Machine-Level Programming II: Arithmetic & Control

15-213/18-243: Introduction to Computer Systems
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Instructors:
Anthony Rowe, Seth Goldstein and Gregory Kesden

The course that gives CMU its "Zip"!

Last Time: Machine Programming, Basics

```
movl $0x4,%eax

movl %eax,%edx

movl (%eax),%edx
```

%eax
%ecx
%edx
%ebx
%esi
%edi
%esp
%ebp

Today

- Memory addressing modes
- Address computation (`leal`)
- Arithmetic operations
- Control: Condition codes
- Conditional branches & moves
- Loops

Complete Memory Addressing Modes

- Most General Form
- D(Rb,Ri,S) Mem[Reg[Rb]+S*Reg[Ri]+ D]
  - D: Constant "displacement" 1, 2, or 4 bytes
  - Rb: Base register: Any of 8 integer registers
  - Ri: Index register: Any, except for `%esp`
    - Unlikely you'd use `%ebp`, either
  - S: Scale: 1, 2, 4, or 8 (why these numbers?)

- Special Cases
- (Rb,Ri) Mem[Reg[Rb]+Reg[Ri]]
- D(Rb,Ri) Mem[Reg[Rb]+Reg[Ri]+D]
- (Rb,Ri,S) Mem[Reg[Rb]+S*Reg[Ri]]

Address Computation Examples

%edx	0xf000
%ecx	0x0100

Expression	Address Computation	Address
0x8(%edx)	0xf000 + 0x8	0xf008
(%edx,%ecx)	0xf000 + 0x100	0xf100
(%edx,%ecx,4)	0xf000 + 4*0x100	0xf400
0x80(,%edx,2)	2*0xf000 + 0x80	0x1e080

Address Computation Instruction

- `leal` Src,Dest
  - Src is address mode expression
  - Set Dest to address denoted by expression
- Uses
  - Computing addresses without a memory reference
    - E.g., translation of `p = &x[i];`
  - Computing arithmetic expressions of the form x + k*y
    - k = 1, 2, 4, or 8
- Example

```
int mul12(int x)
{
  return x*12;
}
```

Converted to ASM by compiler:

```
leal (%eax,%eax,2), %eax  ;t <- x+x*2
sall $2, %eax             ;return t<<2
```


Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- Control: Condition codes
- Conditional branches
- While loops

Some Arithmetic Operations

- Two Operand Instructions:

Format		Computation	
addl	Src,Dest	Dest = Dest + Src	
subl	Src,Dest	Dest = Dest - Src	
imull	Src,Dest	Dest = Dest * Src	
sall	Src,Dest	Dest = Dest << Src	Also called shll
sarl	Src,Dest	Dest = Dest >> Src	Arithmetic
shrl	Src,Dest	Dest = Dest >> Src	Logical
xorl	Src,Dest	Dest = Dest ^ Src	
andl	Src,Dest	Dest = Dest & Src	
orl	Src,Dest	Dest = Dest | Src	

- Watch out for argument order!
- No distinction between signed and unsigned int (why?)

Some Arithmetic Operations

- One Operand Instructions

`incl`	Dest	Dest = Dest + 1
`decl`	Dest	Dest = Dest - 1
`negl`	Dest	Dest = - Dest
`notl`	Dest	Dest = ~Dest

- See book for more instructions

Arithmetic Expression Example

```
int arith(int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```

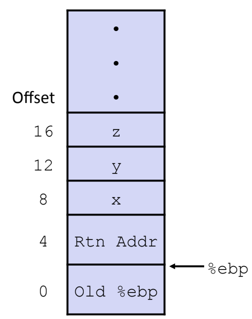
```
arith:
  pushl  %ebp                    } Set
  movl   %esp, %ebp              } Up

  movl   8(%ebp), %ecx           }
  movl   12(%ebp), %edx          }
  leal   (%edx,%edx,2), %eax     }
  sall   $4, %eax                } Body
  leal   4(%ecx,%eax), %eax      }
  addl   %ecx, %edx              }
  addl   16(%ebp), %edx          }
  imull  %edx, %eax              }

  popl   %ebp                    } Finish
  ret                            }
```


Understanding `arith`

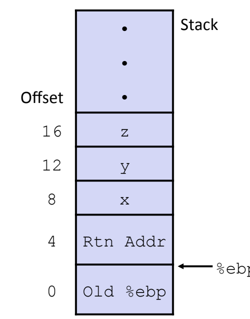
```
int arith(int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
  movl   8(%ebp), %ecx
  movl   12(%ebp), %edx
  leal   (%edx,%edx,2), %eax
  sall   $4, %eax
  leal   4(%ecx,%eax), %eax
  addl   %ecx, %edx
  addl   16(%ebp), %edx
  imull  %edx, %eax
```


Understanding `arith`

