COS 217: Introduction to Programming Systems

Assembly Language

Part 2

PRINCETON UNIVERSITY

Goals of this Lecture

Help you learn:

- Intermediate aspects of AARCH64 assembly language:
- Control flow with signed integers
- Control flow with unsigned integers
- Arrays
- Structures

Agenda

Flattened C code

Control flow with signed integers

Control flow with unsigned integers

Arrays

Structures

Flattened C Code

Problem

- Translating from C to assembly language is difficult when the C code doesn’t proceed in consecutive lines

Solution

- **Flatten** the C code to eliminate all nesting

Flattened C Code

C

```
if (expr)
{  statement1;
   ...
   statementN;
}
```

```
if (expr)
{  statementT1;
   ...
   statementTN;
}
else
{  statementF1;
   ...
   statementFN;
}
```

Flattened C

```
   if (! expr) goto endif1;
      statement1;
      ...
      statementN;
endif1:
```

```
   if (! expr) goto else1;
      statementT1;
      ...
      statementTN;
      goto endif1;
else1:
      statementF1;
      ...
      statementFN;
endif1:
```

Flattened C Code

C

```
while (expr)
{  statement1;
   ...
   statementN;
}
```

```
for (expr1; expr2; expr3}
{  statement1;
   ...
   statementN;
}
```

Flattened C

```
loop1:
   if (! expr) goto endloop1;
      statement1;
      ...
      statementN;
      goto loop1;
endloop1:
```

```
   expr1;
loop1:
   if (! expr2) goto endloop1;
   statement1;
   ...
   statementN;
   expr3;
   goto loop1;
endloop1:
```

Agenda

Flattened C code

Control flow with signed integers

Control flow with unsigned integers

Arrays

Structures

`if` Example

C

```
int i;
...
if (i < 0)
   i = -i;
```

Flattened C

```
int i;
...
   if (i >= 0) goto endif1;
   i = -i;
endif1:
```

`if` Example

Flattened C

```
int i;
...
   if (i >= 0) goto endif1;
   i = -i;
endif1:
```

Assembler shorthand for
`subs wzr, w1, 0`

Assembly

```
   .section ".bss"
i: .skip 4
...
   .section ".text"
...
   adr  x0, i
   ldr w1, [x0]
   cmp w1, 0
   bge endif1
   neg w1, w1
endif1:
```

Notes:

`cmp` instruction: compares operands, sets condition flags

`bge` instruction (conditional branch if greater than or equal):
Examines condition flags in PSTATE register

`if`…`else` Example

C

```
int i;
int j;
int smaller;
...
if (i < j)
   smaller = i;
else
   smaller = j;
```

Flattened C

```
int i;
int j;
int smaller;
...
   if (i >= j) goto else1;
   smaller = i;
   goto endif1;
else1:
   smaller = j;
endif1:
```

`if`…`else` Example

Flattened C

```
int i;
int j;
int smaller;
...
   if (i >= j) goto else1;
   smaller = i;
   goto endif1;
else1:
   smaller = j;
endif1:
```

Assembly

```
...
   adr x0, i
   ldr w1, [x0]
   adr x0, j
   ldr w2, [x0]
   cmp w1, w2
   bge else1
   adr x0, smaller
   str w1, [x0]
   b endif1
else1:
   adr x0, smaller
   str w2, [x0]
endif1:
```

Note:

`b` instruction (unconditional branch)

`while` Example

C

```
int n;
int fact;
...
fact = 1;
while (n > 1)
{ fact *= n;
  n--;
}
```

Flattened C

```
int n;
int fact;
...
   fact = 1;
loop1:
   if (n <= 1) goto endloop1;
   fact *= n;
   n--;
   goto loop1;
endloop1:
```

`while` Example

Flattened C

```
int n;
int fact;
...
   fact = 1;
loop1:
   if (n <= 1) goto endloop1;
   fact *= n;
   n--;
   goto loop1;
endloop1:
```

Assembly

```
...
   adr x0, n
   ldr w1, [x0]
   mov w2, 1
loop1:
   cmp w1, 1
   ble endloop1
   mul w2, w2, w1
   sub w1, w1, 1
   b loop1
endloop1:
# str w2 into fact
```

We *could* store here, but not needed for this code

Note:

`ble` instruction (conditional branch if less than or equal)

`for` Example

C

```
int power = 1;
int base;
int exp;
int i;
...
for (i = 0; i < exp; i++)
  power *= base;
```

Flattened C

```
int power = 1;
int base;
int exp;
int i;
...
   i = 0;
loop1:
   if (i >= exp) goto endloop1;
   power *= base;
   i++;
   goto loop1;
endloop1:
```

What goes where?

Q: Which section(s) would (globals) `power`, `base`, `exp`, `i` go into?

```
int power = 1;
int base;
int exp;
int i;
```

A. All on stack
B. `power` in .data and rest in .rodata
C. All in .data
D. `power` in .bss and rest in .data
E. `power` in .data and rest in .bss

E

none are string literals: not RODATA

all are file scope, process duration: not STACK

power is initialized: DATA

the rest are not: BSS

`for` Example

Flattened C

```
int power = 1;
int base;
int exp;
int i;
...
   i = 0;
loop1:
   if (i >= exp) goto endloop1;
   power *= base;
   i++;
   goto loop1;
endloop1:
```

Assembly

```
 .section ".data"
power:  .word 1
...
 .section ".bss"
base:   .skip 4
exp:    .skip 4
i:      .skip 4
...
```

for Example

Flattened C

```
int power = 1;
int base;
int exp;
int i;
...
   i = 0;
loop1:
   if (i >= exp) goto endloop1;
   power *= base;
   i++;
   goto loop1;
endloop1:
```

Assembly

```
   adr x0, power
   ldr w1, [x0]
   adr x0, base
   ldr w2, [x0]
   adr x0, exp
   ldr w3, [x0]
   mov w4, 0
loop1:
   cmp w4, w3
   bge endloop1
   mul w1, w1, w2
   add w4, w4, 1
   b loop1
endloop1:
# str w1 into power
```

Missing anything?

