CSE P 501 – Compilers

x86-64 Lite for Compiler Writers
A quick (a) introduction (b) review
[pick one]

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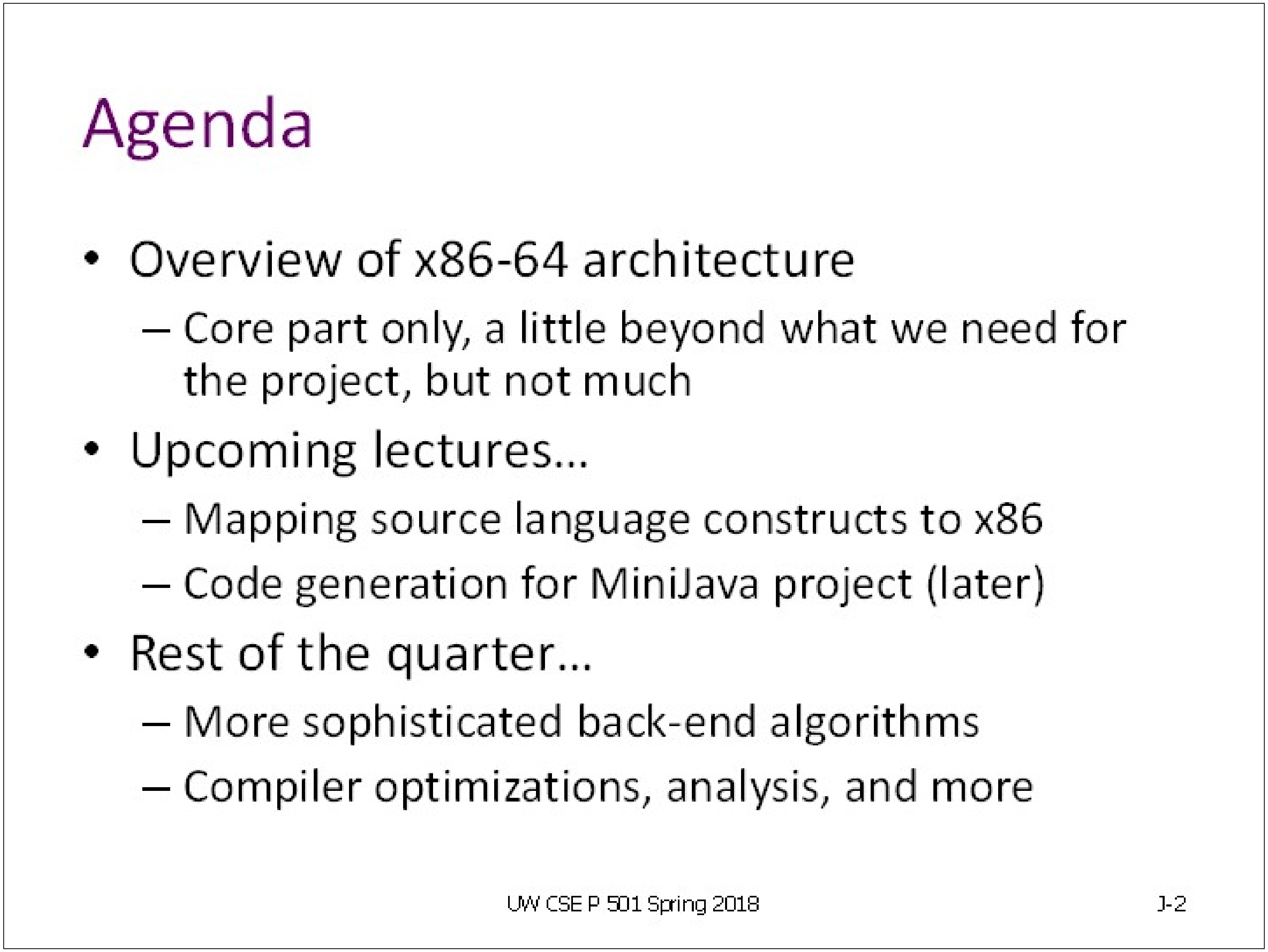
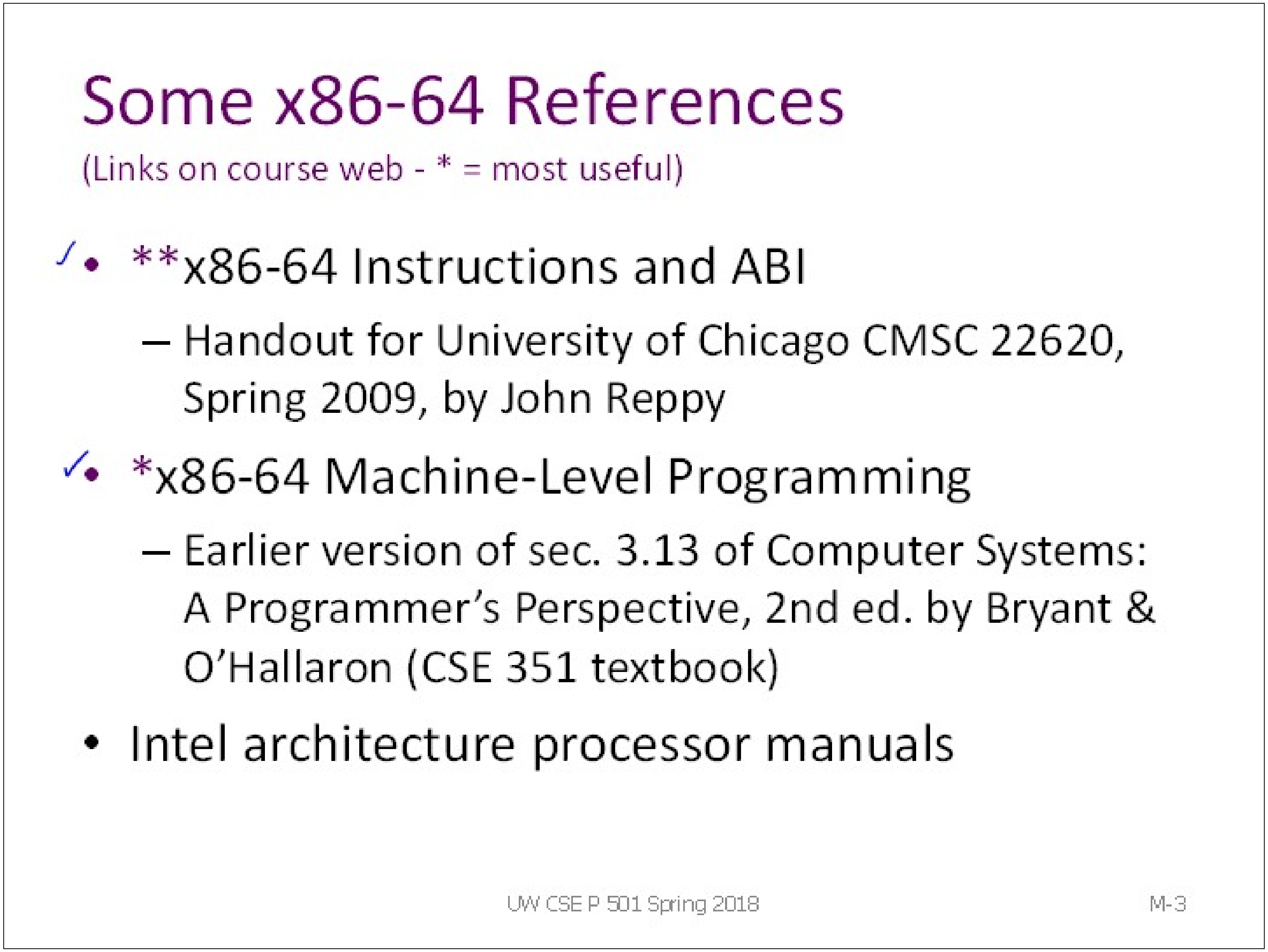
Spring 2018



Agenda

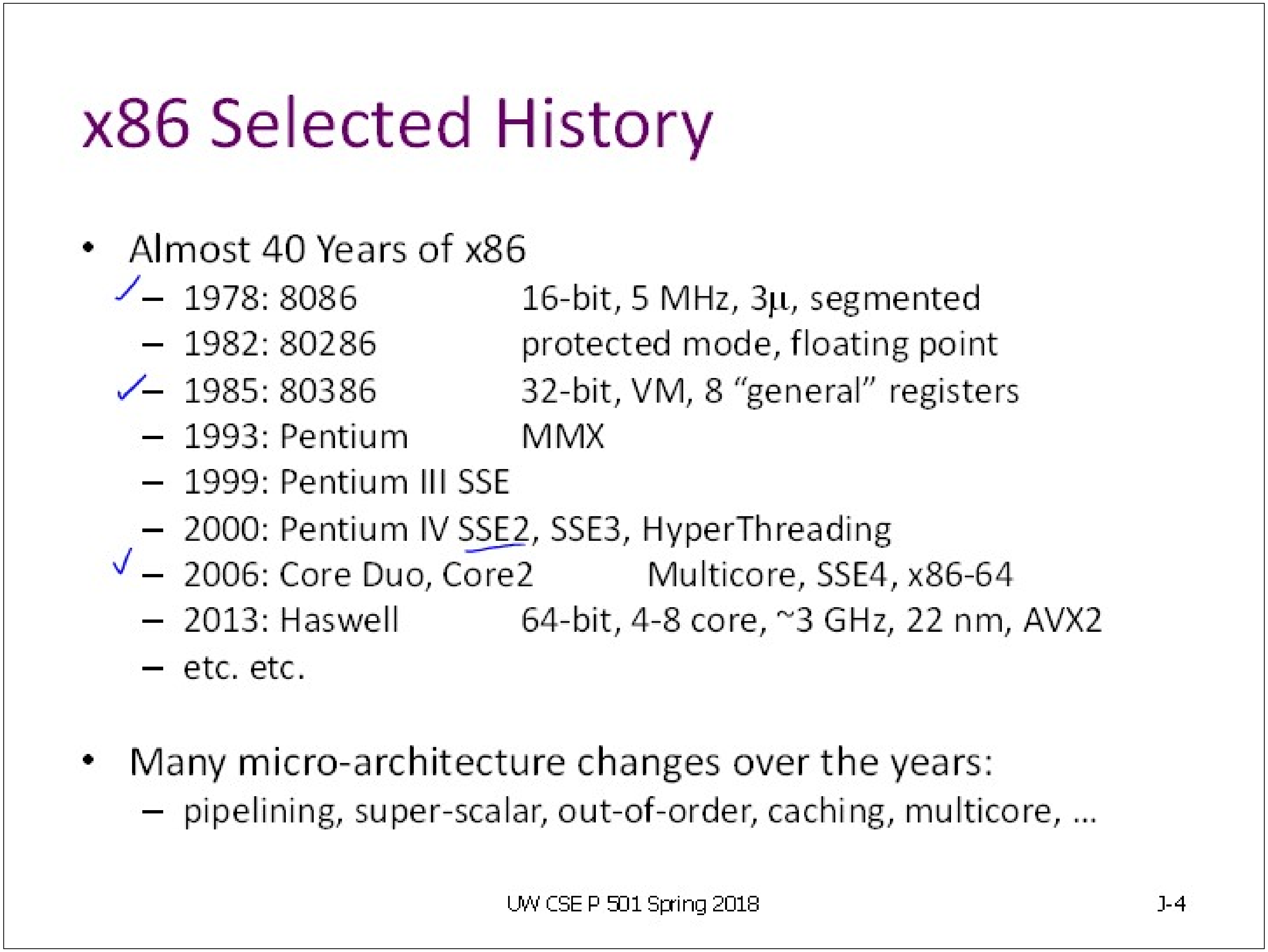
- Overview of x86-64 architecture
  - Core part only, a little beyond what we need for the project, but not much
- Upcoming lectures...
  - Mapping source language constructs to x86
  - Code generation for MiniJava project (later)
- Rest of the quarter...
  - More sophisticated back-end algorithms
  - Compiler optimizations, analysis, and more



Some x86-64 References

(Links on course web - * = most useful)

