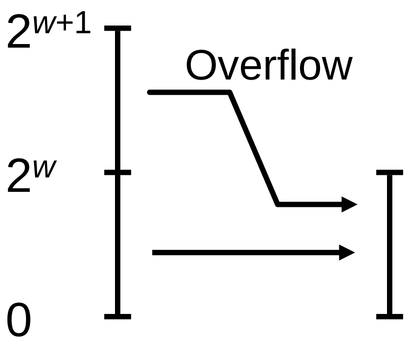


Visualizing Unsigned Addition

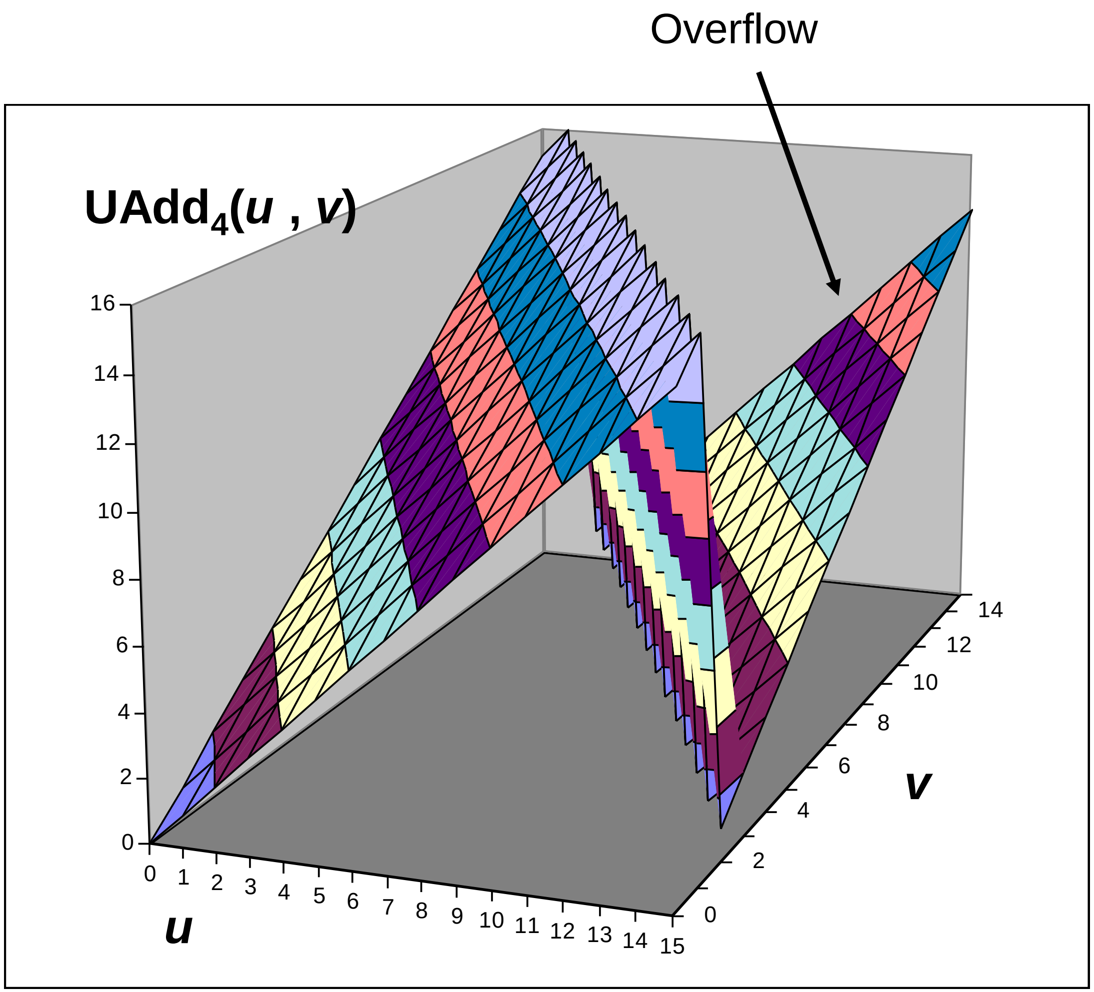
Wraps Around

- If true sum ≥ 2^w
- At most once

True Sum



Modular Sum



Mathematical Properties

Modular Addition Forms an *Abelian Group*

- **Closed under addition**

  $0 \leq \mathrm{UAdd}_w(u, v) \leq 2^w - 1$

- **Commutative**

  $\mathrm{UAdd}_w(u, v) = \mathrm{UAdd}_w(v, u)$

- **Associative**

  $\mathrm{UAdd}_w(t, \mathrm{UAdd}_w(u, v)) = \mathrm{UAdd}_w(\mathrm{UAdd}_w(t, u), v)$