Control Flow with Signed Integers

Unconditional branch

```
b label          Branch to label
```

Compare

```
cmp Xm, Xn       Compare Xm to Xn
cmp Wm, Wn       Compare Wm to Wn
```

- Set condition flags in PSTATE register

Conditional branches after comparing signed integers

```
beq label        Branch to label if equal
bne label        Branch to label if not equal
blt label        Branch to label if less than
ble label        Branch to label if less or equal
bgt label        Branch to label if greater than
bge label        Branch to label if greater or equal
```

- Examine condition flags in PSTATE register

Signed vs. Unsigned Integers

In C

- Integers are signed or unsigned
- Compiler generates assembly language instructions accordingly

In assembly language

- Integers are neither signed nor unsigned
- Distinction is in the instructions used to manipulate them

Distinction matters for

- Division (`sdiv` vs. `udiv`)
- Control flow
  - Which is the larger 32-bit integer value?
    11111111111111111111111111111111
    00000000000000000000000000000000

(Yes, there are 32 bits there. You don’t have to count)

Control Flow with Unsigned Integers

Unconditional branch

`b label`	`b label`	`Branch to label`

Compare

`cmp Xm, Xn`	`cmp Xm, Xn`	`Compare Xm to Xn`
`cmp Wm, Wn`	`cmp Wm, Wn`	`Compare Wm to Wn`

- Set condition flags in PSTATE register

Conditional branches after comparing unsigned integers

`beq label`	`beq label`	`Branch to label if equal`
`bne label`	`bne label`	`Branch to label if not equal`
~~`blt label`~~	`blo label`	`Branch to label if lower`
~~`ble label`~~	`bls label`	`Branch to label if lower or same`
~~`bgt label`~~	`bhi label`	`Branch to label if higher`
~~`bge label`~~	`bhs label`	`Branch to label if higher or same`

- Examine condition flags in PSTATE register

`while` Example

Flattened C

```
unsigned int n;
unsigned int fact;
...
   fact = 1;
loop1:
   if (n <= 1)
      goto endloop1;
   fact *= n;
   n--;
   goto loop1;
endloop1:
```

Assembly: Signed → Unsigned

```
...
   adr x0, n
   ldr w1, [x0]
   mov w2, 1
loop1:
   cmp w1, 1
   ble endloop1
   mul w2, w2, w1
   sub w1, w1, 1
   b loop1
endloop1:
# str w2 into fact
```

```
...
   adr x0, n
   ldr w1, [x0]
   mov w2, 1
loop1:
   cmp w1, 1
   bls endloop1
   mul w2, w2, w1
   sub w1, w1, 1
   b loop1
endloop1:
# str w2 into fact
```

Note:

`bls` instruction (instead of `ble`)

Alternative Control Flow: CBZ, CBNZ

Special-case, all-in-one compare-and-branch instructions

- DO NOT examine condition flags in PSTATE register

```
cbz Xn, label  Branch to label if Xn is zero
cbz Wn, label  Branch to label if Wn is zero
cbnz Xn, label Branch to label if Xn is nonzero
cbnz Wn, label Branch to label if Wn is nonzero
```

Agenda

Flattened C

Control flow with signed integers

Control flow with unsigned integers

Arrays

Structures

Arrays: Brute Force (Setup)

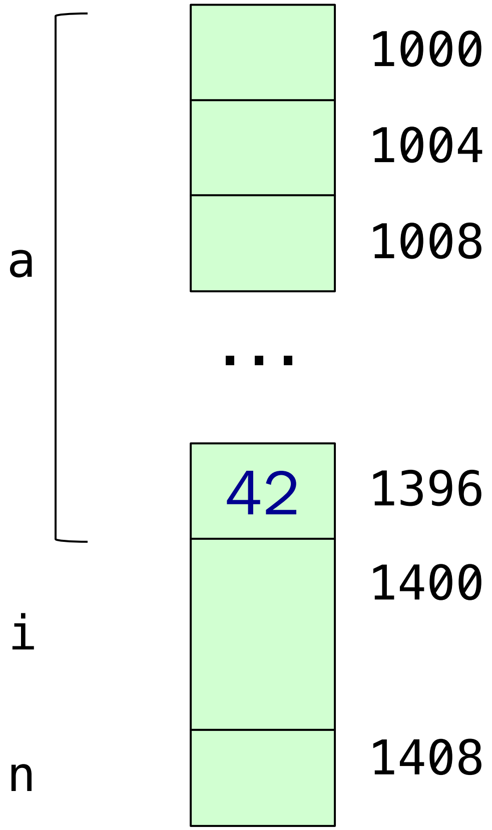
C

```
int a[100];
long i;
int n;
...
i = 99;
...
n = a[i]
...
```