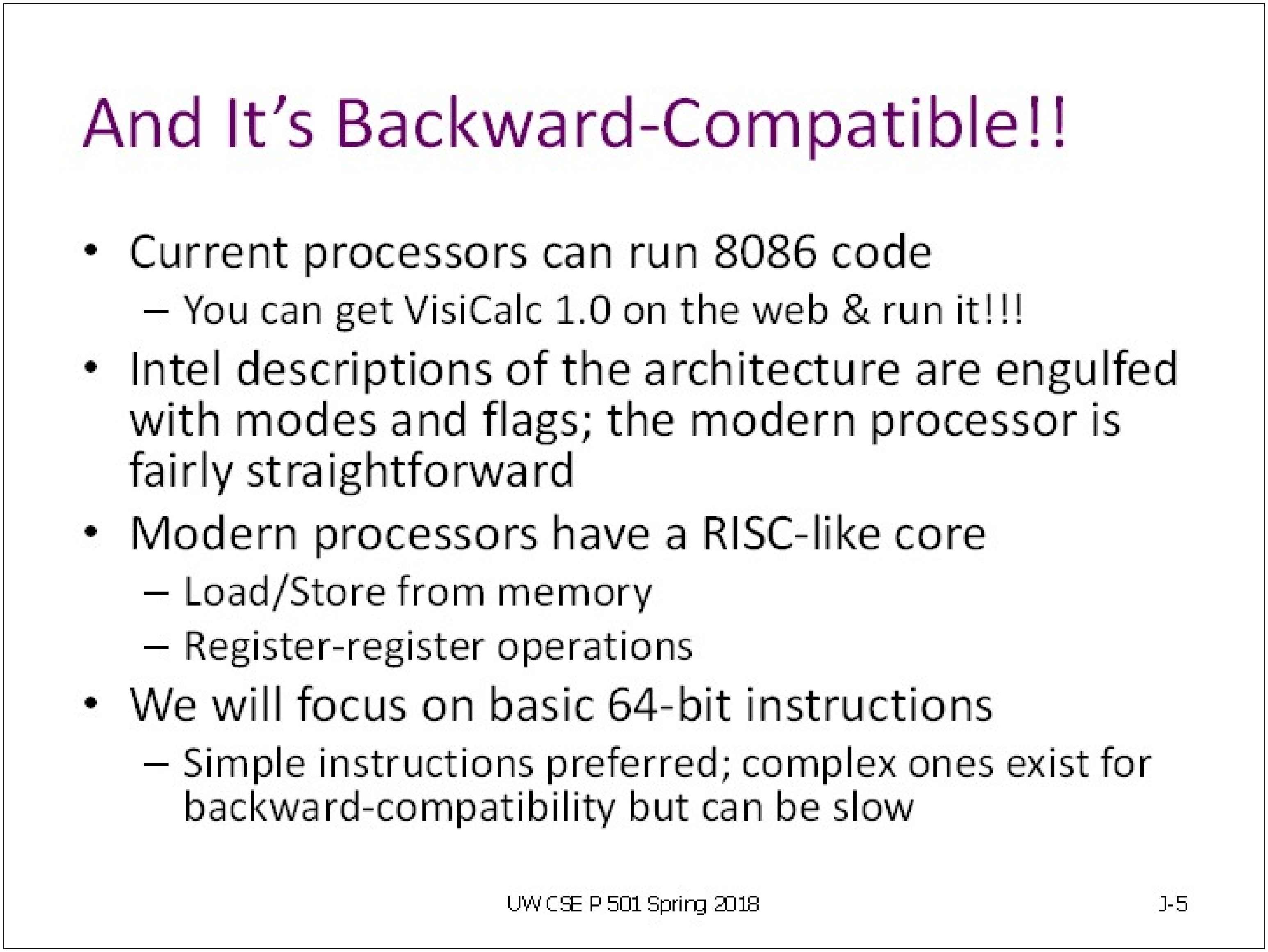
- ✓ **x86-64 Instructions and ABI
  - – Handout for University of Chicago CMSC 22620, Spring 2009, by John Reppy
- ✓ *x86-64 Machine-Level Programming
  - – Earlier version of sec. 3.13 of Computer Systems: A Programmer’s Perspective, 2nd ed. by Bryant & O’Hallaron (CSE 351 textbook)
- Intel architecture processor manuals



x86 Selected History

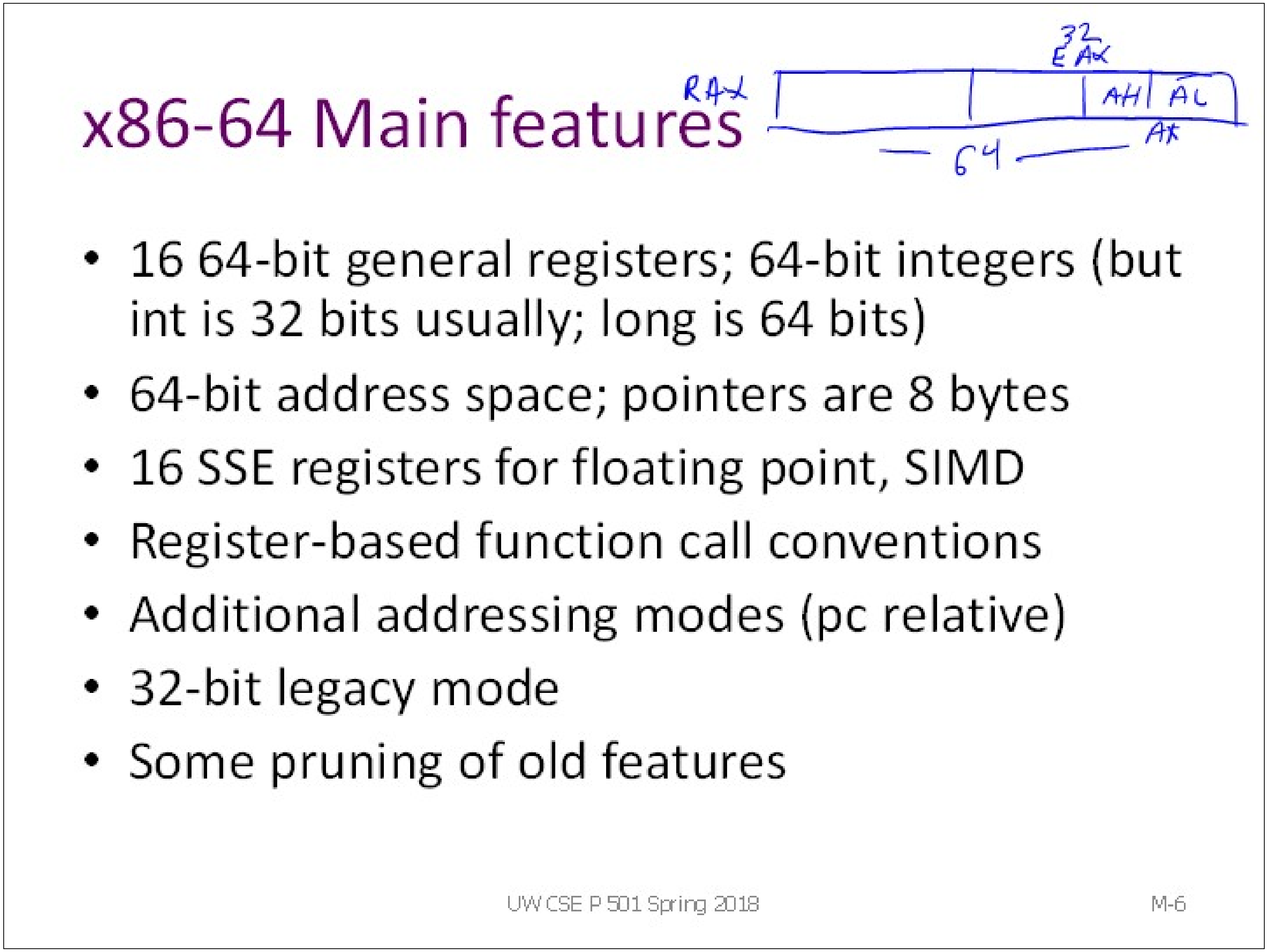
- Almost 40 Years of x86
  - ✓ 1978: 8086 16-bit, 5 MHz, 3μ, segmented
  - 1982: 80286 protected mode, floating point
  - ✓ 1985: 80386 32-bit, VM, 8 "general" registers
  - 1993: Pentium MMX
  - 1999: Pentium III SSE
  - 2000: Pentium IV SSE2, SSE3, HyperThreading
  - ✓ 2006: Core Duo, Core2 Multicore, SSE4, x86-64
  - 2013: Haswell 64-bit, 4-8 core, ~3 GHz, 22 nm, AVX2
  - etc. etc.

- Many micro-architecture changes over the years:
  - pipelining, super-scalar, out-of-order, caching, multicore, …



And It’s Backward-Compatible!!

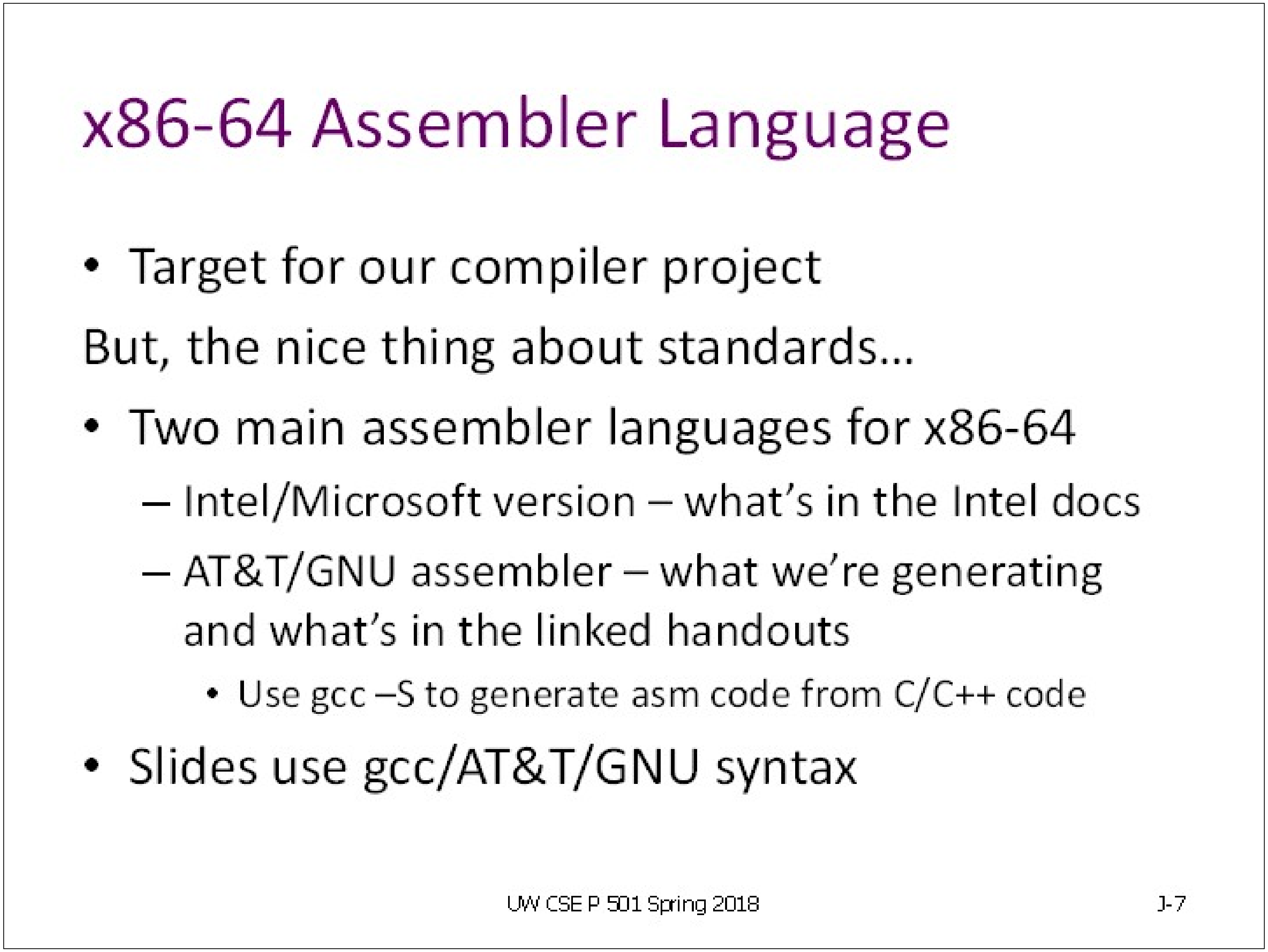
- Current processors can run 8086 code
  - You can get VisiCalc 1.0 on the web & run it!!!
- Intel descriptions of the architecture are engulfed with modes and flags; the modern processor is fairly straightforward
- Modern processors have a RISC-like core
  - Load/Store from memory
  - Register-register operations
- We will focus on basic 64-bit instructions
  - Simple instructions preferred; complex ones exist for backward-compatibility but can be slow



32
EAX
RAX
AH
AL
AX
64

x86-64 Main features

- 16 64-bit general registers; 64-bit integers (but int is 32 bits usually; long is 64 bits)
- 64-bit address space; pointers are 8 bytes
- 16 SSE registers for floating point, SIMD
- Register-based function call conventions
- Additional addressing modes (pc relative)
- 32-bit legacy mode
- Some pruning of old features