- **0 is additive identity**

  $\mathrm{UAdd}_w(u, 0) = u$

- **Every element has additive inverse**
  - Let $\mathrm{UComp}_w(u) = 2^w - u$

  $\mathrm{UAdd}_w(u, \mathrm{UComp}_w(u)) = 0$

Detecting Unsigned Overflow

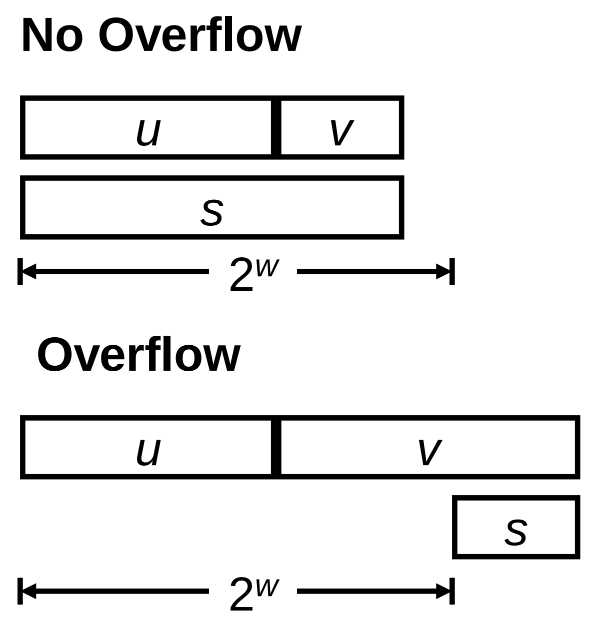
Task

- **Given** $s = \text{UAdd}_w(u, v)$
- **Determine if** $s = u + v$

Application

```
unsigned s, u, v;
s = u + v;
```

- **Did addition overflow?**



Claim

- **Overflow iff** $s < u$

```
ovf = (s < u)
```

- **Or symmetrically iff** $s < v$

Proof

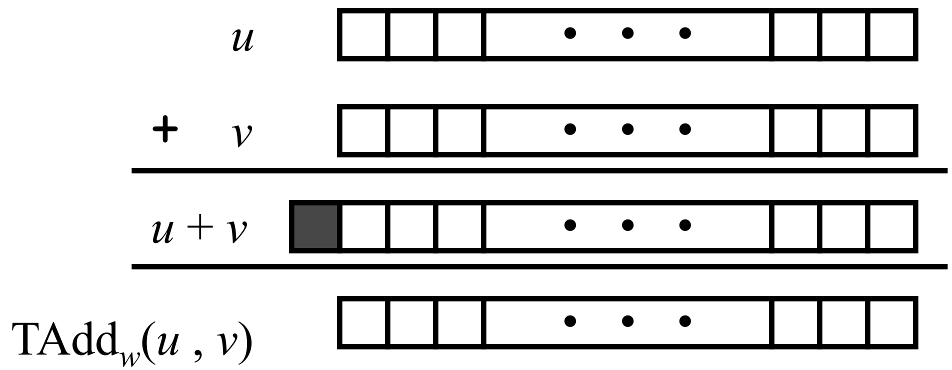
- **Know that** $0 \leq v < 2^w$
- **No overflow** $\Rightarrow \quad s = u + v \quad \geq \quad u + 0 = u$
- **Overflow** $\Rightarrow \quad s = u + v - 2^w \quad < \quad u + 0 = u$

Two’s Complement Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



TAdd and UAdd have Identical Bit-Level Behavior

- **Signed vs. unsigned addition in C:**

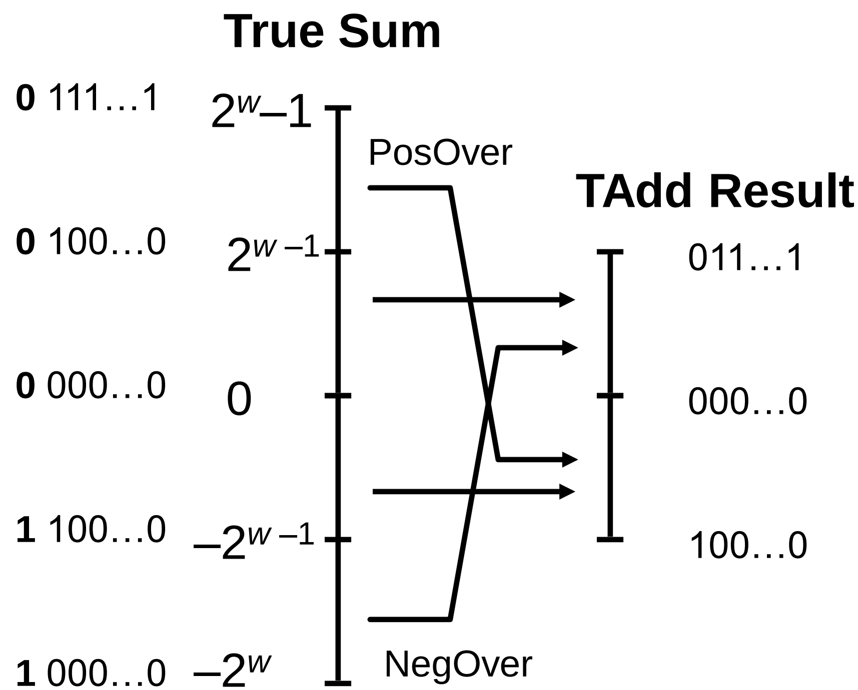
```
int s, t, u, v;
s = (int) ((unsigned) u + (unsigned) v);
 t = u + v
```

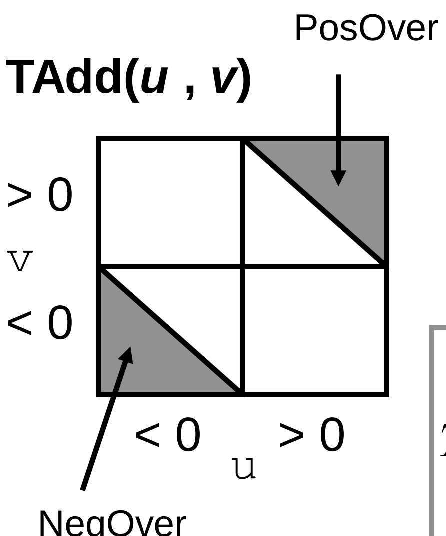
- **Will give** `s == t`

Characterizing TAdd

Functionality

- **True sum requires** *w*+1 **bits**
- **Drop off MSB**
- **Treat remaining bits as 2's comp. integer**





$$TAdd_w(u,v) = \begin{cases} u+v+2^{w-1} & u+v < TMin_w \quad \text{(NegOver)} \\ u+v & TMin_w \le u+v \le TMax_w \\ u+v-2^{w-1} & TMax_w < u+v \quad \text{(PosOver)} \end{cases}$$