Assembly

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```

Memory

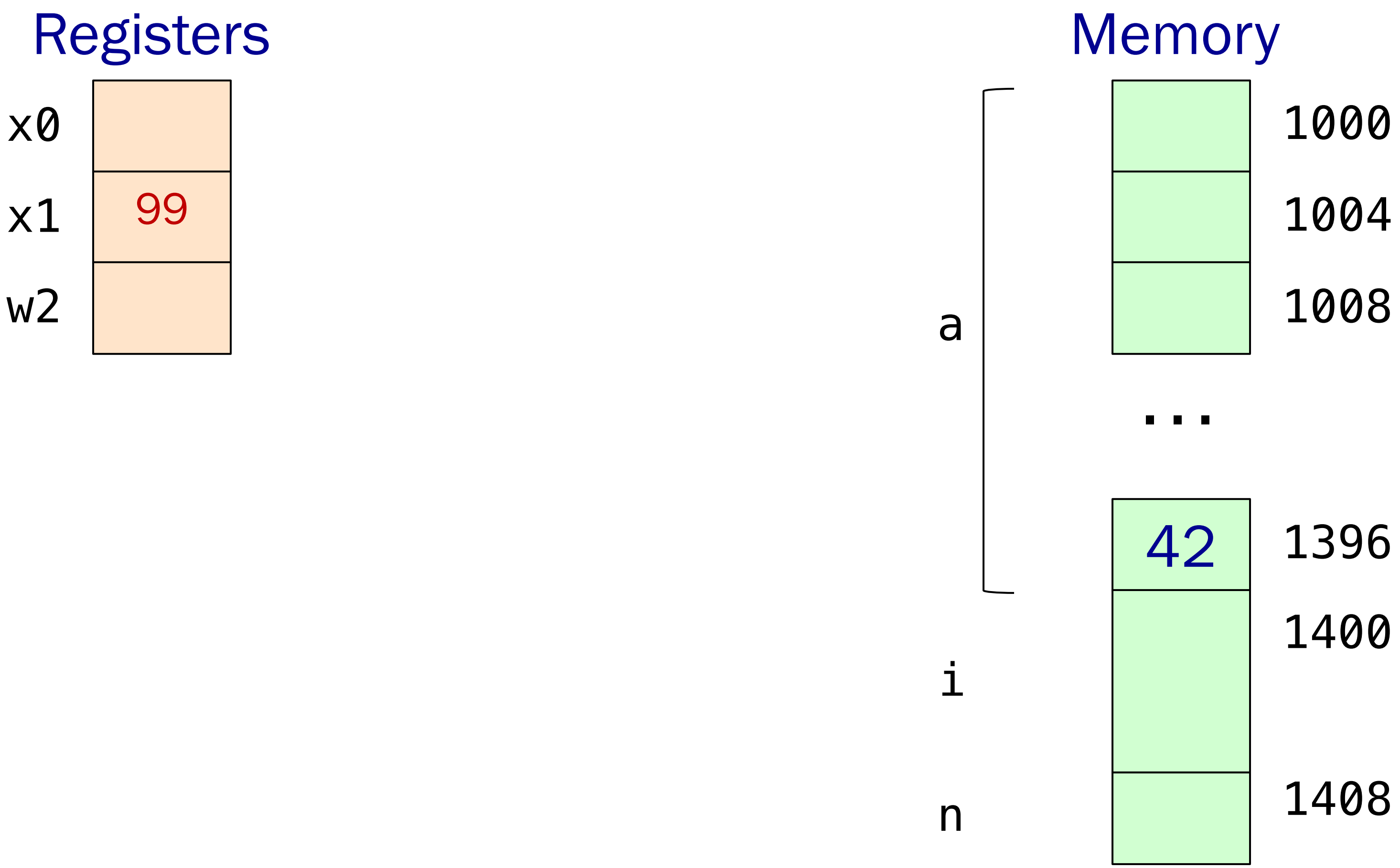


To do array lookup, need to compute address of a[i] ≡ *(a+i)
Let’s take it one step at a time…

Arrays: Brute Force (Initialize `i`)