```
int arith(int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
  movl   8(%ebp), %ecx           # ecx = x
  movl   12(%ebp), %edx          # edx = y
  leal   (%edx,%edx,2), %eax     # eax = y*3
  sall   $4, %eax                # eax *= 16 (t4)
  leal   4(%ecx,%eax), %eax      # eax = t4 +x+4 (t5)
  addl   %ecx, %edx              # edx = x+y (t1)
  addl   16(%ebp), %edx          # edx += z (t2)
  imull  %edx, %eax              # eax = t2 * t5 (rval)
```

Observations about `arith`

```
int arith(int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```

- Instructions in different order from C code
- Some expressions require multiple instructions
- Some instructions cover multiple expressions
- Get exact same code when compile:
- `(x+y+z)*(x+4+48*y)`

```
movl   8(%ebp), %ecx          # ecx = x
movl   12(%ebp), %edx         # edx = y
leal   (%edx,%edx,2), %eax    # eax = y*3
sall   $4, %eax               # eax *= 16 (t4)
leal   4(%ecx,%eax), %eax     # eax = t4 +x+4 (t5)
addl   %ecx, %edx             # edx = x+y (t1)
addl   16(%ebp), %edx         # edx += z (t2)
imull  %edx, %eax             # eax = t2 * t5 (rval)
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp              } Set Up
    movl %esp,%ebp

    movl 12(%ebp),%eax      } Body
    xorl 8(%ebp),%eax
    sarl $17,%eax
    andl $8185,%eax

    popl %ebp               } Finish
    ret
```

```
movl 12(%ebp),%eax     # eax = y
xorl 8(%ebp),%eax      # eax = x^y        (t1)
sarl $17,%eax          # eax = t1>>17     (t2)
andl $8185,%eax        # eax = t2 & mask  (rval)
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp              } Set Up
    movl %esp,%ebp

    movl 12(%ebp),%eax      } Body
    xorl 8(%ebp),%eax
    sarl $17,%eax
    andl $8185,%eax

    popl %ebp               } Finish
    ret
```

```
movl 12(%ebp),%eax     # eax = y
xorl 8(%ebp),%eax      # eax = x^y        (t1)
sarl $17,%eax          # eax = t1>>17     (t2)
andl $8185,%eax        # eax = t2 & mask  (rval)
```

Another Example

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int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp          } Set
    movl %esp,%ebp      } Up

    movl 12(%ebp),%eax  }
    xorl 8(%ebp),%eax   } Body
    sarl $17,%eax       }
    andl $8185,%eax     }

    popl %ebp           } Finish
    ret                 }
```

```
movl 12(%ebp),%eax    # eax = y
xorl 8(%ebp),%eax     # eax = x^y        (t1)
sarl $17,%eax         # eax = t1>>17     (t2)
andl $8185,%eax       # eax = t2 & mask  (rval)
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp          } Set
    movl %esp,%ebp      } Up

    movl 12(%ebp),%eax  }
    xorl 8(%ebp),%eax   } Body
    sarl $17,%eax       }
    andl $8185,%eax     }

    popl %ebp           } Finish
    ret                 }
```

2^{13} = 8192, 2^{13} – 7 = 8185