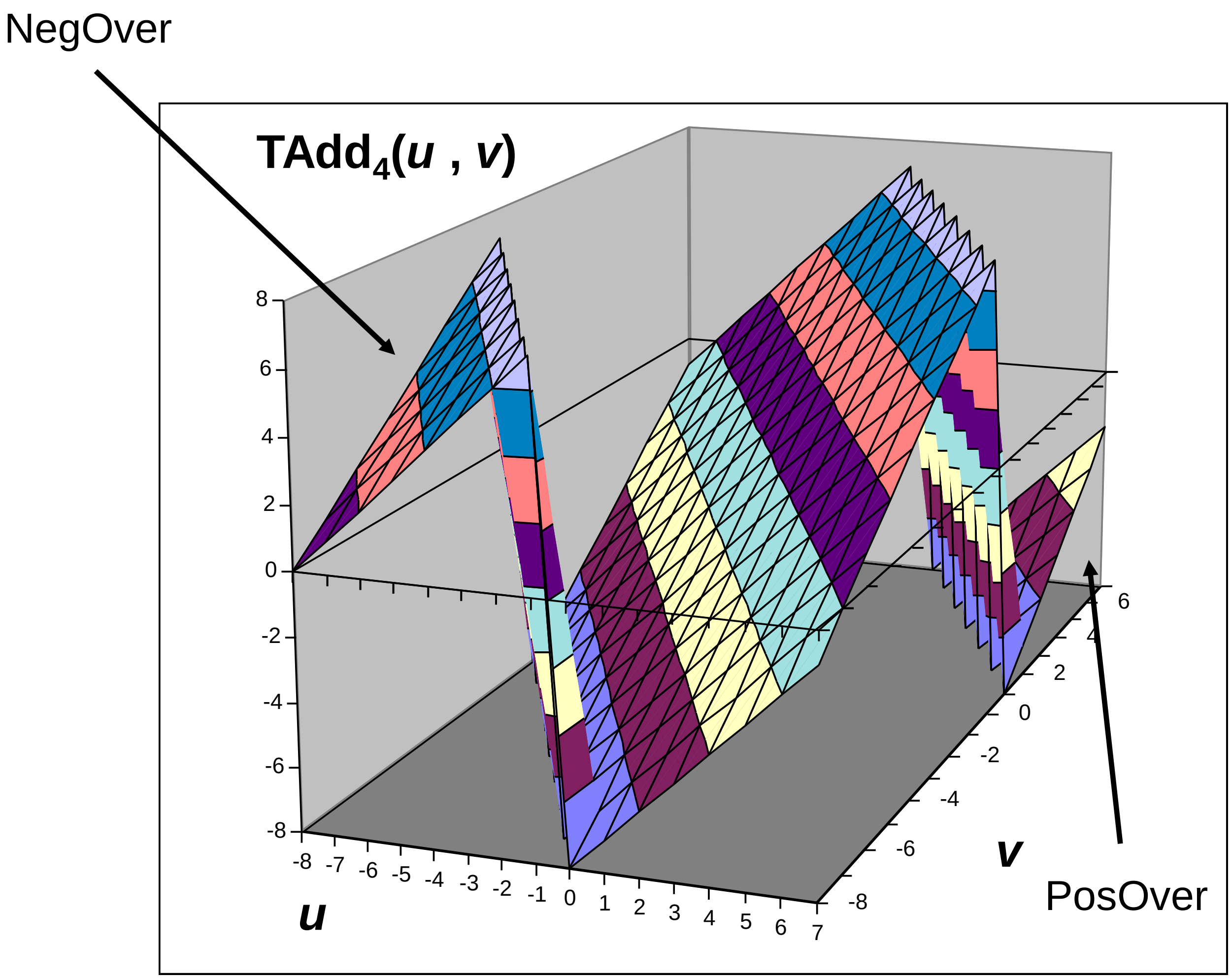
Visualizing 2's Comp. Addition

Values

- **4-bit two's comp.**
- **Range from -8 to +7**

Wraps Around

- **If sum $\geq 2^{w-1}$**
  - Becomes negative
  - At most once
- **If sum $< -2^{w-1}$**
  - Becomes positive
  - At most once

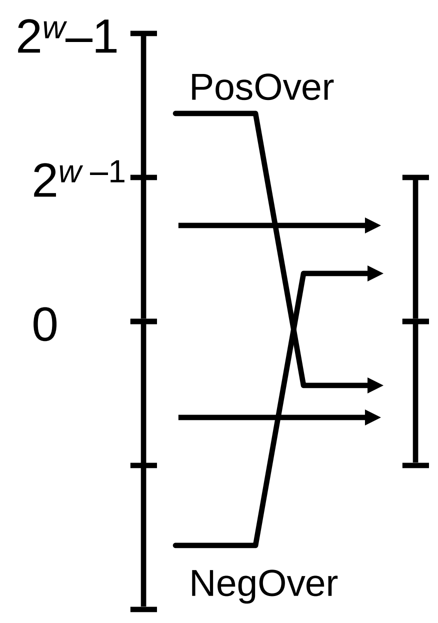


Detecting 2's Comp. Overflow

Task

- **Given** $s = \text{TAdd}_w(u, v)$
- **Determine if** $s = \text{Add}_w(u, v)$
- **Example**

```
int s, u, v;
s = u + v;
```



Claim

- **Overflow iff either:**

$u, v < 0, s \geq 0$ (NegOver)

$u, v \geq 0, s < 0$ (PosOver)

```
ovf = (u<0 == v<0) && (u<0 != s<0);
```

Proof

- **Easy to see that if** $u \geq 0$ **and** $v < 0$**, then** $TMin_w \leq u + v \leq TMax_w$
- **Symmetrically if** $u < 0$ **and** $v \geq 0$
- **Other cases from analysis of** TAdd

Mathematical Properties of TAdd

Isomorphic Algebra to UAdd

- $\mathrm{TAdd}_w(u, v) = \mathrm{U2T}(\mathrm{UAdd}_w(\mathrm{T2U}(u), \mathrm{T2U}(v)))$
  - Since both have identical bit patterns

Two's Complement Under TAdd Forms a Group

- **Closed, Commutative, Associative, 0 is additive identity**
- **Every element has additive inverse**

Let $\mathrm{TComp}_w(u) = \mathrm{U2T}(\mathrm{UComp}_w(\mathrm{T2U}(u))$

$\mathrm{TAdd}_w(u, \mathrm{TComp}_w(u)) = 0$

$$TComp_w(u) = \begin{cases} -u & u \neq TMin_w \\ TMin_w & u = TMin_w \end{cases}$$