Assembly

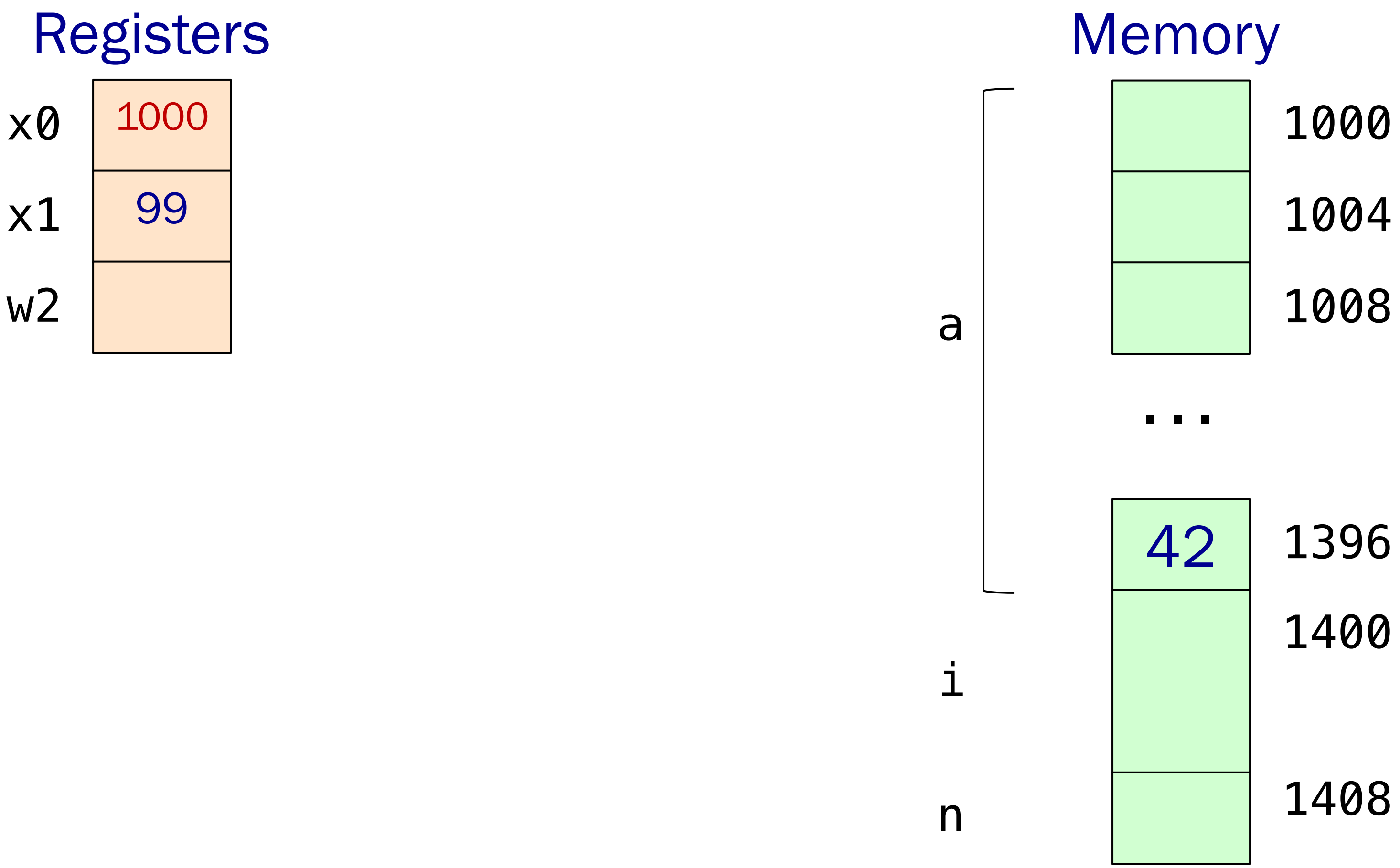
```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Arrays: Brute Force (Get a's base address)

Assembly

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Registers

x0 1000

x1 99

w2

Memory

a

1000

1004

1008

...