```
movl 12(%ebp),%eax    # eax = y
xorl 8(%ebp),%eax     # eax = x^y        (t1)
sarl $17,%eax         # eax = t1>>17     (t2)
andl $8185,%eax       # eax = t2 & mask  (rval)
```


Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- Control: Condition codes
- Conditional branches
- Loops

Processor State (IA32, Partial)

- Information about currently executing program
  - Temporary data (%eax, …)
  - Location of runtime stack (%ebp,%esp)
  - Location of current code control point (%eip, …)
  - Status of recent tests (CF, ZF, SF, OF)

%eax	General purpose registers
%ecx	
%edx	
%ebx	
%esi	
%edi	
%esp	Current stack top
%ebp	Current stack frame
%eip	Instruction pointer
CF ZF SF OF	Condition codes

Condition Codes (Implicit Setting)

- Single bit registers
  - CF Carry Flag (for unsigned) SF Sign Flag (for signed)
  - ZF Zero Flag OF Overflow Flag (for signed)
- Implicitly set (think of it as side effect) by arithmetic operations

  Example: `addl/addq` Src,Dest ↔ `t = a+b`

  CF set if carry out from most significant bit (unsigned overflow)

  ZF set if `t == 0`

  SF set if `t < 0` (as signed)

  OF set if two's-complement (signed) overflow
  `(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`
- Not set by `lea` instruction
- Full documentation (IA32), link on course website

Condition Codes (Explicit Setting: Compare)

- Explicit Setting by Compare Instruction
  - `cmpl/cmpq` Src2, Src1
  - `cmpl b,a` like computing `a-b` without setting destination

  - CF set if carry out from most significant bit (used for unsigned comparisons)
  - ZF set if `a == b`
  - SF set if `(a-b) < 0` (as signed)
  - OF set if two's-complement (signed) overflow
  `(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

Condition Codes (Explicit Setting: Test)

- Explicit Setting by Test instruction
  - `testl/testq` Src2, Src1
  `testl b,a` like computing `a&b` without setting destination

  - Sets condition codes based on value of Src1 & Src2
  - Useful to have one of the operands be a mask

  - ZF set when `a&b == 0`
  - SF set when `a&b < 0`

Reading Condition Codes

- SetX Instructions
  - Set single byte based on combinations of condition codes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~ZF`	Not Equal / Not Zero
`sets`	`SF`	Negative
`setns`	`~SF`	Nonnegative
`setg`	`~(SF^OF)&~ZF`	Greater (Signed)
`setge`	`~(SF^OF)`	Greater or Equal (Signed)
`setl`	`(SF^OF)`	Less (Signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

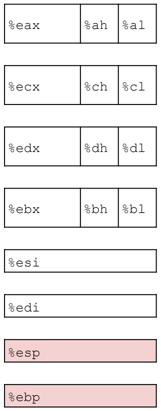
Reading Condition Codes (Cont.)

- SetX Instructions:
  - Set single byte based on combination of condition codes
- One of 8 addressable byte registers
  - Does not alter remaining 3 bytes
  - Typically use `movzbl` to finish job

```
int gt (int x, int y)
{
  return x > y;
}
```

Body

```
movl 12(%ebp),%eax    # eax = y
cmpl %eax,8(%ebp)     # Compare x : y
setg %al              # al = x > y
movzbl %al,%eax       # Zero rest of %eax
```



Reading Condition Codes: x86-64

- SetX Instructions:
  - Set single byte based on combination of condition codes
  - Does not alter remaining 3 bytes

```
int gt (long x, long y)
{
  return x > y;
}
```

```
long lgt (long x, long y)
{
  return x > y;
}
```

Bodies

```
cmpl %esi, %edi
setg %al
movzbl %al, %eax
```

```
cmpq %rsi, %rdi
setg %al
movzbl %al, %eax
```

Is `%rax` zero?
Yes: 32-bit instructions set high order 32 bits to 0!

Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- x86-64
- Control: Condition codes
- Conditional branches & Moves
- Loops

Jumping

- jX Instructions
  - Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (Signed)
`jge`	`~(SF^OF)`	Greater or Equal (Signed)
`jl`	`(SF^OF)`	Less (Signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jb`	`CF`	Below (unsigned)

Conditional Branch Example

```
int absdiff(int x, int y)
{
    int result;
    if (x > y) {
      result = x-y;
    } else {
      result = y-x;
    }
    return result;
}
```

```
absdiff:
    pushl   %ebp              } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx     } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L6
    subl    %eax, %edx        } Body2a
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax           } Body2b
.L7:
    popl %ebp                 } Finish
    ret
```


Conditional Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

- C allows "goto" as means of transferring control
  - Closer to machine-level programming style
- Generally considered bad coding style

```
absdiff:
    pushl   %ebp              } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx     } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L6
    subl    %eax, %edx        } Body2a
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax           } Body2b
.L7:
    popl %ebp                 } Finish
    ret
```


Conditional Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

```
absdiff:
    pushl   %ebp              } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx     } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L6
    subl    %eax, %edx        } Body2a
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax           } Body2b
.L7:
    popl %ebp                 } Finish
    ret
```


Conditional Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

```
absdiff:
    pushl   %ebp              } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx     } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L6
    subl    %eax, %edx        } Body2a
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax           } Body2b
.L7:
    popl %ebp                 } Finish
    ret
```

Conditional Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

```
absdiff:
   pushl  %ebp              } Setup
   movl   %esp, %ebp
   movl   8(%ebp), %edx     } Body1
   movl   12(%ebp), %eax
   cmpl   %eax, %edx
   jle    .L6
   subl   %eax, %edx        } Body2a
   movl   %edx, %eax
   jmp .L7
.L6:
   subl %edx, %eax          } Body2b
.L7:
   popl %ebp                } Finish
   ret
```


General Conditional Expression Translation

C Code