Two's Complement Negation

Mostly like Integer Negation

- TComp(*u*) = –*u*

TMin is Special Case

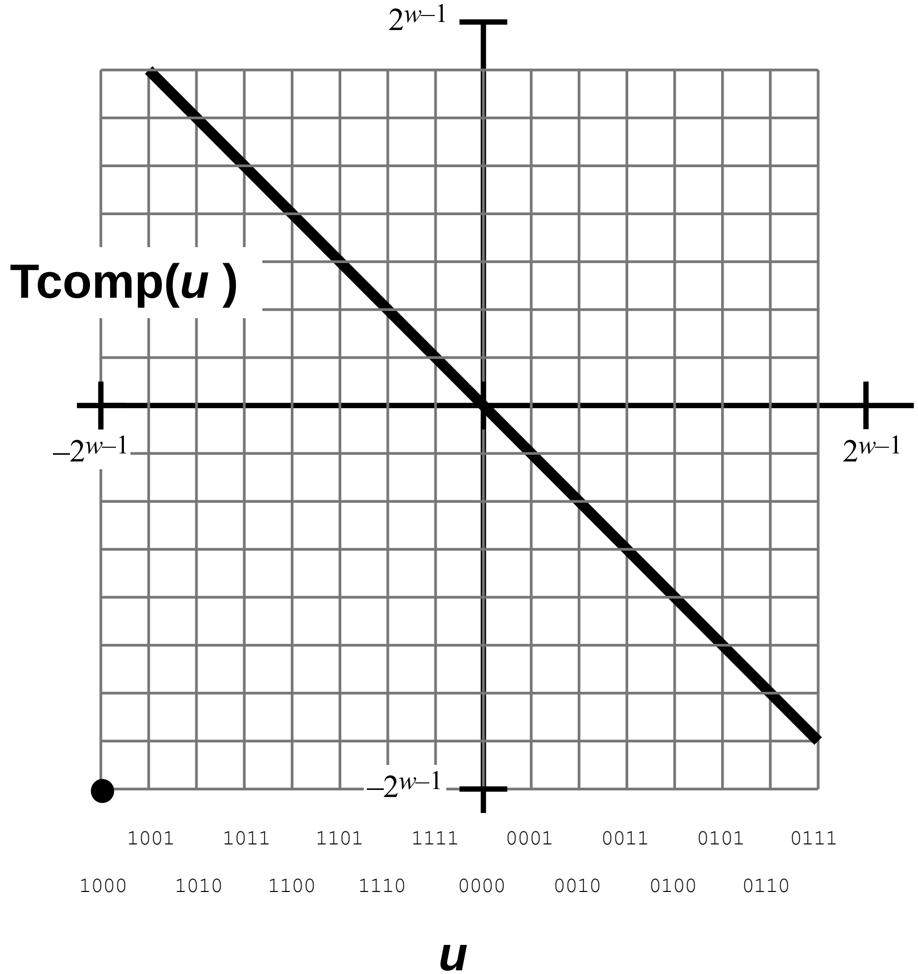
- TComp(*TMin*) = *TMin*

Negation in C is Actually TComp

```
mx = -x
```

- *mx* = TComp(*x*)
- **Computes additive inverse for** TAdd

```
x + -x == 0
```



Negating with Complement & Increment

In C

`~x + 1 == -x`

Complement

- **Observation: `~x + x == 1111…11`$_2$ `== -1`**

x	1	0	0	1	1	1	0	1
+ ~x	0	1	1	0	0	0	1	0
-1	1	1	1	1	1	1	1	1

Increment

- $\sim x + \cancel{x} + (-\cancel{x} + 1) \quad == \quad -\cancel{1} + (-x + \cancel{1})$
- $\sim x + 1 \quad == \quad -x$

Warning: Be cautious treating `int`'s as integers

- **OK here: We are using group properties of** TAdd **and** TComp

Comp. & Incr. Examples

x = 15213

	Decimal	Hex	Binary
`x`	15213	`3B 6D`	`00111011 01101101`
`~x`	-15214	`C4 92`	`11000100 10010010`
`~x+1`	-15213	`C4 93`	`11000100 1001001`**`1`**
`y`	-15213	`C4 93`	`11000100 10010011`

TMin

	Decimal	Hex	Binary
`TMin`	-32768	`80 00`	`10000000 00000000`
`~TMin`	32767	`7F FF`	`01111111 11111111`
`~TMin+1`	-32768	`80 00`	`10000000 00000000`

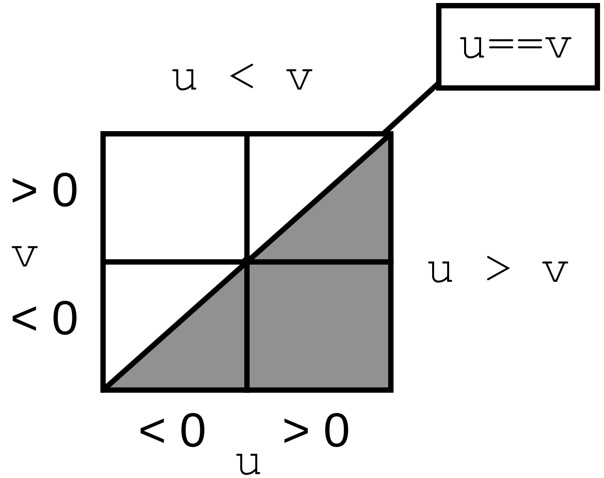
0

	Decimal	Hex	Binary
`0`	0	`00 00`	`00000000 00000000`
`~0`	-1	`FF FF`	`11111111 11111111`
`~0+1`	0	`00 00`	`00000000 00000000`

Comparing Two's Complement Numbers

Task

- **Given** signed numbers *u*, *v*
- Determine whether or not *u* > *v*
  - Return 1 for numbers in shaded region below