42 1396

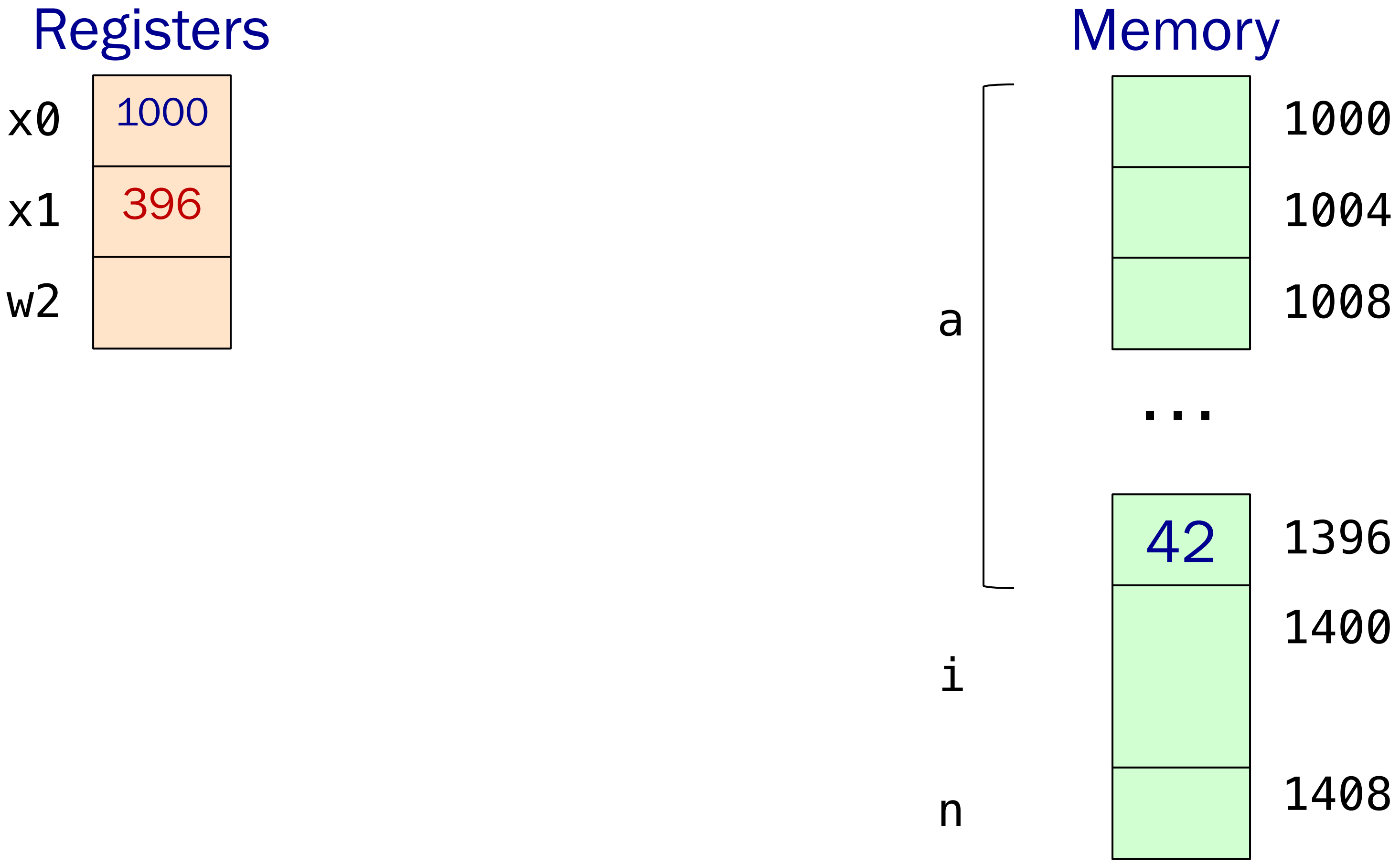
i 1400

n 1408

Arrays: Brute Force (Calculate byte-offset of `i`)

Assembly

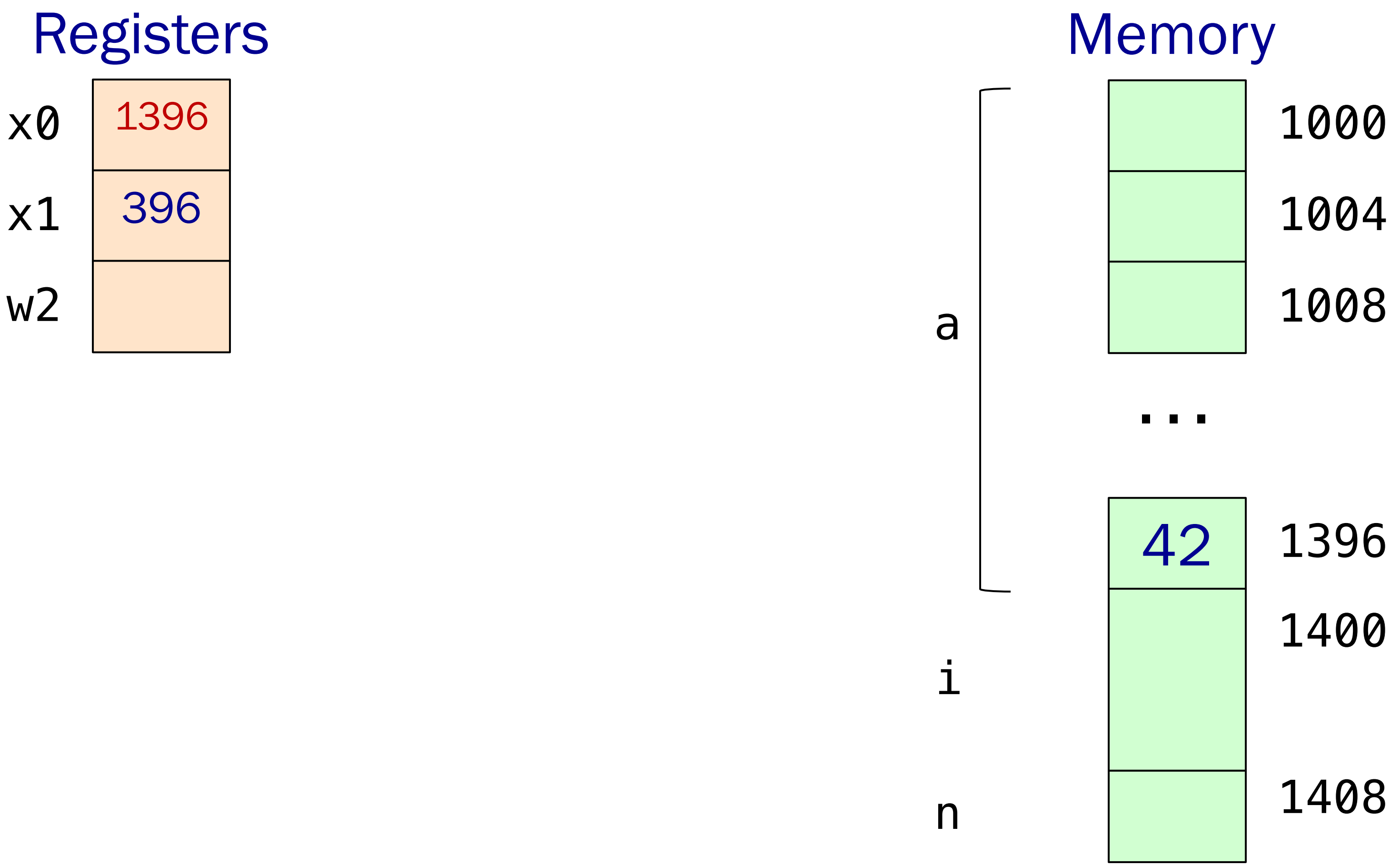
```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Arrays: Brute Force (Calculate address of `a[i]`)