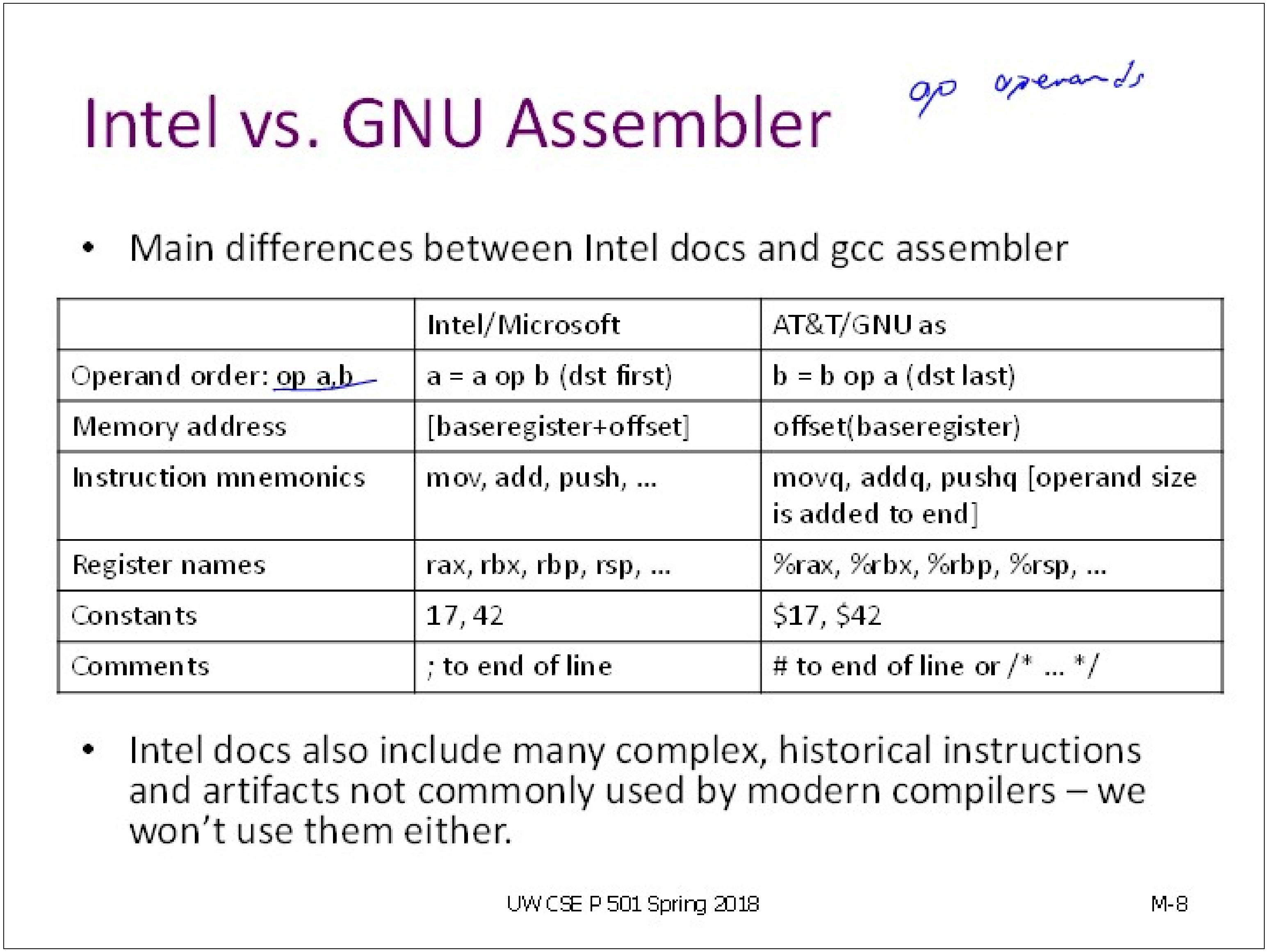


x86-64 Assembler Language

- Target for our compiler project

But, the nice thing about standards…

- Two main assembler languages for x86-64
  - Intel/Microsoft version – what's in the Intel docs
  - AT&T/GNU assembler – what we're generating and what's in the linked handouts
    - Use gcc –S to generate asm code from C/C++ code
- Slides use gcc/AT&T/GNU syntax



Intel vs. GNU Assembler

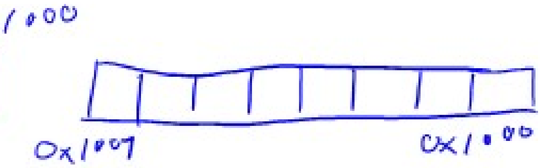
op operands

- Main differences between Intel docs and gcc assembler

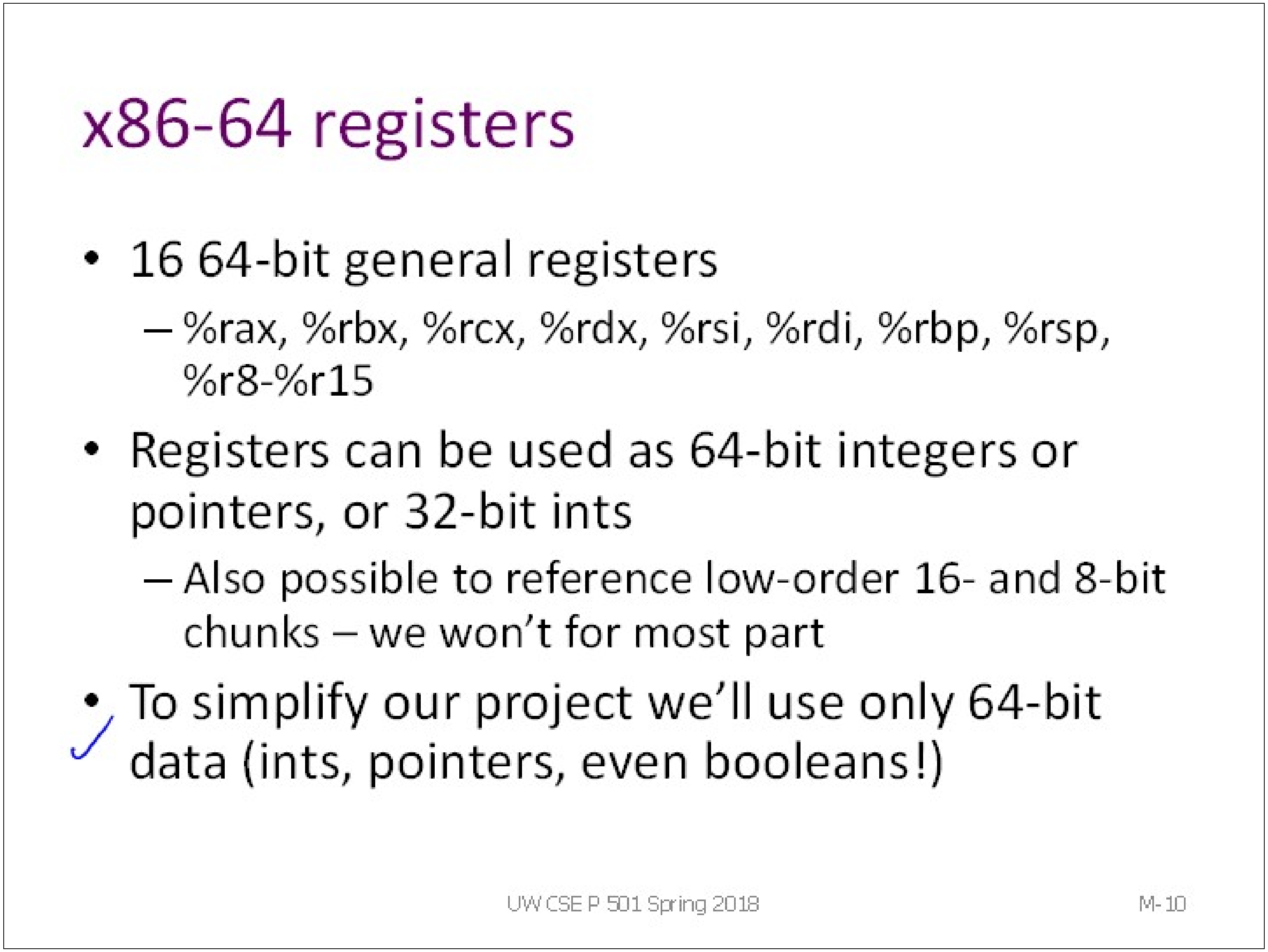
	Intel/Microsoft	AT&T/GNU as
Operand order: op a,b	a = a op b (dst first)	b = b op a (dst last)
Memory address	[baseregister+offset]	offset(baseregister)
Instruction mnemonics	mov, add, push, …	movq, addq, pushq [operand size is added to end]
Register names	rax, rbx, rbp, rsp, …	%rax, %rbx, %rbp, %rsp, …
Constants	17, 42	$17, $42
Comments	; to end of line	# to end of line or /* … */

- Intel docs also include many complex, historical instructions and artifacts not commonly used by modern compilers – we won't use them either.

x86-64 Memory Model

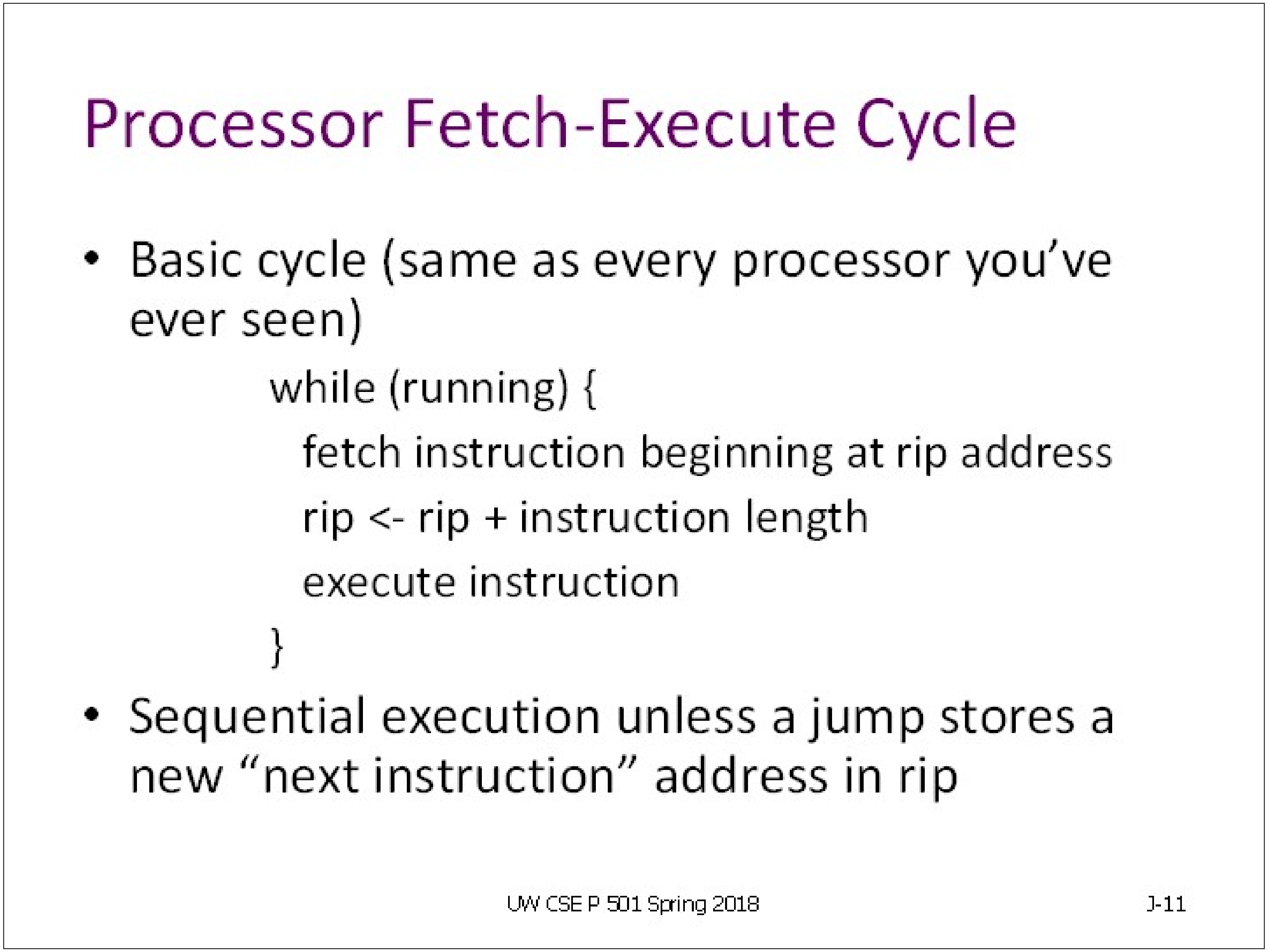


- 8-bit bytes, byte addressable
- 16-, 32-, 64-bit words, double words and quad words (Intel terminology)
  - That's why the 'q' in 64-bit instructions like movq, addq, etc.
- Data should normally be aligned on "natural" boundaries for performance, although unaligned accesses are generally supported – but with a big performance penalty on many machines
- Little-endian – address of a multi-byte integer is address of low-order byte



x86-64 registers

- 16 64-bit general registers
  - %rax, %rbx, %rcx, %rdx, %rsi, %rdi, %rbp, %rsp, %r8-%r15
- Registers can be used as 64-bit integers or pointers, or 32-bit ints
  - Also possible to reference low-order 16- and 8-bit chunks – we won't for most part
- ✓ To simplify our project we'll use only 64-bit data (ints, pointers, even booleans!)

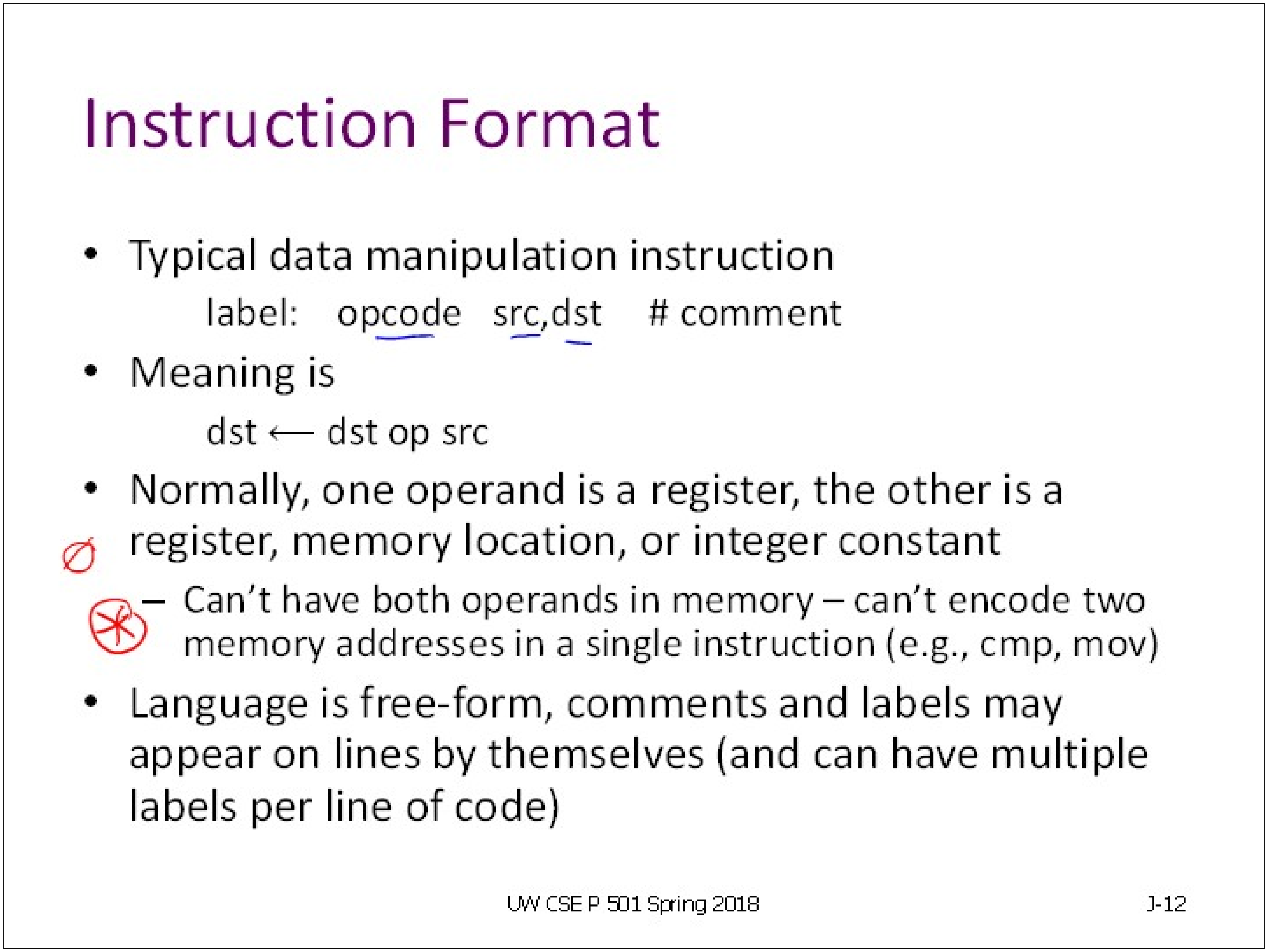


Processor Fetch-Execute Cycle

- Basic cycle (same as every processor you've ever seen)

```
while (running) {
  fetch instruction beginning at rip address
  rip <- rip + instruction length
  execute instruction
}
```