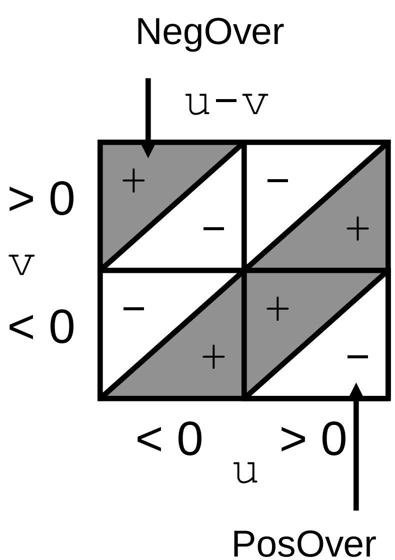
Bad Approach

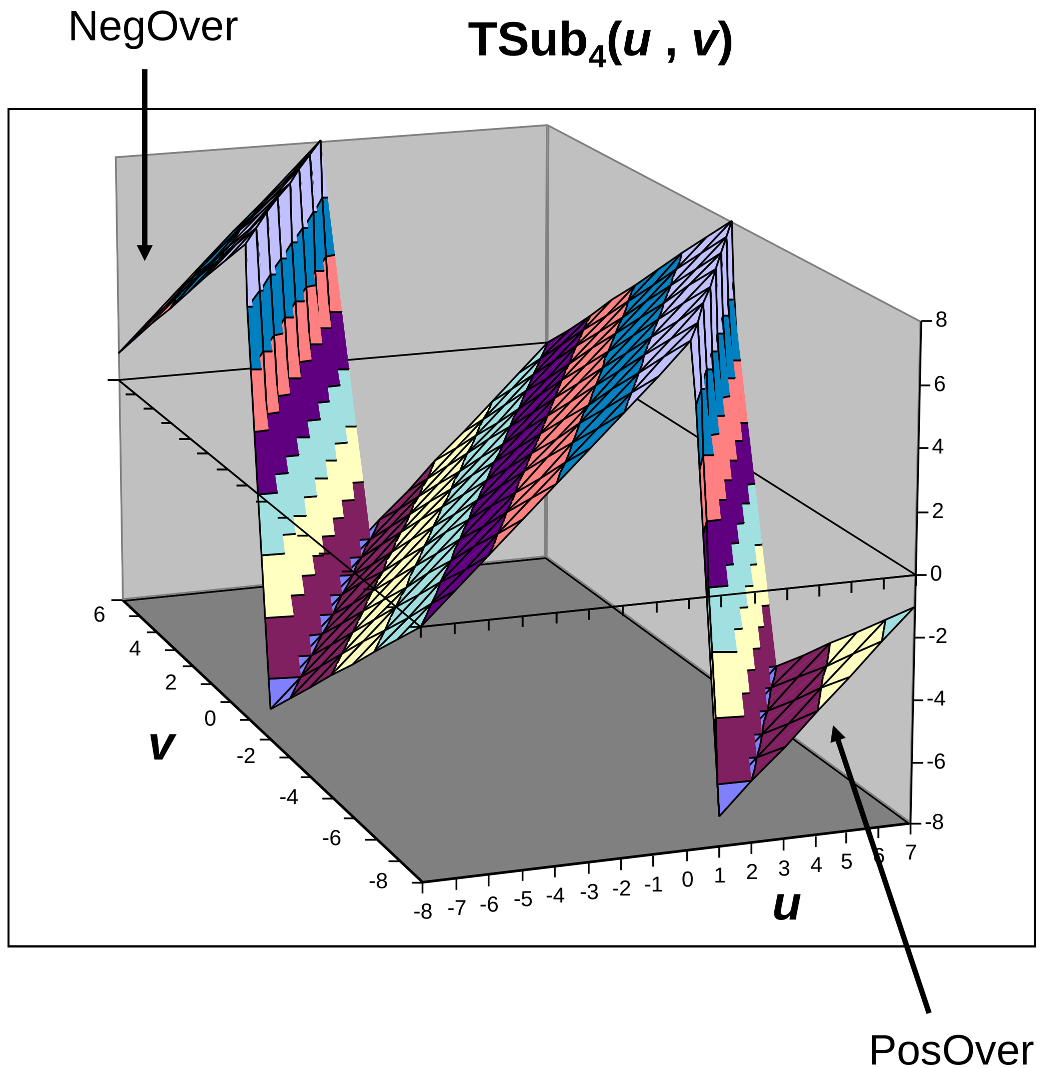
- Test `(u-v) > 0`
  - TSub(*u*,*v*) = TAdd(*u*, TComp(*v*))
- Problem: Thrown off by either Negative or Positive Overflow

Comparing with TSub

Will Get Wrong Results

- **NegOver:** `u < 0`**,** `v > 0`
  - but `u-v > 0`
- **PosOver:** `u > 0`**,** `v < 0`
  - but `u-v < 0`

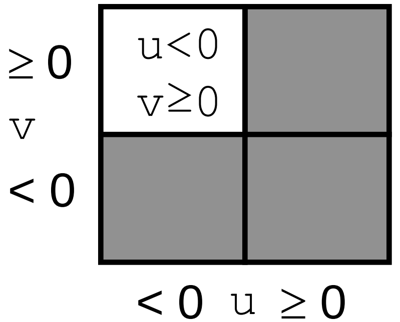




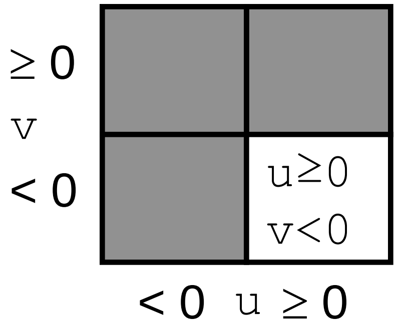
Working Around Overflow Problems

Partition into Three Regions

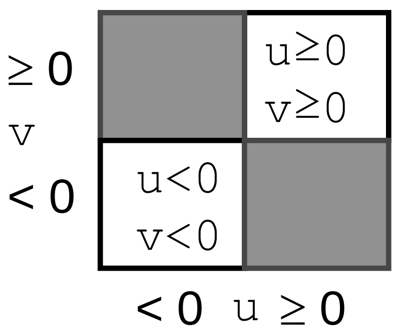
- $u < 0, v \geq 0 \quad \Rightarrow \quad u < v$

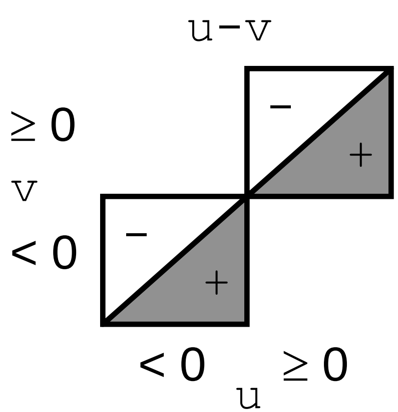


- $u \geq 0, v < 0 \quad \Rightarrow \quad u > v$



- u, v same sign $\Rightarrow$ `u-v` does not overflow
  - **Can safely use test** `(u-v) > 0`





Multiplication

Computing Exact Product of *w*-bit numbers *x*, *y*

- **Either signed or unsigned**

Ranges

- **Unsigned:** $0 \le x * y \le (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$
  - Up to $2w$ bits
- **Two's complement min:** $x * y \ge (-2^{w-1})*(2^{w-1}-1) = -2^{2w-2} + 2^{w-1}$
  - Up to $2w-1$ bits
- **Two's complement max:** $x * y \le (-2^{w-1})^2 = 2^{2w-2}$
  - Up to $2w$ bits, but only for $TMin_w^2$

Maintaining Exact Results

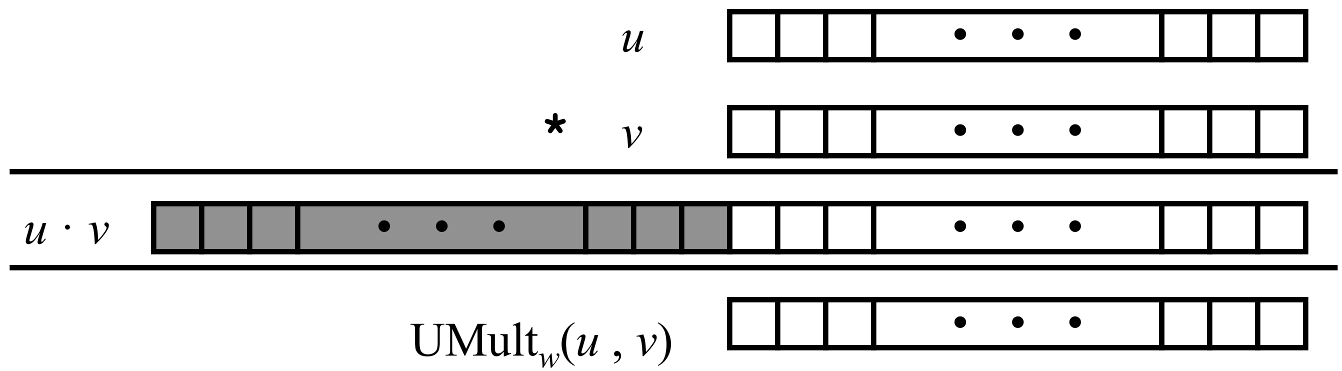
- **Would need to keep expanding word size with each product computed**
- **Done in software by "arbitrary precision" arithmetic packages**
- **Also implemented in Lisp, ML, and other "advanced" languages**