Assembly

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Arrays: Brute Force (Read value at `a[i]` into `w2`)

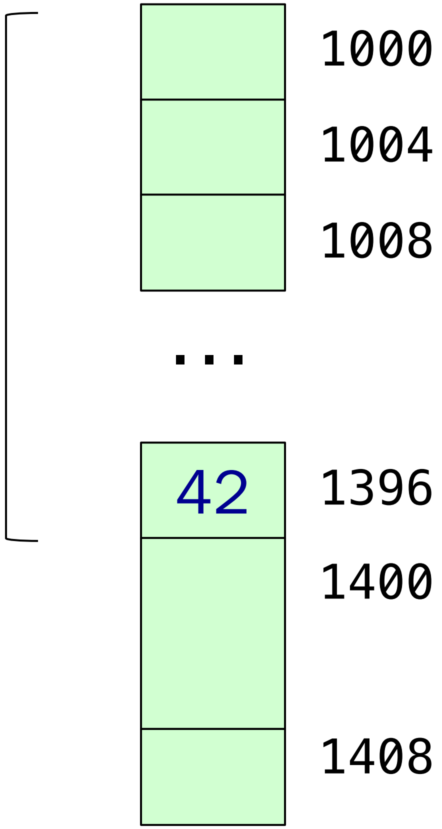
Assembly

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```

Registers

x0	1396
x1	396
w2	42

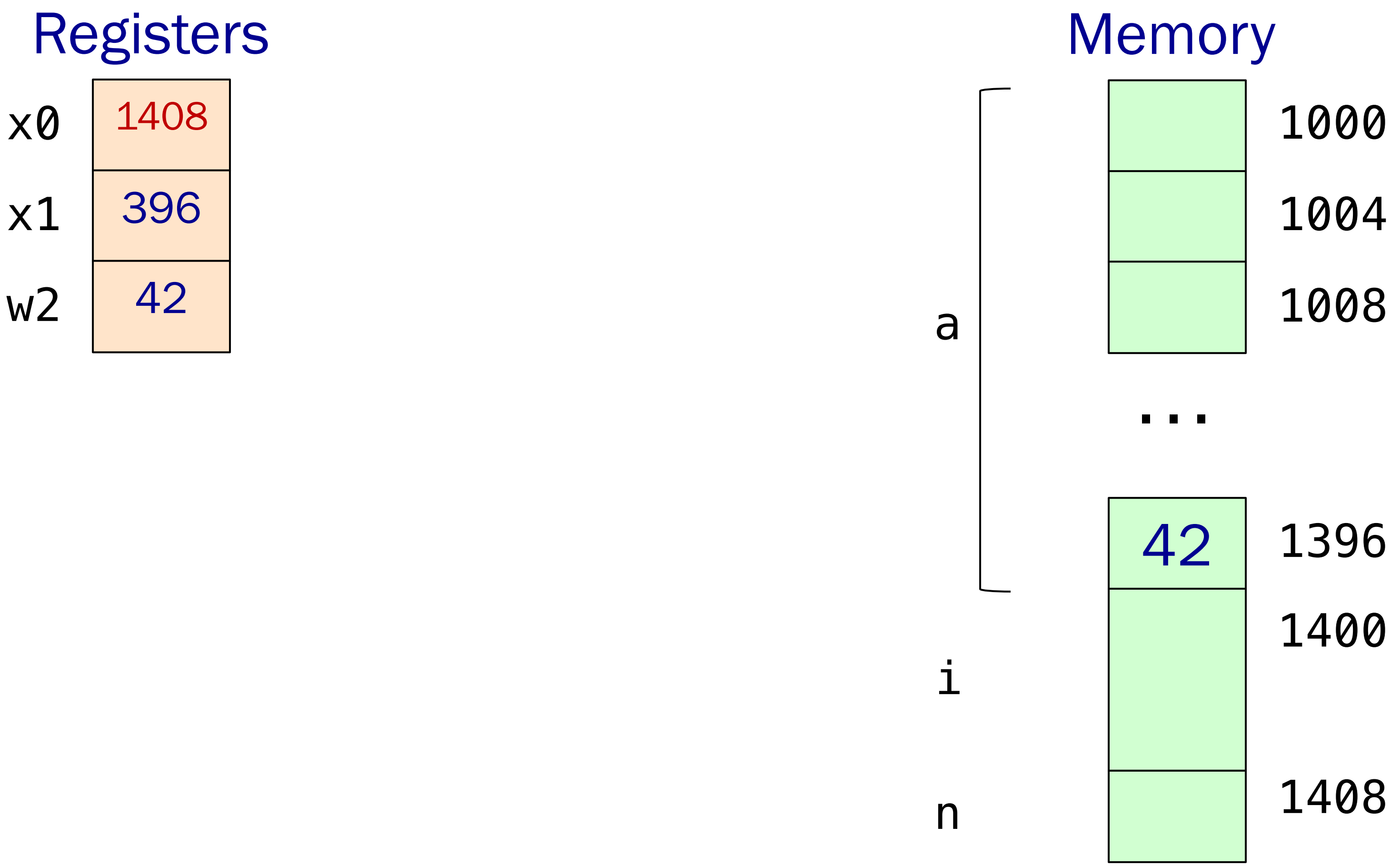
Memory



Arrays: Brute Force (Get n's address)

Assembly

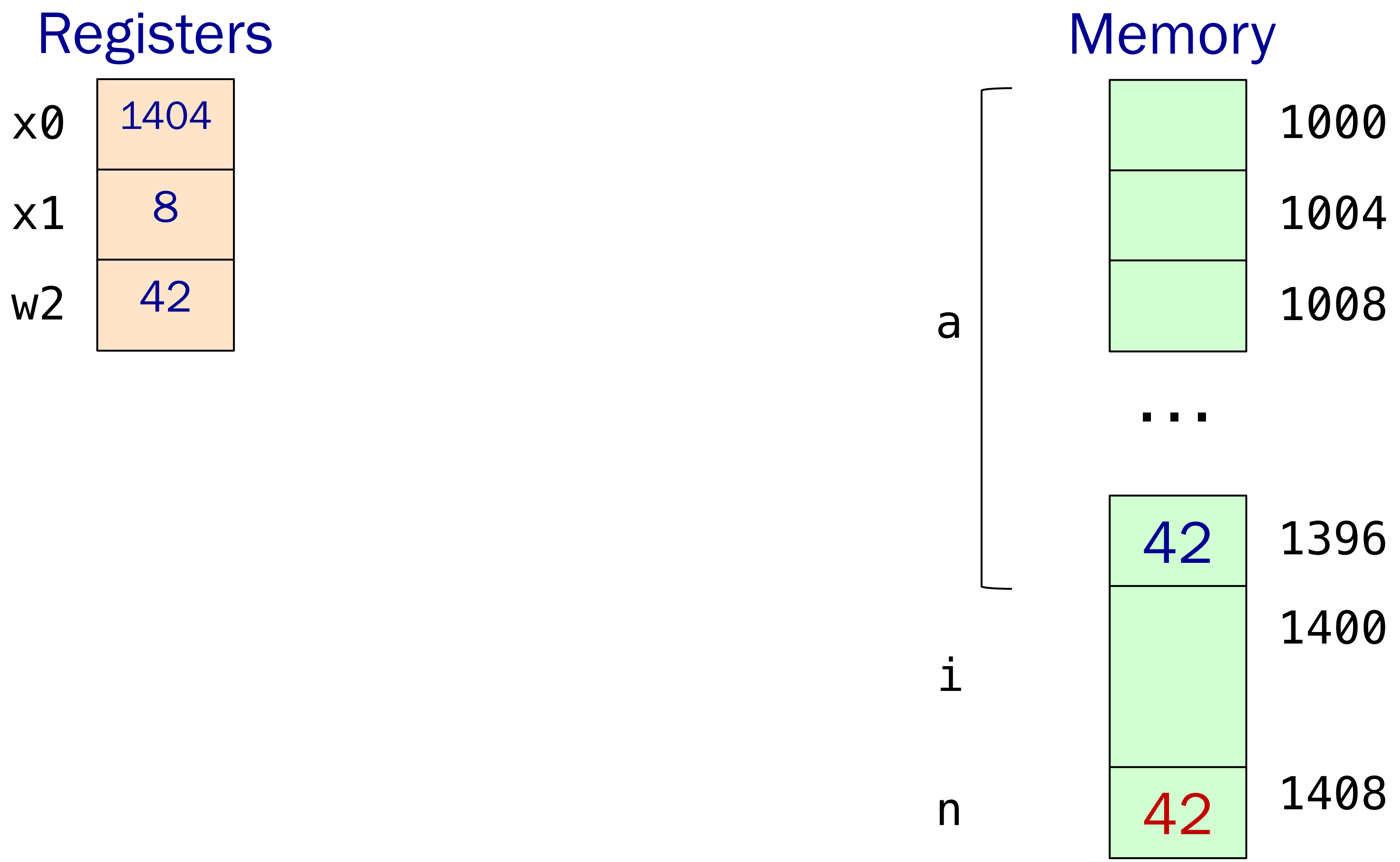
```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Arrays: Brute Force (Store value into n)

Assembly

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```



Registers

x0	1404
x1	8
w2	42

Memory

Arrays: Register Offset Addressing

C