- Sequential execution unless a jump stores a new "next instruction" address in rip



Instruction Format

- Typical data manipulation instruction

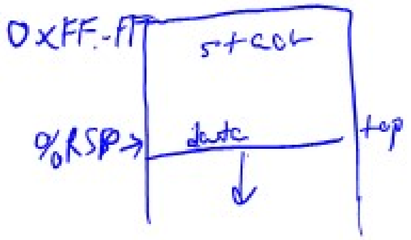
  label: opcode src,dst # comment

- Meaning is

  dst ⟵ dst op src

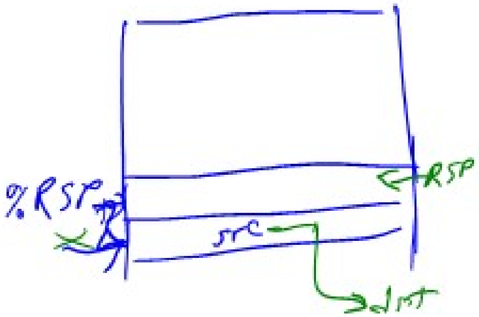
- Normally, one operand is a register, the other is a register, memory location, or integer constant ∅
  - ⊛ Can't have both operands in memory – can't encode two memory addresses in a single instruction (e.g., cmp, mov)
- Language is free-form, comments and labels may appear on lines by themselves (and can have multiple labels per line of code)

x86-64 Memory Stack



- Register %rsp points to the “top” of stack
  - Dedicated for this use; don’t use otherwise
  - Points to the last 64-bit quadword pushed onto the stack (not next “free” quadword)
  - Should always be quadword (8-byte) aligned
    - It will start out this way, and will stay aligned unless your code does something bad
    - ✓ Software generally requires 16-byte alignment when function is called
  - Stack grows down

Stack Instructions



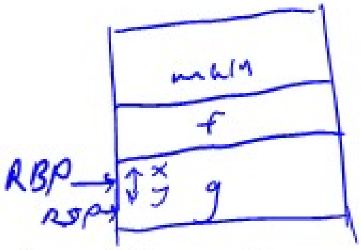
✓pushq src

%rsp ⟵ %rsp – 8; memory[%rsp] ⟵ src
(e.g., push src onto the stack)

✓popq dst

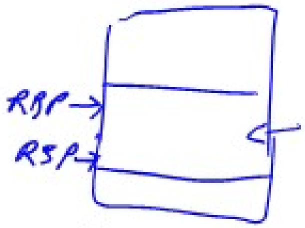
dst ⟵ memory[%rsp]; %rsp ⟵ %rsp + 8
(e.g., pop top of stack into dst and logically remove it from the stack)

Stack Frames



- When a method is called, a stack frame is traditionally allocated on logical "top" of the stack to hold its local variables
- Frame is popped on method return
- By convention, %rbp (base pointer) points to a known offset into the stack frame
  - Local variables referenced relative to %rbp
  - Base pointer common in 32-bit x86 code; less so in x86-64 code where push/pop used less & stack frame normally has fixed size so locals can be referenced from %rsp easily
  - We will use %rbp in our project – simplifies addressing of local variables and compiler bookkeeping

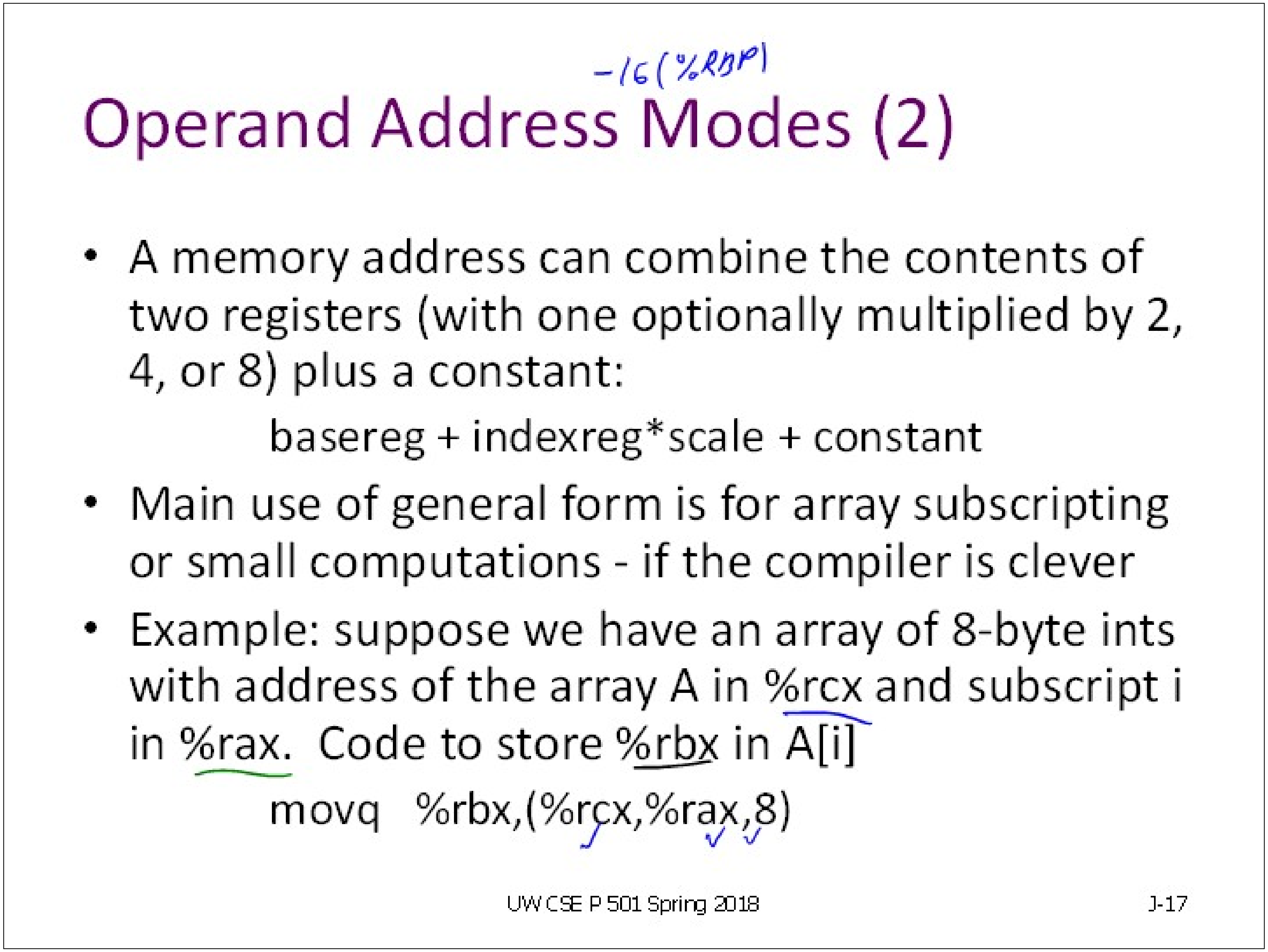
Operand Address Modes (1)



- These should cover most of what we'll need

```
movq  $17,%rax           # store 17 in %rax
movq  %rcx,%rax          # copy %rcx to %rax
movq  16(%rbp),%rax      # copy memory to %rax
movq  %rax,-24(%rbp)     # copy %rax to memory
```

- References to object fields work similarly – put the object's memory address in a register and use that address plus an offset
- Remember: can't have two memory addresses in a single instruction



-16(%RBP)

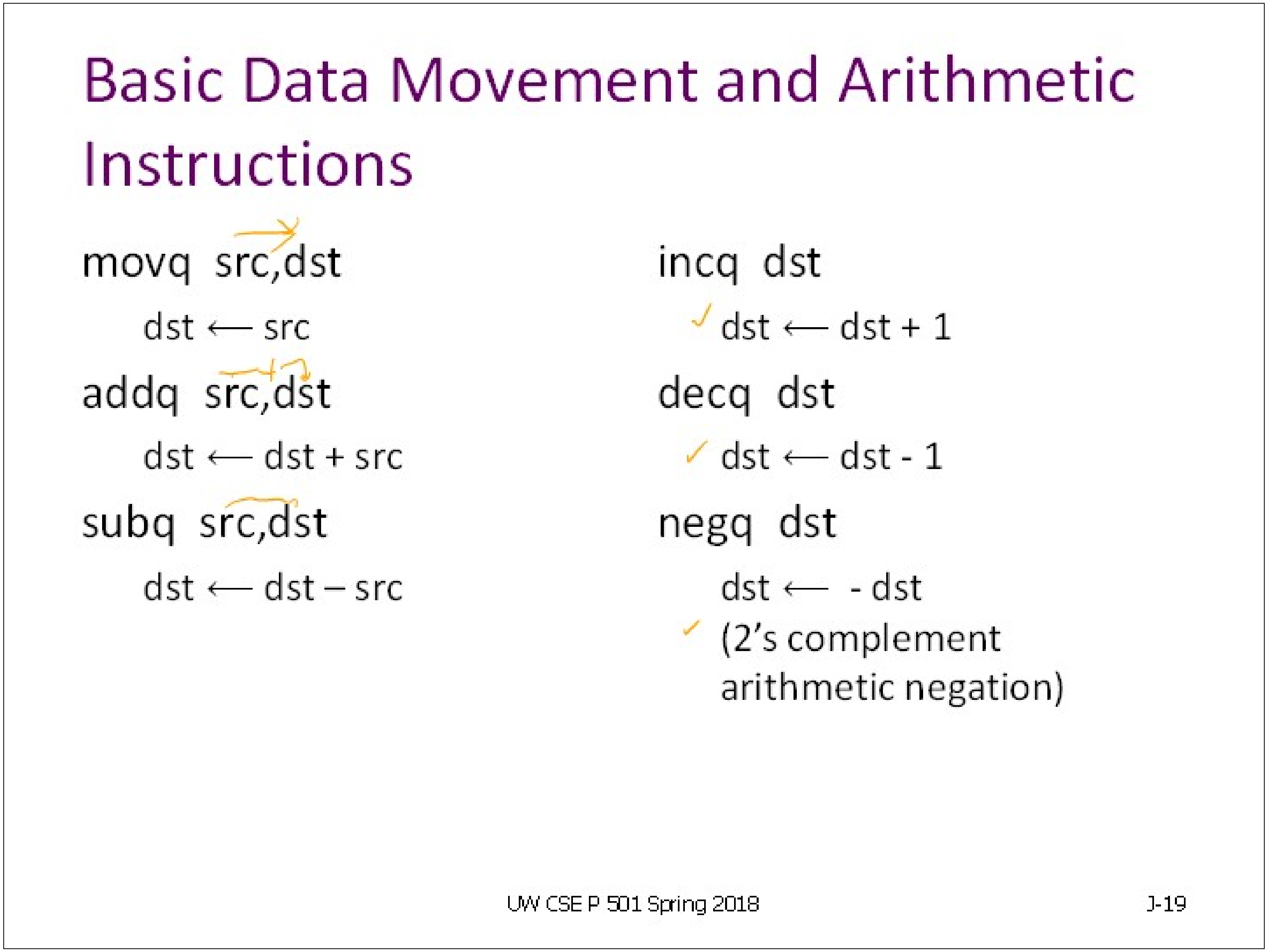
Operand Address Modes (2)

- A memory address can combine the contents of two registers (with one optionally multiplied by 2, 4, or 8) plus a constant:

  basereg + indexreg*scale + constant

- Main use of general form is for array subscripting or small computations - if the compiler is clever
- Example: suppose we have an array of 8-byte ints with address of the array A in %rcx and subscript i in %rax. Code to store %rbx in A[i]

```
movq   %rbx,(%rcx,%rax,8)
```



Basic Data Movement and Arithmetic Instructions

movq src,dst

dst ⟵ src

addq src,dst

dst ⟵ dst + src

subq src,dst

dst ⟵ dst – src

incq dst

✓ dst ⟵ dst + 1

decq dst

✓ dst ⟵ dst - 1

negq dst

dst ⟵ - dst

✓ (2’s complement arithmetic negation)

Integer Multiply and Divide

imulq src,dst

dst ⟵ dst * src

dst must be a register

cqto

%rdx:%rax ⟵ 128-bit sign extended copy of %rax

(why??? To prep numerator for idivq!)