Unsigned Multiplication in C

Operands: *w* bits

True Product: 2**w* bits

Discard *w* bits: *w* bits



Standard Multiplication Function

- **Ignores high order *w* bits**

Implements Modular Arithmetic

$\mathrm{UMult}_w(u , v) \;=\; u \cdot v \bmod 2^w$

Unsigned vs. Signed Multiplication

Unsigned Multiplication

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

- **Truncates product to *w*-bit number** *up* **=** $\text{UMult}_w(ux, uy)$
- **Simply modular arithmetic**

  $up = ux \cdot uy \mod 2^w$

Two's Complement Multiplication

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

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

Relation

- **Signed multiplication gives same bit-level result as unsigned**
- `up == (unsigned) p`

Multiplication Examples

```
short int x  =  15213;
int     txx  =  ((int) x) * x;
int      xx  =  (int) (x * x);
int     xx2  =  (int) (2 * x * x);
```

```
x   =      15213:                            00111011 01101101
txx =  231435369: 00001101 11001011 01101100 01101001
xx  =      27753: 00000000 00000000 01101100 01101001
xx2 =     -10030: 11111111 11111111 11011000 11010010
```

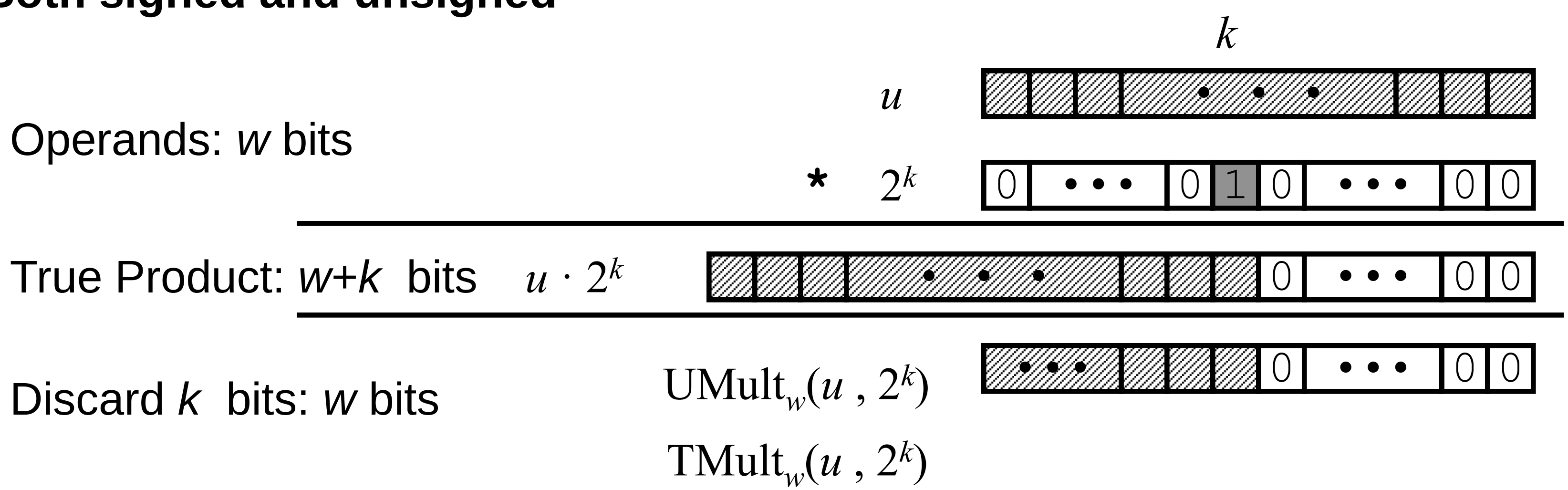
Observations

- **Casting order important**
  - If either operand **`int`**, will perform **`int`** multiplication
  - If both operands **`short int`**, will perform **`short int`** multiplication
- **Really is modular arithmetic**
  - Computes for `xx`: `15213`^{2} mod `65536 = 27753`
  - Computes for `xx2`: `(int) 55506U = -10030`
- **Note that `xx2 == (xx << 1)`**

Power-of-2 Multiply with Shift

Operation

- **`u << k` gives `u *` 2^k**
- **Both signed and unsigned**



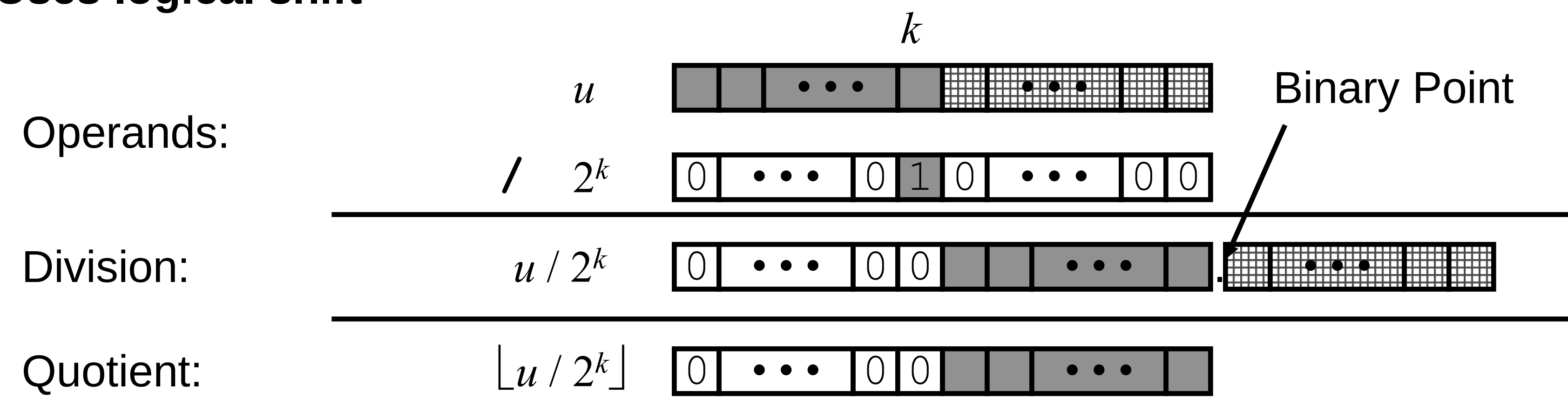
Examples

- `u << 3               ==   u * 8`
- `u << 5 - u << 3      ==   u * 24`
- **Most machines shift and add much faster than multiply**
  - Compiler will generate this code automatically