```
int a[100];
long i;
int n;
...
i = 99;
...
n = a[i]
...
```

Brute-Force

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a
   lsl x1, x1, 2
   add x0, x0, x1
   ldr w2, [x0]
   adr x0, n
   str w2, [x0]
...
```

Register Offset

```
   .section ".bss"
a: .skip 400
i: .skip 8
n: .skip 4
...
   .section ".text"
...
   mov x1, 99
...
   adr x0, a


   ldr w2, [x0, x1, lsl 2]
   adr x0, n
   str w2, [x0]
...
```

Doesn't change x0 or x1

This uses a different addressing mode for the load

Memory Addressing Modes

	Address loaded:	
ldr Wt, [Xn, offset]	Xn+offset	($-2^8 \leq$ offset $< 2^{14}$)
ldr Wt, [Xn]	Xn	(shortcut for offset=0)
ldr Wt, [Xn, Xm]	Xn+Xm	
ldr Wt, [Xn, Xm, LSL n]	Xn+(Xm<<n)	(n = 3 for 64-bit elements, 2 for 32-bit elements, ...)

All these addressing modes are also available for 64-bit loads:

ldr Xt, [Xn, offset]	Xn+offset

etc.

Agenda

Flattened C

Control flow with signed integers

Control flow with unsigned integers

Arrays

Structures

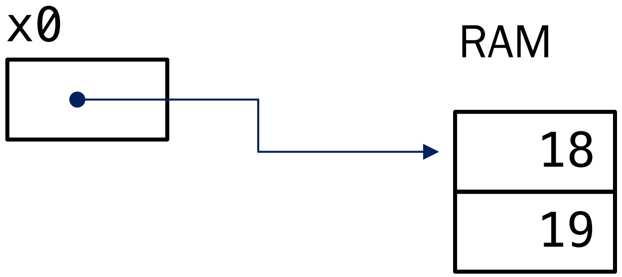
Structures: Brute Force

C

```
struct S
{ int i;
  int j;
};
...
struct S myStruct;
...
myStruct.i = 18;
...
myStruct.j = 19;
```

Assembly

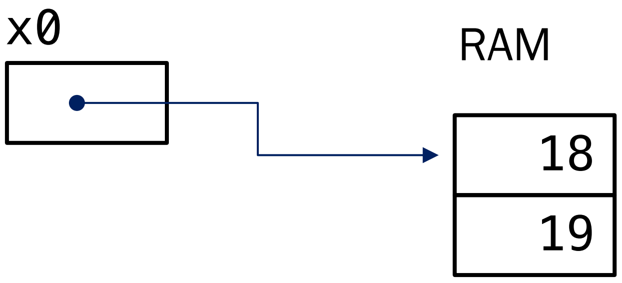
```
   .section ".bss"
myStruct: .skip 8
...
   .section ".text"
...
   adr x0, myStruct
...
   mov w1, 18
   str w1, [x0]
...
   mov w1, 19
   str ???
```



Which mode is à la mode?

Q: Which addressing mode is most appropriate to store `myStruct.j`?

```
   .section ".bss"
myStruct: .skip 8
...
   .section ".text"
...
   adr x0, myStruct
...
   mov w1, 18
   str w1, [x0]
...
   mov w1, 19
   str ???
```



A. str W1, [X0, offset]

B. str W1, [X0]

C. str W1, [X0, Xm, LSL 2]

D. str W1, [X0, Xm]

A is the simplest option: the only one that requires no additional setup.

Structures: Offset Addressing

C

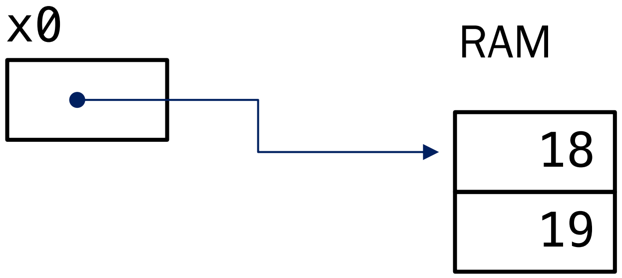
```
struct S
{ int i;
  int j;
};
...
struct S myStruct;
...
myStruct.i = 18;
...
myStruct.j = 19;
```

Brute-Force

```
   .section ".bss"
myStruct: .skip 8
...
   .section ".text"
...
   adr x0, myStruct
...
   mov w1, 18
   str w1, [x0]
...
   mov w1, 19
   add x0, x0, 4
   str w1, [x0]
```