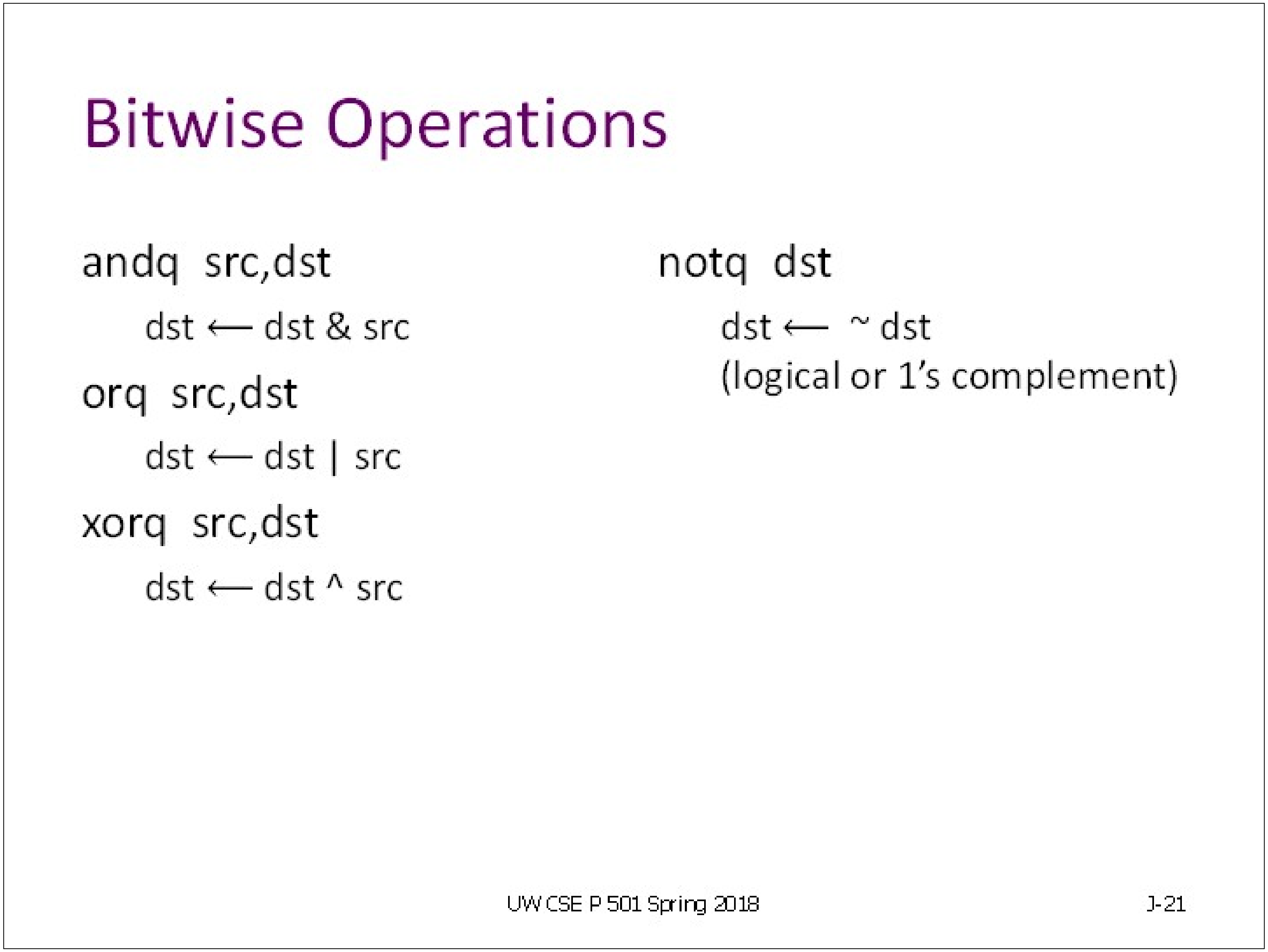
✓ idivq src

Divide %rdx:%rax by src (%rdx:%rax holds sign-extended 128-bit value; cannot use other registers for division)

✓ %rax ⟵ quotient

✓ %rdx ⟵ remainder

(no division in MiniJava!)



Bitwise Operations

andq src,dst

dst ⟵ dst & src

orq src,dst

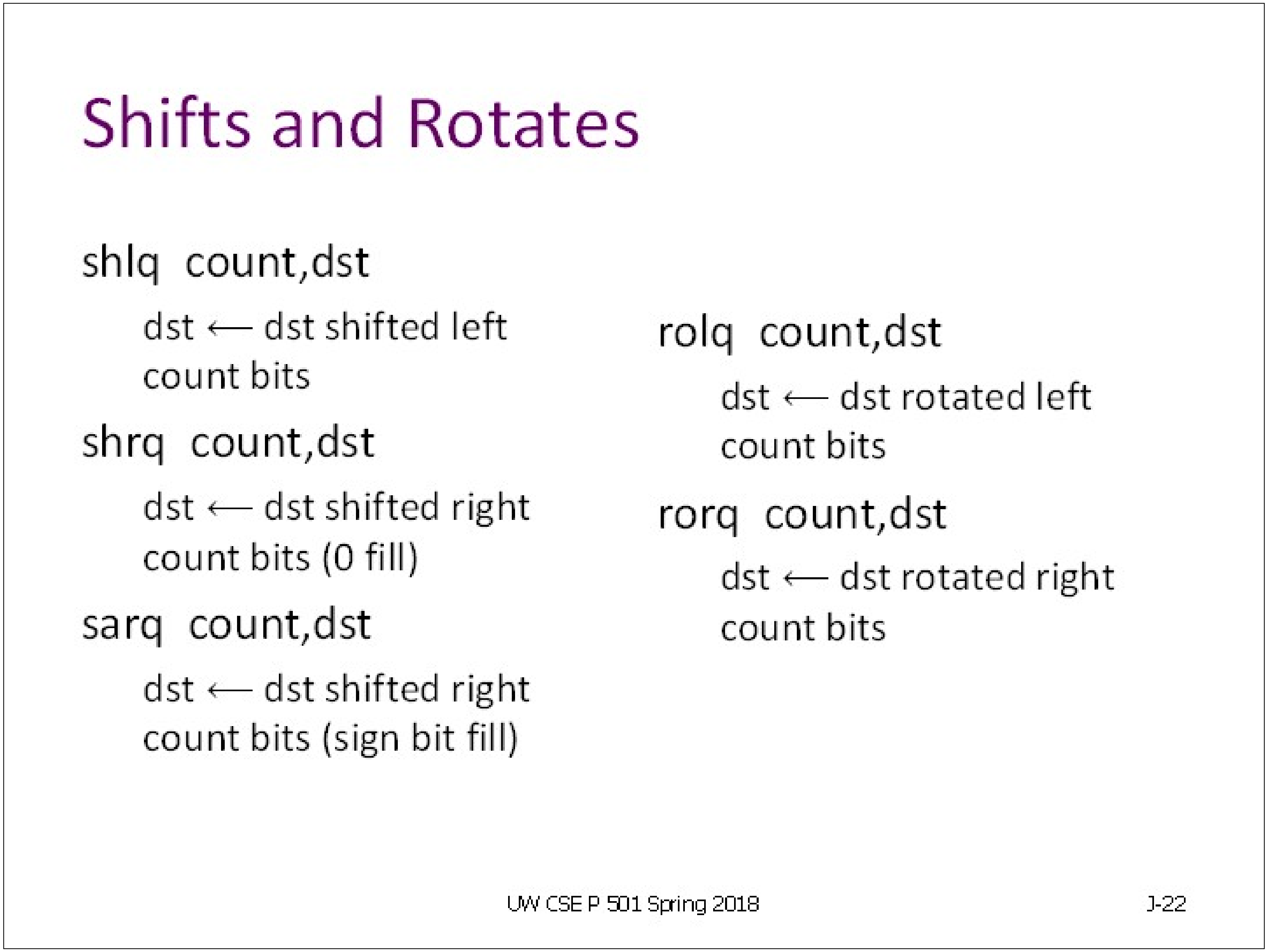
dst ⟵ dst | src

xorq src,dst

dst ⟵ dst ^ src

notq dst

dst ⟵ ~ dst
(logical or 1's complement)



Shifts and Rotates

shlq count,dst

dst ← dst shifted left count bits

shrq count,dst

dst ← dst shifted right count bits (0 fill)

sarq count,dst

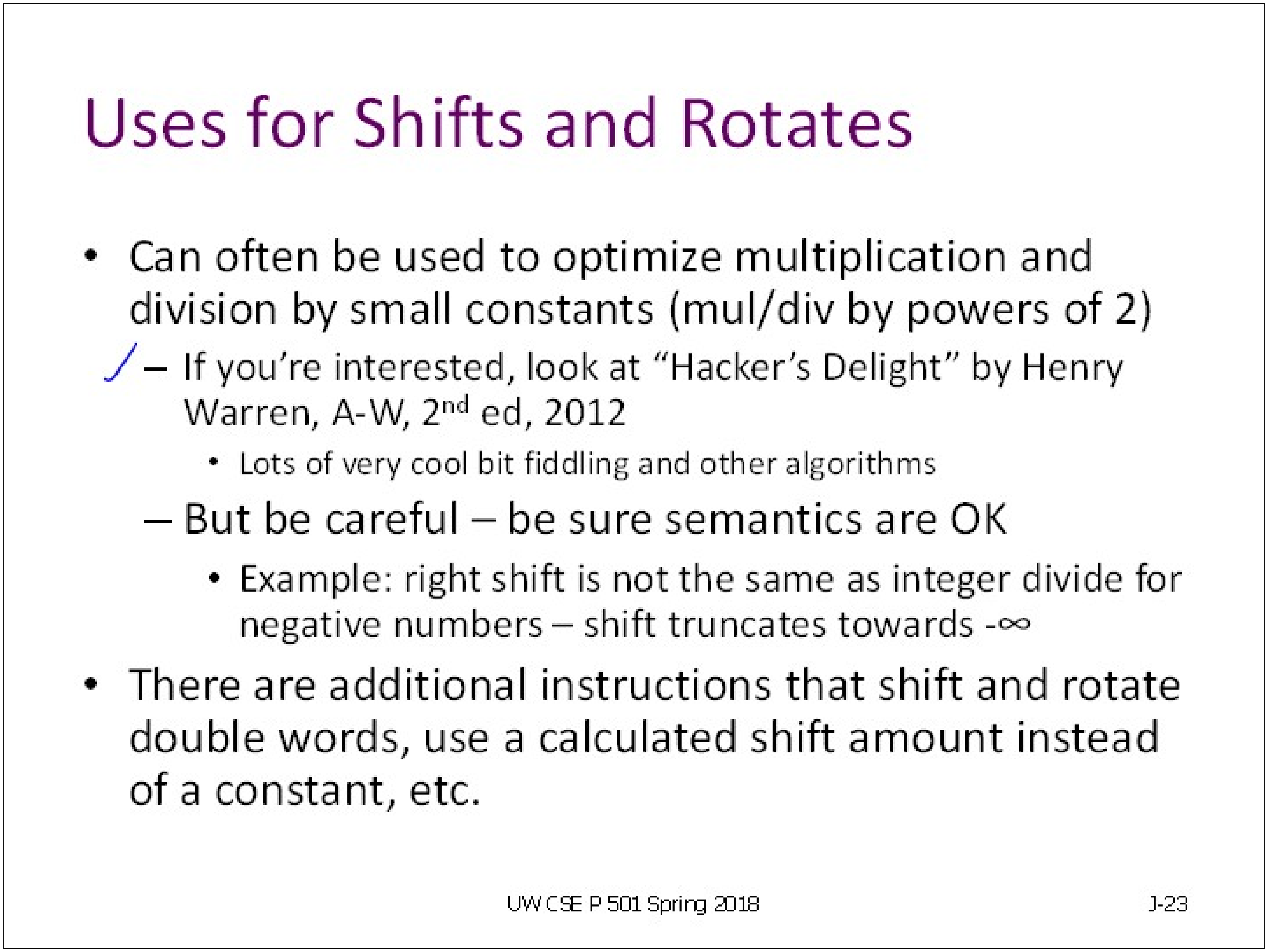
dst ← dst shifted right count bits (sign bit fill)

rolq count,dst

dst ← dst rotated left count bits

rorq count,dst

dst ← dst rotated right count bits



Uses for Shifts and Rotates

- Can often be used to optimize multiplication and division by small constants (mul/div by powers of 2)
  - – If you're interested, look at "Hacker's Delight" by Henry Warren, A-W, 2nd ed, 2012
    - Lots of very cool bit fiddling and other algorithms
  - – But be careful – be sure semantics are OK
    - Example: right shift is not the same as integer divide for negative numbers – shift truncates towards -∞
- There are additional instructions that shift and rotate double words, use a calculated shift amount instead of a constant, etc.

int *p = & a[k]

Load Effective Address

- The unary & operator in C/C++

```
leaq  src,dst        # dst ⟵ address of src
```

  - dst must be a register
  - Address of src includes any address arithmetic or indexing
  - Useful to capture addresses for pointers, reference parameters, etc.
  - Also useful for computing arithmetic expressions that match r1 + scale*r2 + const