Unsigned Power-of-2 Divide with Shift

Quotient of Unsigned by Power of 2

- **`u >> k` gives $\lfloor$ `u /` $2^k \rfloor$**
- **Uses logical shift**

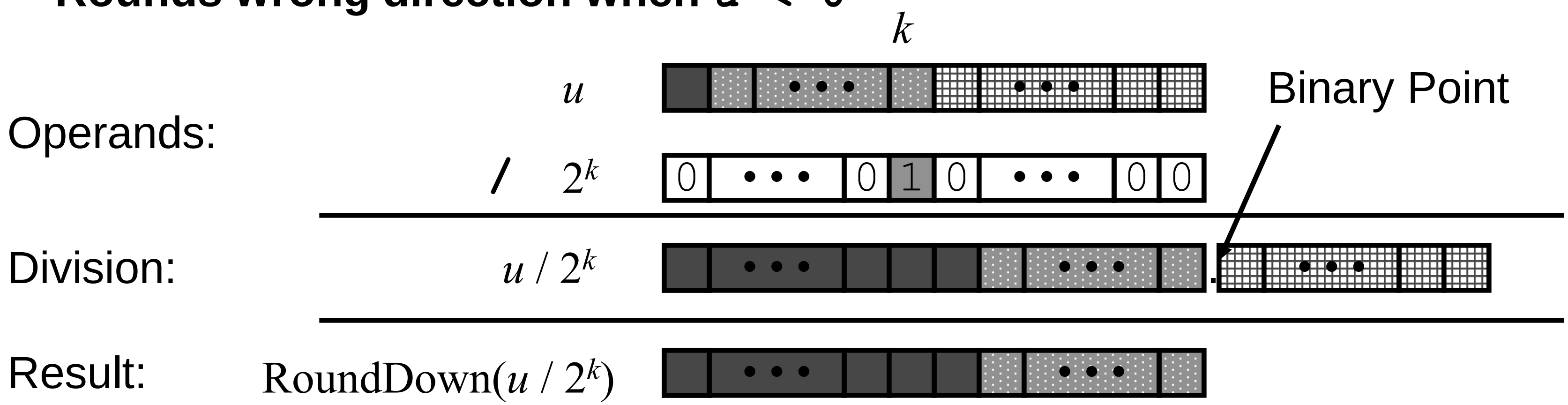


	Division	Computed	Hex	Binary
`x`	15213	15213	`3B 6D`	`00111011 01101101`
`x >> 1`	7606.5	7606	`1D B6`	**0**`0011101 10110110`
`x >> 4`	950.8125	950	`03 B6`	**0000**`0011 10110110`
`x >> 8`	59.4257813	59	`00 3B`	**00000000** `00111011`

2's Comp Power-of-2 Divide with Shift

Quotient of Signed by Power of 2

- `u >> k` gives $\lfloor$ `u / ` 2^k $\rfloor$
- Uses arithmetic shift
- Rounds wrong direction when `u < 0`



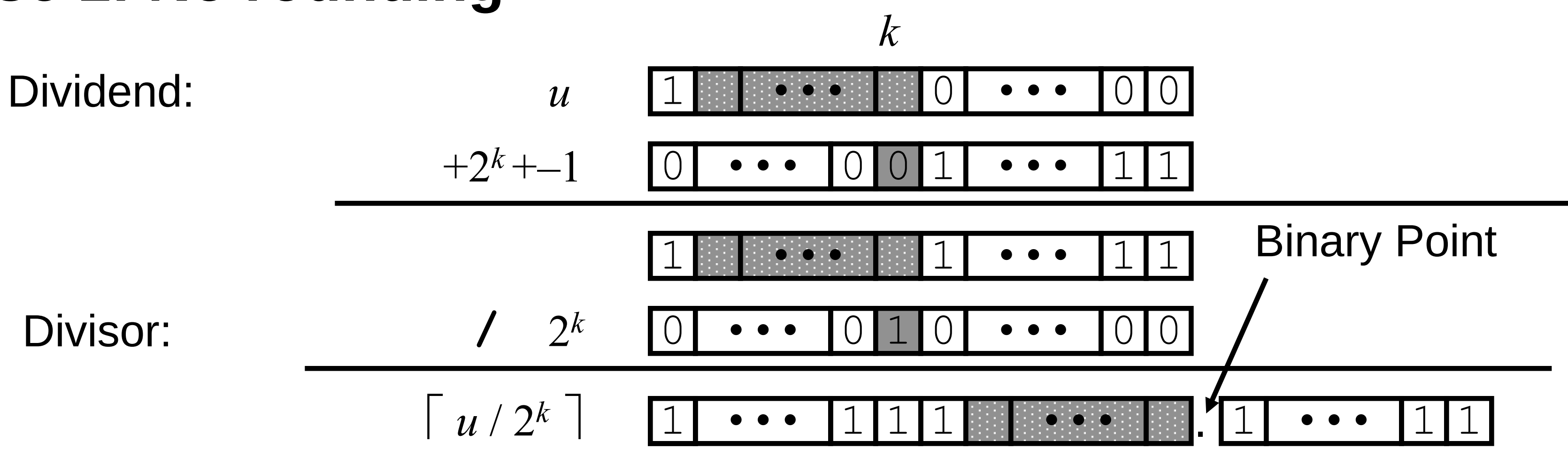
	Division	Computed	Hex	Binary
`y`	-15213	-15213	`C4 93`	`11000100 10010011`
`y >> 1`	-7606.5	-7607	`E2 49`	`**1**1100010 01001001`
`y >> 4`	-950.8125	-951	`FC 49`	`**1111**1100 01001001`
`y >> 8`	-59.4257813	-60	`FF C4`	`**11111111** 11000100`

Correct Power-of-2 Divide

Quotient of Negative Number by Power of 2

- **Want** $\lceil$ **`u / `**$2^k \rceil$ **(**Round Toward 0)
- **Compute as** $\lfloor$ **`(u+`**2^k**`-1)/ `**$2^k \rfloor$
  - In C: **`(u + (1<<k)-1) >> k`**
  - Biases dividend toward 0