Offset

```
   .section ".bss"
myStruct: .skip 8
...
   .section ".text"
...
   adr x0, myStruct
...
   mov w1, 18
   str w1, [x0]
...
   mov w1, 19
   str w1, [x0, 4]
```



Structures: Padding

C

```
struct S
{ char c;
  int i;
};
…
struct S myStruct;
…
myStruct.c = 'A';
…
myStruct.i = 18;
```

Three-byte pad here

Assembly

```
   .section ".bss"
myStruct: .skip 8
...
   .section ".text"
...
   adr x0, myStruct
...
   mov w1, 'A'
   strb w1, [x0]
...
   mov w1, 18
   str w1, [x0, 4]
```

Still 8, not 5

Still 4, not 1

Beware:

As we've seen, the Compiler sometimes inserts padding after fields

So now that you're the "Compiler" ...

Structures: Padding

AARCH64 rules

Data type	Within a struct, field must begin at address that is evenly divisible by:
(unsigned) char	1
(unsigned) short	2
(unsigned) int	4
(unsigned) long	8
float	4
double	8
long double	16
any pointer	8

- Compiler may add padding after last field if struct is within an array

Summary

Intermediate aspects of AARCH64 assembly language...

Flattened C code

Control transfer with signed integers

Control transfer with unsigned integers

Arrays

- Addressing modes

Structures

- Padding

Appendix

Setting and using condition flags in PSTATE register

Setting Condition Flags

Question

- How does `cmp` (or arithmetic instructions with “s” suffix) set condition flags?

Condition Flags

Condition flags

- **N**: **negative** flag: set to 1 iff result is **negative**
- **Z**: **zero** flag: set to 1 iff result is **zero**
- **C**: **carry** flag: set to 1 iff carry/borrow from msb (**unsigned overflow**)
- **V**: **overflow** flag: set to 1 iff **signed overflow** occurred

Condition Flags

Example: `adds dest, src1, src2`

- Compute sum (`src1+src2`)
- Assign sum to `dest`
- N: set to 1 iff sum < 0
- Z: set to 1 iff sum == 0
- C: set to 1 iff unsigned overflow: sum < `src1` or `src2`
- V: set to 1 iff signed overflow:
  (`src1` > 0 && `src2` > 0 && sum < 0) ||
  (`src1` < 0 && `src2` < 0 && sum >= 0)

Condition Flags

Example: `cmp src1, src2`

- Recall that this is a shorthand for `subs xzr, src1, src2`
- Compute sum (`src1`+(-`src2`))
- Throw away result
- N: set to 1 iff sum < 0
- Z: set to 1 iff sum == 0 (i.e., src1 == src2)
- C: set to 1 iff unsigned overflow (i.e., src1 >= src2)
- V: set to 1 iff signed overflow:
  (`src1` > 0 && `src2` < 0 && sum < 0) ||
  (`src1` < 0 && `src2` > 0 && sum >= 0)

Unsigned comparison

Why is carry bit set if src1 >= src2? Informal explanation:

(1) largenum – smallnum

- largenum + (two's complement of smallnum) *does* cause carry
- ⇒ C=1

(2) smallnum – largenum (below)

- smallnum + (two's complement of largenum) *does not* cause carry
- ⇒ C=0

Using Condition Flags

Question

- How do conditional branch instructions use the condition flags?

Answer

- (See following slides)

Conditional Branches: Unsigned

After comparing **unsigned** data

Branch instruction	Use of condition flags
beq label	Z
bne label	~Z
blo label	~C
bhs label	C
bls label	(~C) | Z
bhi label	C & (~Z)

Note:

- If you can understand why `blo` branches iff ~C
- … then the others follow

Conditional Branches: Unsigned

Why does blo branch iff C? Informal explanation:

(1) largenum – smallnum (not below)

- largenum + (two's complement of smallnum) *does* cause carry
- ⇒ C=1 ⇒ don't branch

(2) smallnum – largenum (below)

- smallnum + (two's complement of largenum) *does not* cause carry
- ⇒ C=0 ⇒ branch

Conditional Branches: Signed

After comparing **signed** data

Branch instruction	Use of condition flags
beq label	Z
bne label	~Z
blt label	V ^ N
bge label	~(V ^ N)
ble label	(V ^ N) | Z
bgt label	~((V ^ N) | Z)

Note:

- If you can understand why `blt` branches iff V^N
- … then the others follow

Conditional Branches: Signed

Why does blt branch iff V^N?
Informal explanation:

(1) largeposnum – smallposnum (not less than)

- Certainly correct result
- ⇒ V=0, N=0, V^N==0 ⇒ don’t branch

(2) smallposnum – largeposnum (less than)

- Certainly correct result
- ⇒ V=0, N=1, V^N==1 ⇒ branch

(3) largenegnum – smallnegnum (less than)

- Certainly correct result
- ⇒ V=0, N=1 ⇒ (V^N)==1 ⇒ branch

(4) smallnegnum – largenegnum (not less than)

- Certainly correct result
- ⇒ V=0, N=0 ⇒ (V^N)==0 ⇒ don't branch

Conditional Branches: Signed

(5) posnum – negnum
(not less than)

- Suppose correct result
- ⇒ V=0, N=0 ⇒ (V^N)==0 ⇒ don't branch

(6) posnum – negnum
(not less than)

- Suppose incorrect result
- ⇒ V=1, N=1 ⇒ (V^N)==0 ⇒ don't branch

(7) negnum – posnum
(less than)

- Suppose correct result
- ⇒ V=0, N=1 ⇒ (V^N)==1 ⇒ branch

(8) negnum – posnum
(less than)

- Suppose incorrect result
- ⇒ V=1, N=0 ⇒ (V^N)==1 ⇒ branch