Control Flow - GOTO

- At this level, all we have is goto and conditional goto
- Loops and conditional statements are synthesized from these
- Note: random jumps play havoc with pipeline efficiency; much work is done in modern compilers and processors to minimize this impact

Unconditional Jumps

jmp dst

    %rip ← address of dst

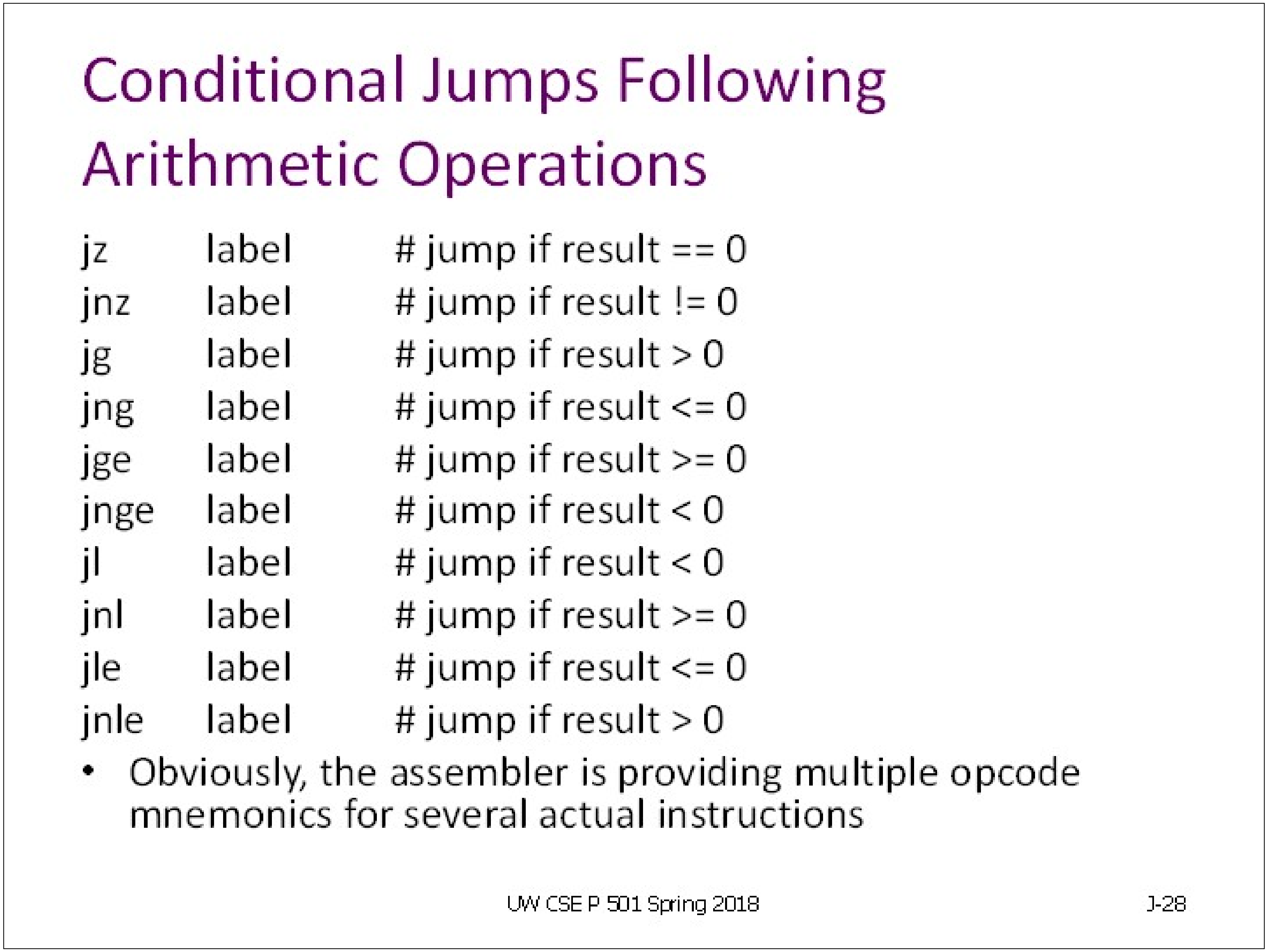
- dst is usually a label in the code (which can be on a line by itself)
- dst address can also be indirect using the address in a register or memory location (*reg or *(reg)) – use for method calls, switch

Conditional Jumps

- Most arithmetic instructions set "condition code" bits to record information about the result (zero, non-zero, >0, etc.)
  - True of addq, subq, andq, orq; but not imulq, idivq, leaq
- Other instructions that set condition codes

```
cmpq src,dst     # compare dst to src (e.g., dst-src)
testq src,dst    # calculate dst & src (logical and)
```

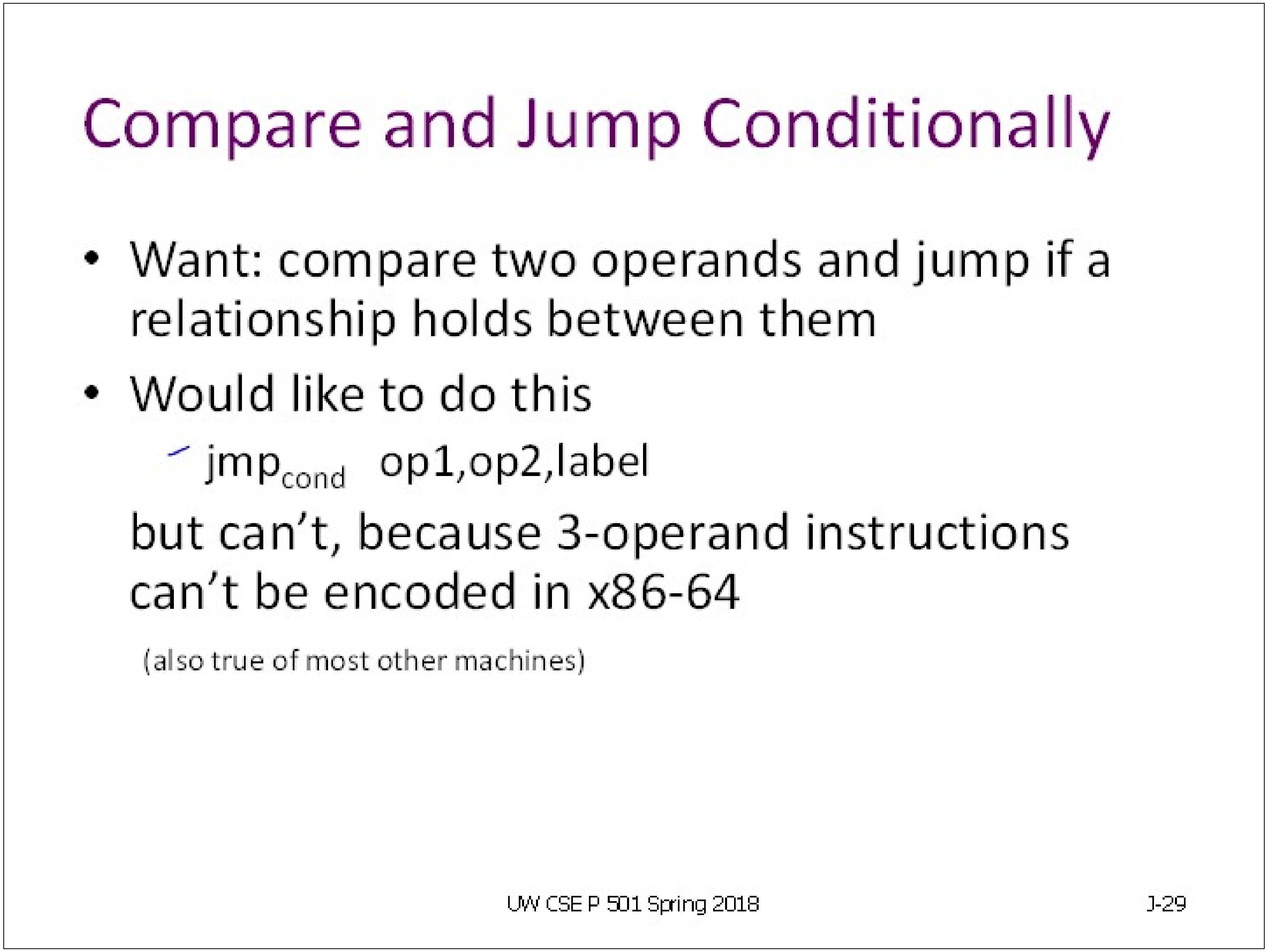
  - These do not alter src or dst



Conditional Jumps Following Arithmetic Operations

```
jz      label     # jump if result == 0
jnz     label     # jump if result != 0
jg      label     # jump if result > 0
jng     label     # jump if result <= 0
jge     label     # jump if result >= 0
jnge    label     # jump if result < 0
jl      label     # jump if result < 0
jnl     label     # jump if result >= 0
jle     label     # jump if result <= 0
jnle    label     # jump if result > 0
```

- Obviously, the assembler is providing multiple opcode mnemonics for several actual instructions



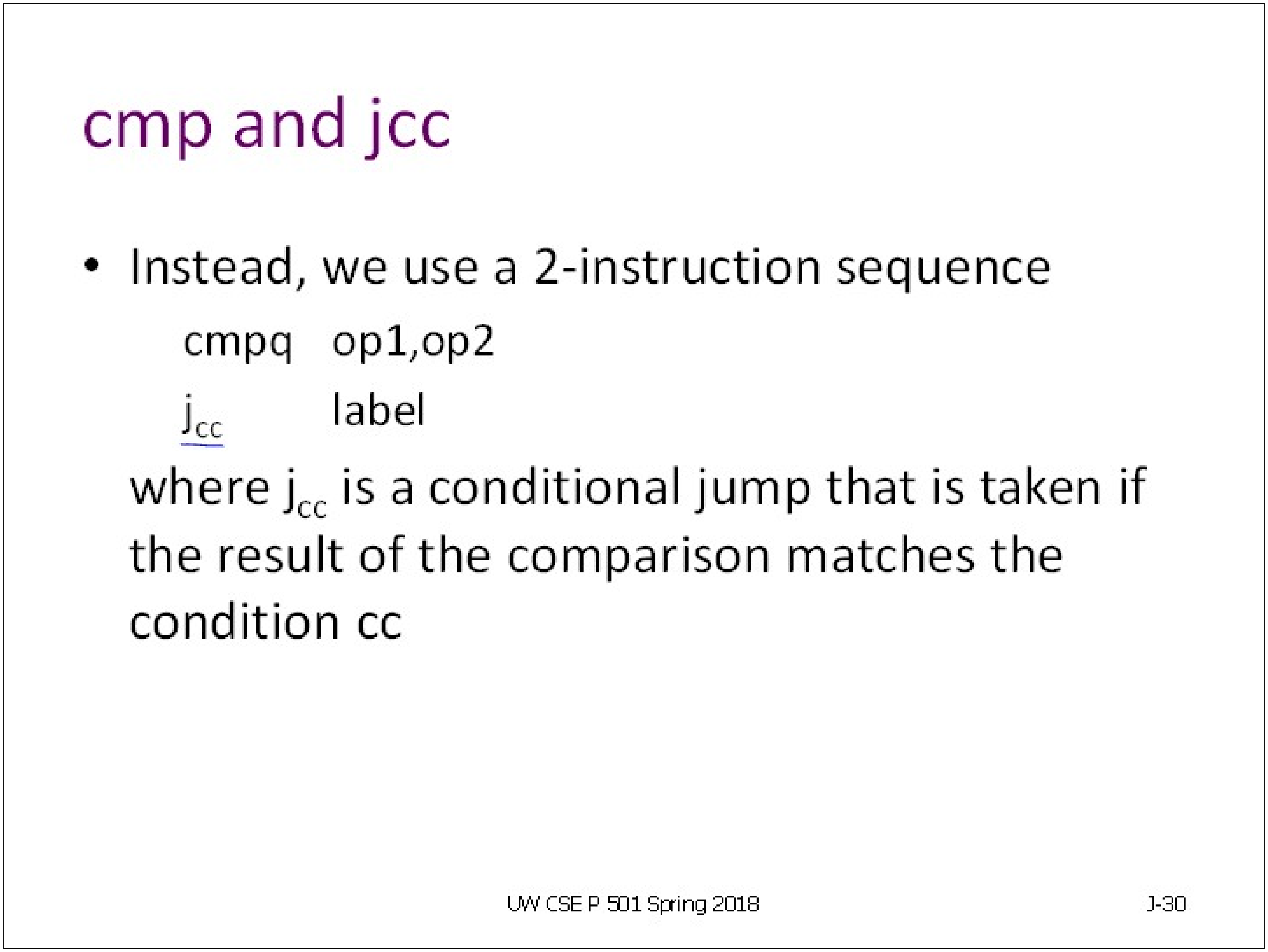
Compare and Jump Conditionally

- Want: compare two operands and jump if a relationship holds between them
- Would like to do this

  - jmp_{cond} op1,op2,label

  but can’t, because 3-operand instructions can’t be encoded in x86-64

  (also true of most other machines)