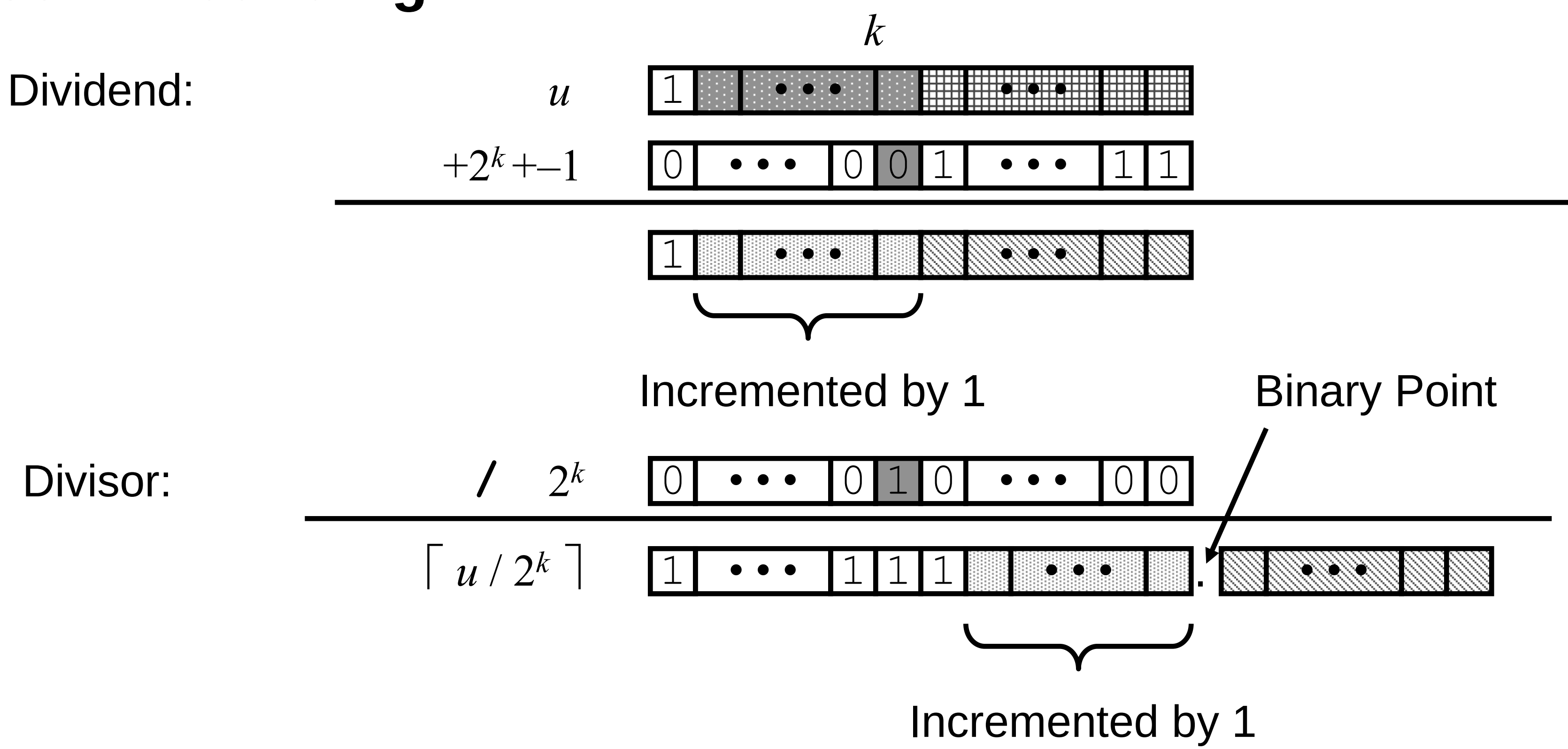
Case 1: No rounding



Biasing has no effect

Correct Power-of-2 Divide (Cont.)

Case 2: Rounding



Biasing adds 1 to final result

Correct Power-of-2 Divide Examples

	$y/2^k$	Computed	Hex	Binary
`y`	-15213	-15213	`C4 93`	`11000100 10010011`
`y+1`		-15212	`C4 94`	`11000100 10010100`
`(y+1)>>1`	-7606.5	-7606	`E2 4A`	**`1`**`1100010 01001010`
`y`	-15213	-15213	`C4 93`	`11000100 10010011`
`y+15`		-15197	`C4 A2`	`11000100 10100010`
`(y+15)>>4`	-950.8125	-950	`FC 4A`	**`1111`**`1100 01001010`
`y`	-15213	-15213	`C4 93`	`11000100 10010011`
`y+255`		-14958	`C5 92`	`11000101 10010010`
`(y+255)>>8`	-59.4257813	-59	`FF C5`	**`11111111`** `11000101`

Properties of Unsigned Arithmetic

Unsigned Multiplication with Addition Forms Commutative Ring

- **Addition is commutative group**
- **Closed under multiplication**

  $0 \leq \mathrm{UMult}_w(u\ ,\ v) \leq 2^w - 1$
- **Multiplication Commutative**

  $\mathrm{UMult}_w(u\ ,\ v) = \mathrm{UMult}_w(v\ ,\ u)$
- **Multiplication is Associative**

  $\mathrm{UMult}_w(t, \mathrm{UMult}_w(u\ ,\ v)) = \mathrm{UMult}_w(\mathrm{UMult}_w(t, u\ ), v)$
- **1 is multiplicative identity**

  $\mathrm{UMult}_w(u\ ,\ 1) = u$
- **Multiplication distributes over addtion**

  $\mathrm{UMult}_w(t, \mathrm{UAdd}_w(u\ ,\ v)) = \mathrm{UAdd}_w(\mathrm{UMult}_w(t, u\ ), \mathrm{UMult}_w(t, v))$

Properties of Two's Comp. Arithmetic

Isomorphic Algebras

- **Unsigned multiplication and addition**
  - Truncating to *w* bits
- **Two's complement multiplication and addition**
  - Truncating 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.,**

$u > 0 \quad \Rightarrow \quad u + v > v$

$u > 0, v > 0 \quad \Rightarrow \quad u \cdot v > 0$

- **These properties are not obeyed by two's complement arithmetic**

TMax `+ 1` `==` *TMin*

`15213 * 30426 == -10030` **(16-bit words)**

C Puzzle Answers

- **Assume machine with 32 bit word size, two's complement integers**
- *TMin* **makes a good counterexample in many cases**

• `x < 0`	⇒	`((x*2) < 0)`	**False:**	*TMin*
• `ux >= 0`			**True:**	0 = *UMin*
• `x & 7 == 7`	⇒	`(x<<30) < 0`	**True:**	$x_1 = 1$
• `ux > -1`			**False:**	0
• `x > y`	⇒	`-x < -y`	**False:**	`-1`, *TMin*
• `x * x >= 0`			**False:**	`65535`
				`(x*x = -131071)`
• `x > 0 && y > 0`	⇒	`x + y > 0`	**False:**	*TMax*, *TMax*
• `x >= 0`	⇒	`-x <= 0`	**True:**	–*TMax* < 0
• `x <= 0`	⇒	`-x >= 0`	**False:**	*TMin*