```
val = Test ? Then_Expr : Else_Expr;
```

```
val = x>y ? x-y : y-x;
```

Goto Version

```
  nt = !Test;
  if (nt) goto Else;
  val = Then_Expr;
  goto Done;
Else:
  val = Else_Expr;
Done:
  . . .
```

- Test is expression returning integer
  - = 0 interpreted as false
  - ≠ 0 interpreted as true
- Create separate code regions for then & else expressions
- Execute appropriate one

Using Conditional Moves

- Conditional Move Instructions
  - Instruction supports:
    if (Test) Dest ← Src
  - Supported in post-1995 x86 processors
  - GCC does not always use them
    - Wants to preserve compatibility with ancient processors
    - Enabled for x86-64
    - Use switch `-march=686` for IA32
- Why?
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional move do not require control transfer

C Code

```
val = Test
   ? Then_Expr
   : Else_Expr;
```

Goto Version

```
  tval = Then_Expr;
  result = Else_Expr;
  t = Test;
  if (t) result = tval;
  return result;
```


Conditional Move Example: x86-64

```
int absdiff(int x, int y)  {
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

x in %edi

y in %esi

```
absdiff:
  movl    %edi, %edx
  subl    %esi, %edx   # tval = x-y
  movl    %esi, %eax
  subl    %edi, %eax   # result = y-x
  cmpl    %esi, %edi   # Compare x:y
  cmovg   %edx, %eax   # If >, result = tval
  ret
```

Bad Cases for Conditional Move

Expensive Computations

```
val = Test(x) ? Hard1(x) : Hard2(x);
```

- Both values get computed
- Only makes sense when computations are very simple

Risky Computations

```
val = p ? *p : 0;
```

- Both values get computed
- May have undesirable effects

Computations with side effects

```
val = x > 0 ? x*=7 : x+=3;
```

- Both values get computed
- Must be side-effect free

Today

- Complete addressing mode, address computation (leal)
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- x86-64
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"Do-While" Loop Example

C Code

```
int pcount_do(unsigned x)
{
  int result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto Version

```
int pcount_do(unsigned x)
{
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

- Count number of 1's in argument x ("popcount")
- Use conditional branch to either continue looping or to exit loop

"Do-While" Loop Compilation

Goto Version

```
int pcount_do(unsigned x) {
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

- Registers:

%edx	x
%ecx	result

```
    movl  $0, %ecx      #   result = 0
.L2:                    # loop:
    movl  %edx, %eax
    andl  $1, %eax      #   t = x & 1
    addl  %eax, %ecx    #   result += t
    shrl  %edx          #   x >>= 1
    jne   .L2           #   If !0, goto loop
```

General "Do-While" Translation

C Code

```
do
  Body
  while (Test);
```

Goto Version

```
loop:
  Body
  if (Test)
    goto loop
```

- Body: {
  $\texttt{Statement}_1$;
  $\texttt{Statement}_2$;
  …
  $\texttt{Statement}_n$;
  }
- Test returns integer
  - = 0 interpreted as false
  - ≠ 0 interpreted as true

"While" Loop Example

C Code

```
int pcount_while(unsigned x) {
  int result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Goto Version

```
int pcount_do(unsigned x) {
  int result = 0;
  if (!x) goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
done:
  return result;
}
```

- Is this code equivalent to the do-while version?

General "While" Translation

While version

```
while (Test)
  Body
```

Do-While Version

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```

Goto Version

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```


"For" Loop Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- Is this code equivalent to other versions?

"For" Loop Form

General Form

```
for (Init; Test; Update )

      Body
```

```
for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned mask = 1 << i;
  result += (x & mask) != 0;
}
```


"For" Loop → While Loop

For Version

```
for (Init; Test; Update )

      Body
```

While Version

```
Init ;

while (Test ) {

    Body

    Update ;

}
```


"For" Loop → … → Goto

For Version

```
for (Init; Test; Update )

    Body
```

While Version

```
Init;

while (Test ) {

    Body

    Update;

}
```

```
  Init;
  if (!Test)
    goto done;
  do
    Body
    Update
  while(Test);
done:
```

```
  Init;
  if (!Test)
    goto done;
loop:
  Body
  Update
  if (Test)
    goto loop;
done:
```


"For" Loop Conversion Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- Initial test can be optimized away

Goto Version

```
int pcount_for_gt(unsigned x) {
  int i;
  int result = 0;           Init
  i = 0;
  if (!(i < WSIZE))         !Test
    goto done;
 loop:                      Body
  {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  i++;  Update
  if (i < WSIZE)  Test
    goto loop;
 done:
  return result;
}
```

Summary

- Today
  - Complete addressing mode, address computation (`leal`)
  - Arithmetic operations
  - Control: Condition codes
  - Conditional branches & conditional moves
  - Loops
- Next Time
  - Switch statements
  - Stack
  - Call / return
  - Procedure call discipline