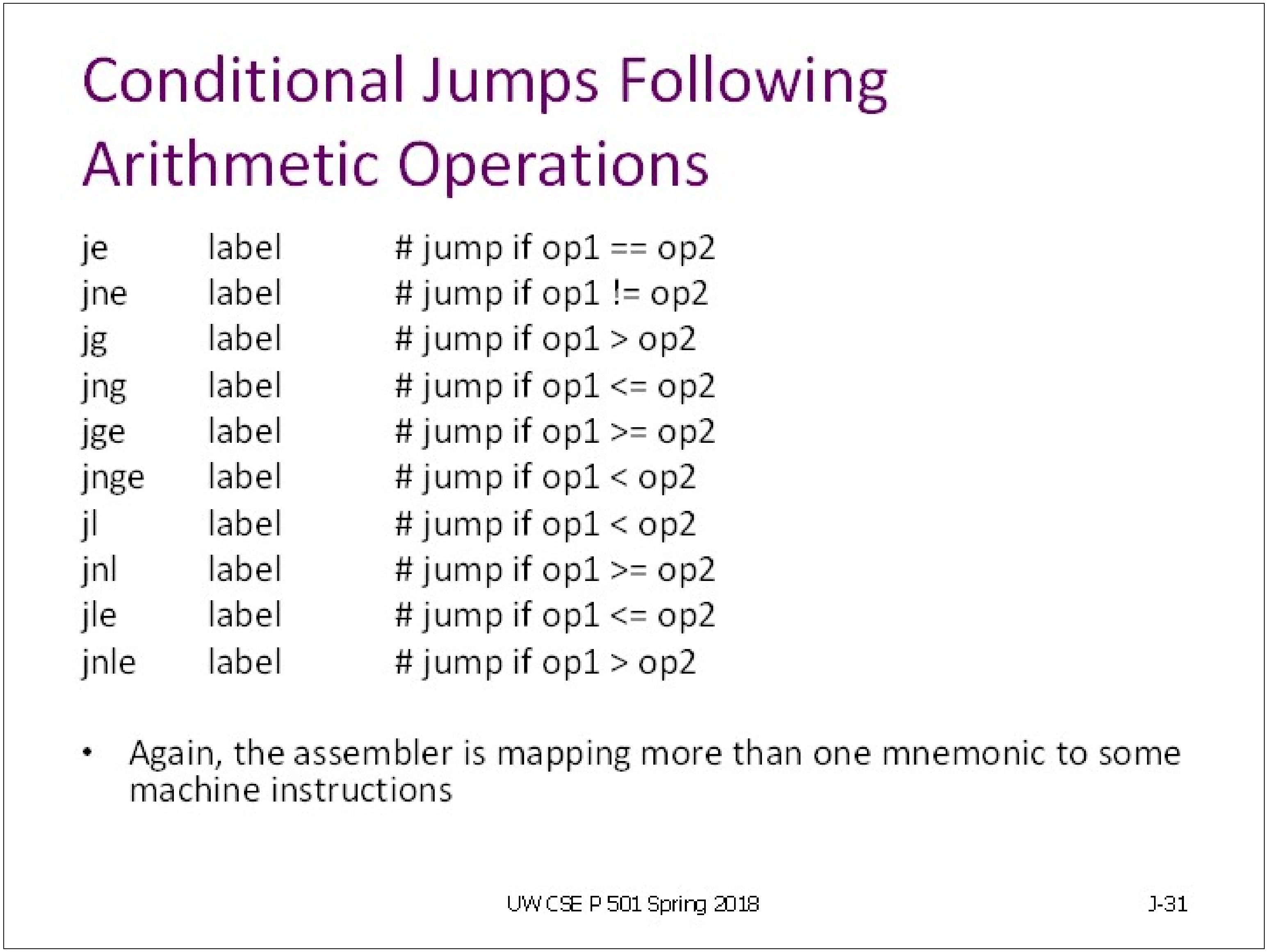


cmp and jcc

- Instead, we use a 2-instruction sequence

```
cmpq   op1,op2
jcc       label
```

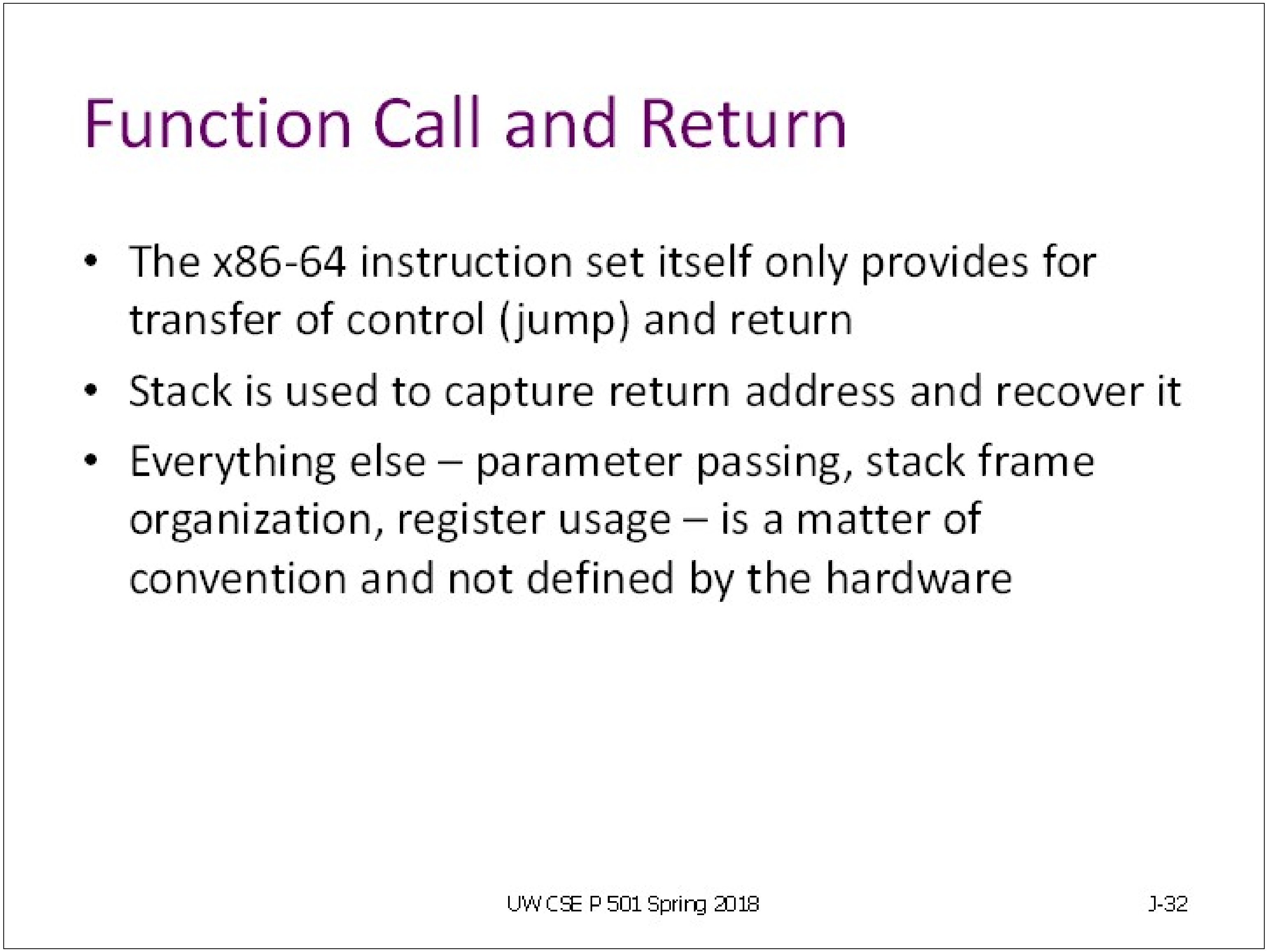
where j_{cc} is a conditional jump that is taken if the result of the comparison matches the condition cc



Conditional Jumps Following Arithmetic Operations

```
je      label      # jump if op1 == op2
jne     label      # jump if op1 != op2
jg      label      # jump if op1 > op2
jng     label      # jump if op1 <= op2
jge     label      # jump if op1 >= op2
jnge    label      # jump if op1 < op2
jl      label      # jump if op1 < op2
jnl     label      # jump if op1 >= op2
jle     label      # jump if op1 <= op2
jnle    label      # jump if op1 > op2
```

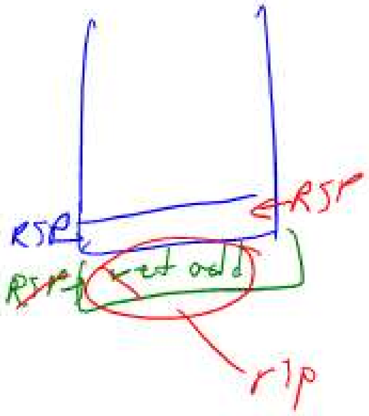
- Again, the assembler is mapping more than one mnemonic to some machine instructions



Function Call and Return

- The x86-64 instruction set itself only provides for transfer of control (jump) and return
- Stack is used to capture return address and recover it
- Everything else – parameter passing, stack frame organization, register usage – is a matter of convention and not defined by the hardware

call and ret Instructions



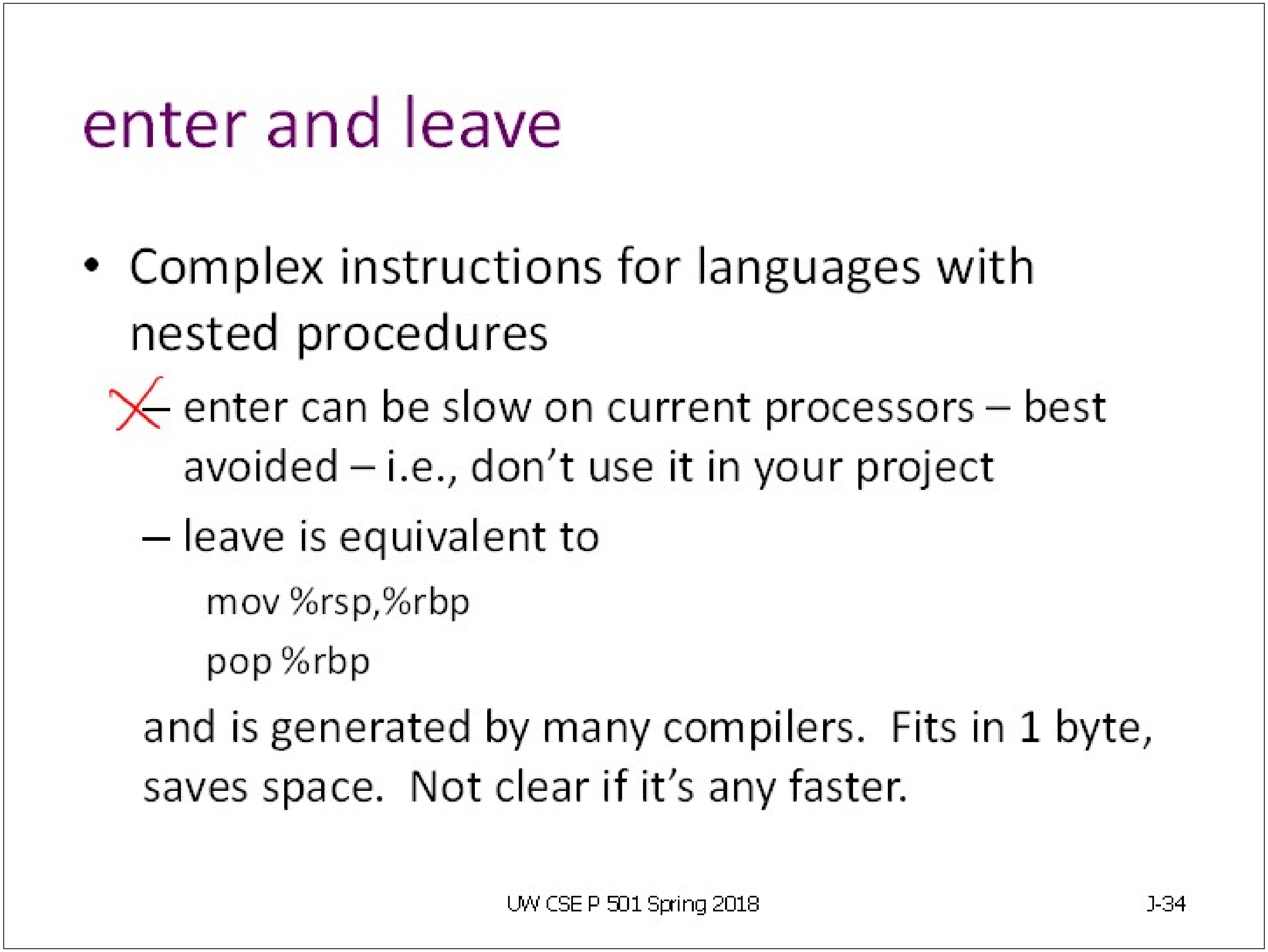
dst

call label

- Push address of next instruction and jump
- %rsp ⟵ %rsp – 8; memory[%rsp] ⟵ %rip
  %rip ⟵ address of label
- Call address can be in a register or memory as with jumps

ret

- Pop address from top of stack and jump
- %rip ⟵ memory[%rsp]; %rsp ⟵ %rsp + 8
- **WARNING!** The word on the top of the stack had better be an address and not some leftover data

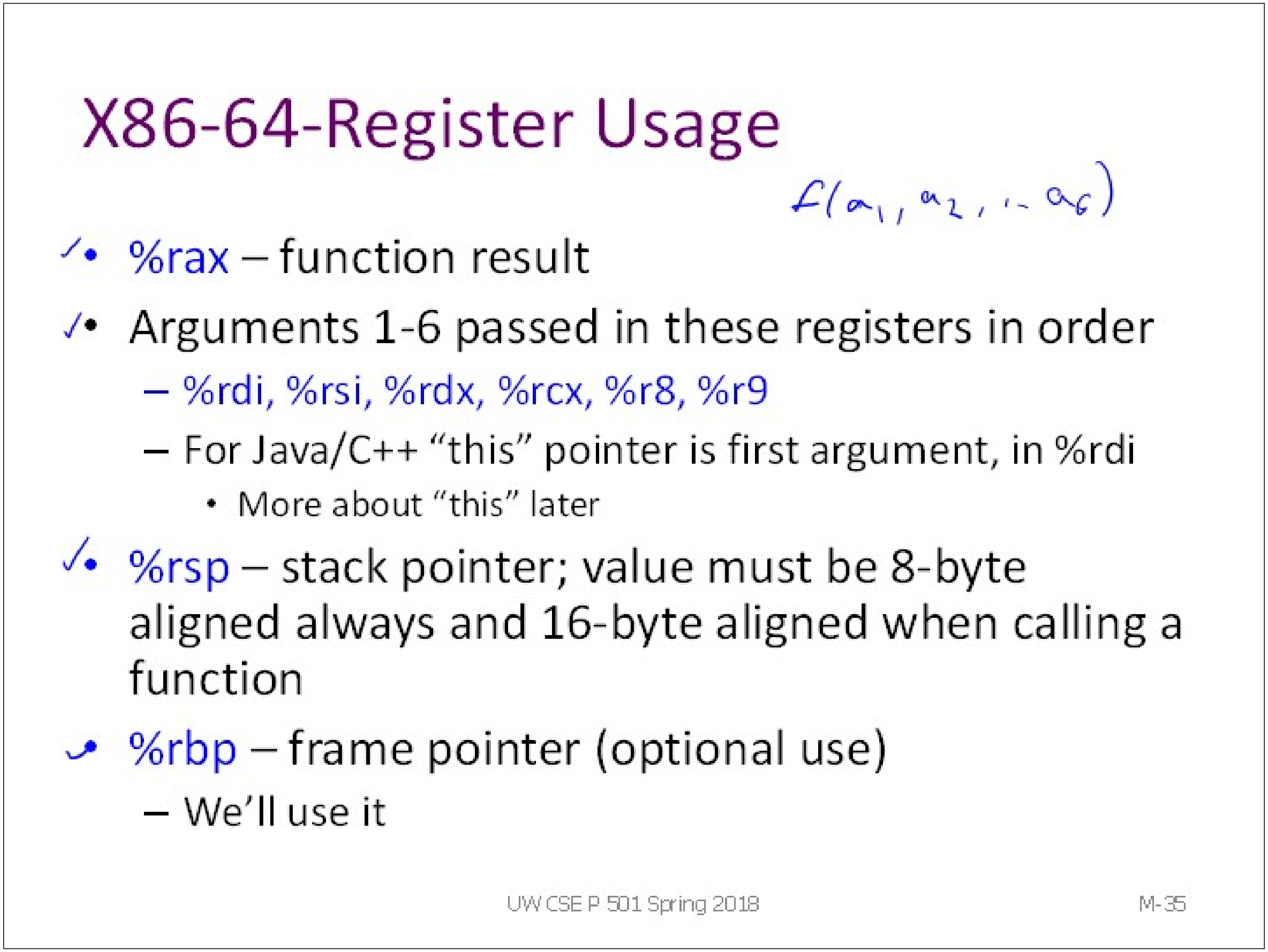


enter and leave

- Complex instructions for languages with nested procedures
  - enter can be slow on current processors – best avoided – i.e., don’t use it in your project
  - leave is equivalent to

```
mov %rsp,%rbp
pop %rbp
```

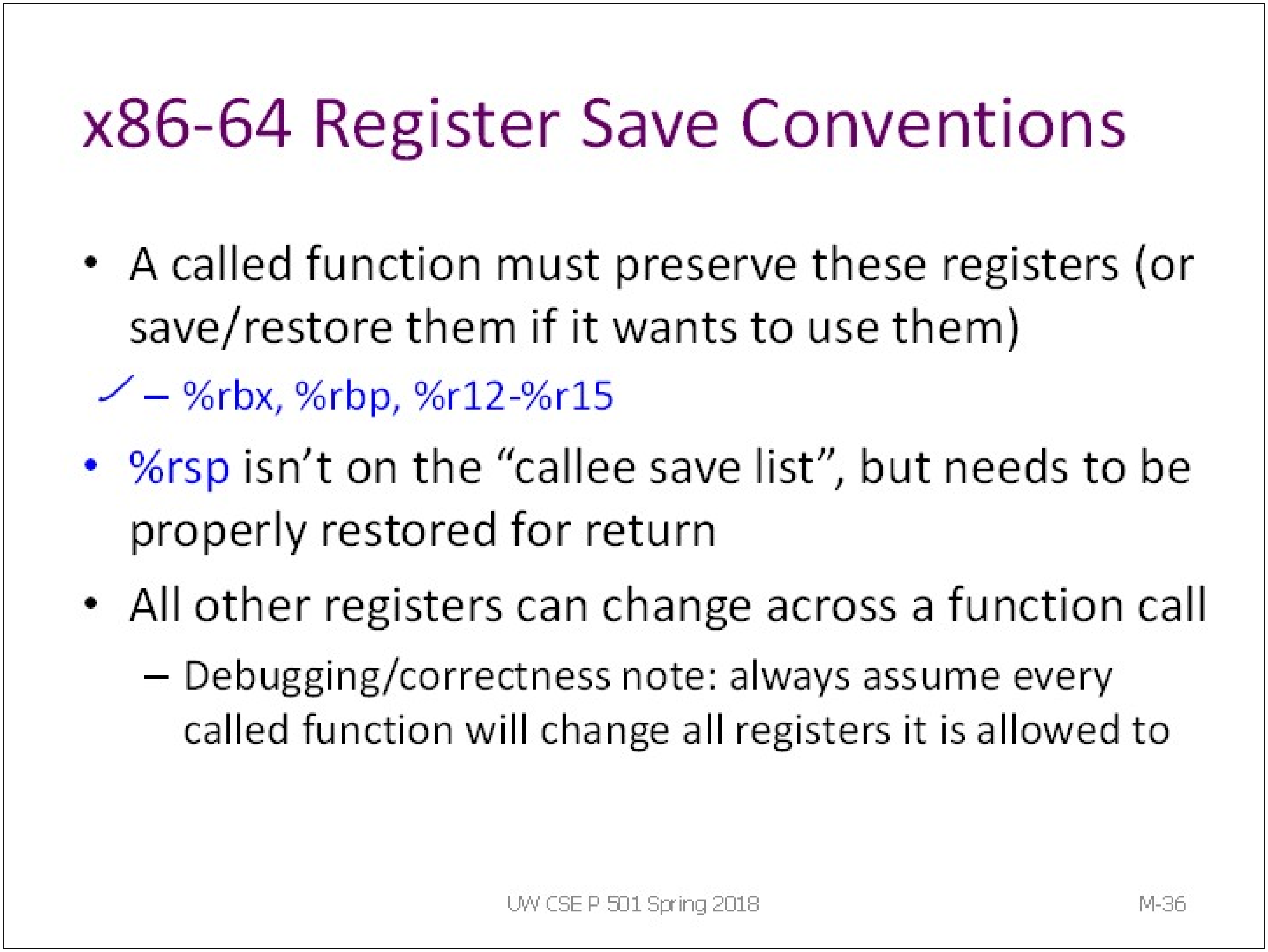
and is generated by many compilers. Fits in 1 byte, saves space. Not clear if it’s any faster.



X86-64-Register Usage

$f(a_1, a_2, .. a_6)$

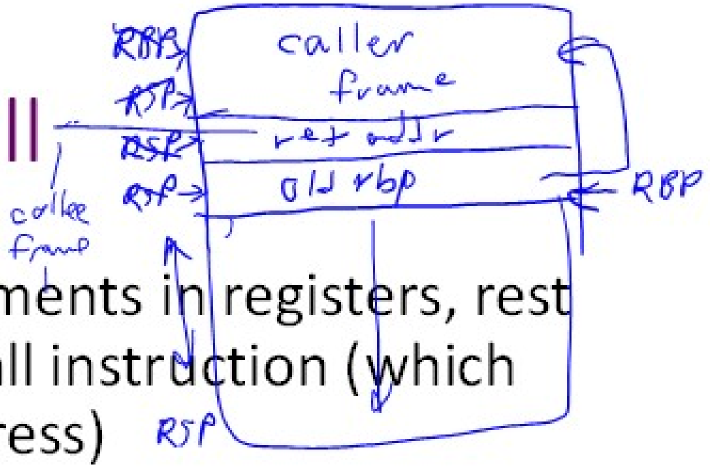
- ✓ %rax – function result
- ✓ Arguments 1-6 passed in these registers in order
  - %rdi, %rsi, %rdx, %rcx, %r8, %r9
  - For Java/C++ "this" pointer is first argument, in %rdi
    - More about "this" later
- ✓ %rsp – stack pointer; value must be 8-byte aligned always and 16-byte aligned when calling a function
- ✓ %rbp – frame pointer (optional use)
  - We'll use it



x86-64 Register Save Conventions

- A called function must preserve these registers (or save/restore them if it wants to use them)
  - ✓ %rbx, %rbp, %r12-%r15
- %rsp isn't on the "callee save list", but needs to be properly restored for return
- All other registers can change across a function call
  - Debugging/correctness note: always assume every called function will change all registers it is allowed to

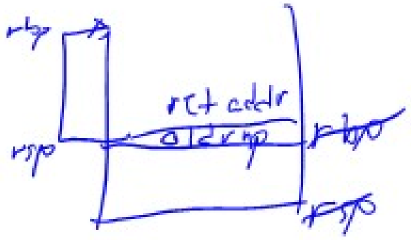
x86-64 Function Call



- Caller places up to 6 arguments in registers, rest on stack, then executes call instruction (which pushes 8-byte return address) ✓
- On entry, called function prologue sets up the stack frame:

```
✓ pushq   %rbp              # save old frame ptr
✓ movq    %rsp,%rbp         # new frame ptr is top of
                            # stack after ret addr and old
                            #    rbp pushed
✓ subq    $framesize,%rsp   # allocate stack frame
```

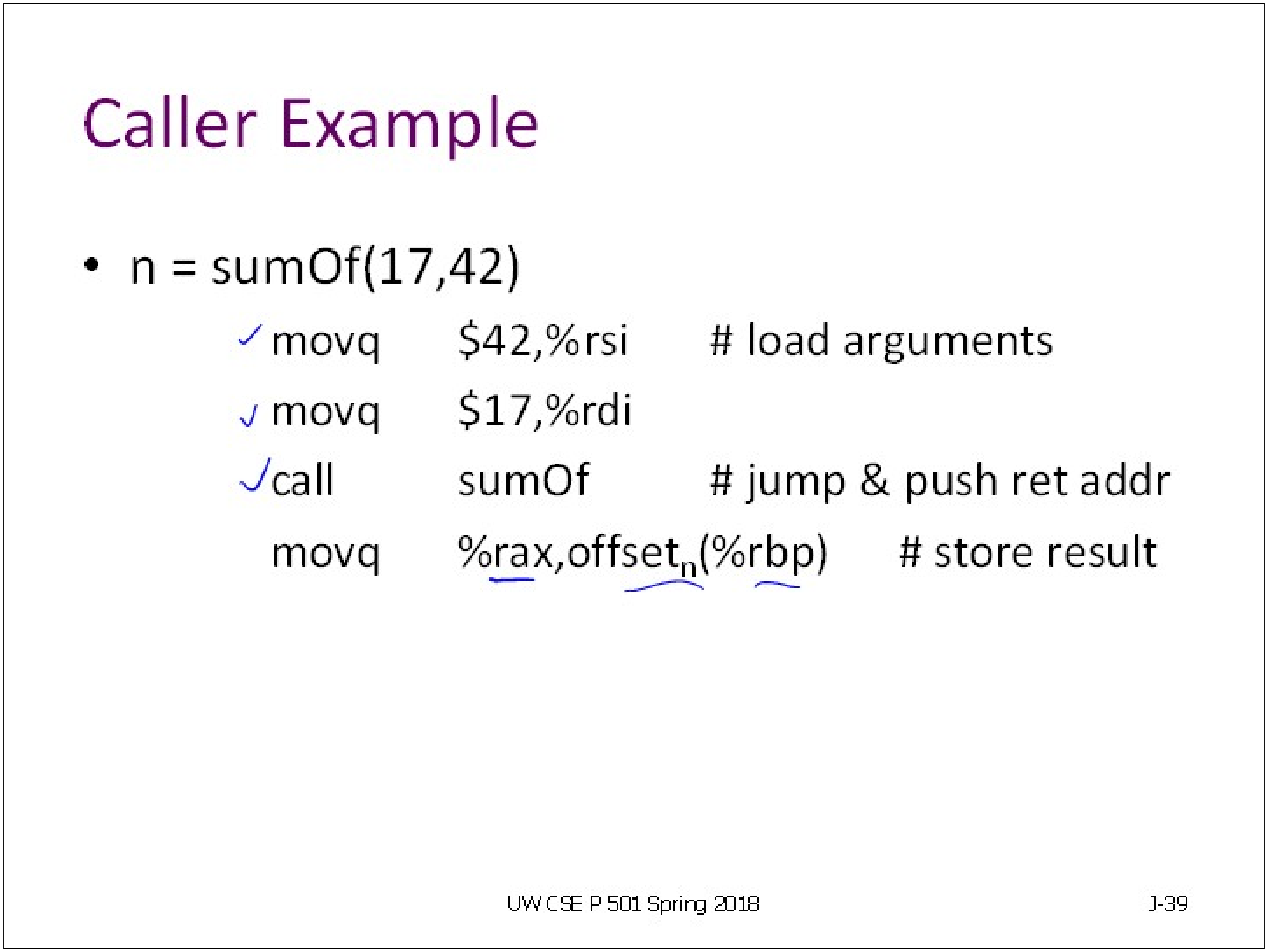
x86-64 Function Return



- Called function puts result (if any) in %rax and restores any callee-save registers if needed
- Called function returns with:

```
✓ movq   %rbp,%rsp          # or use leave instead
✓ popq   %rbp               #     of movq/popq
✓ ret
```

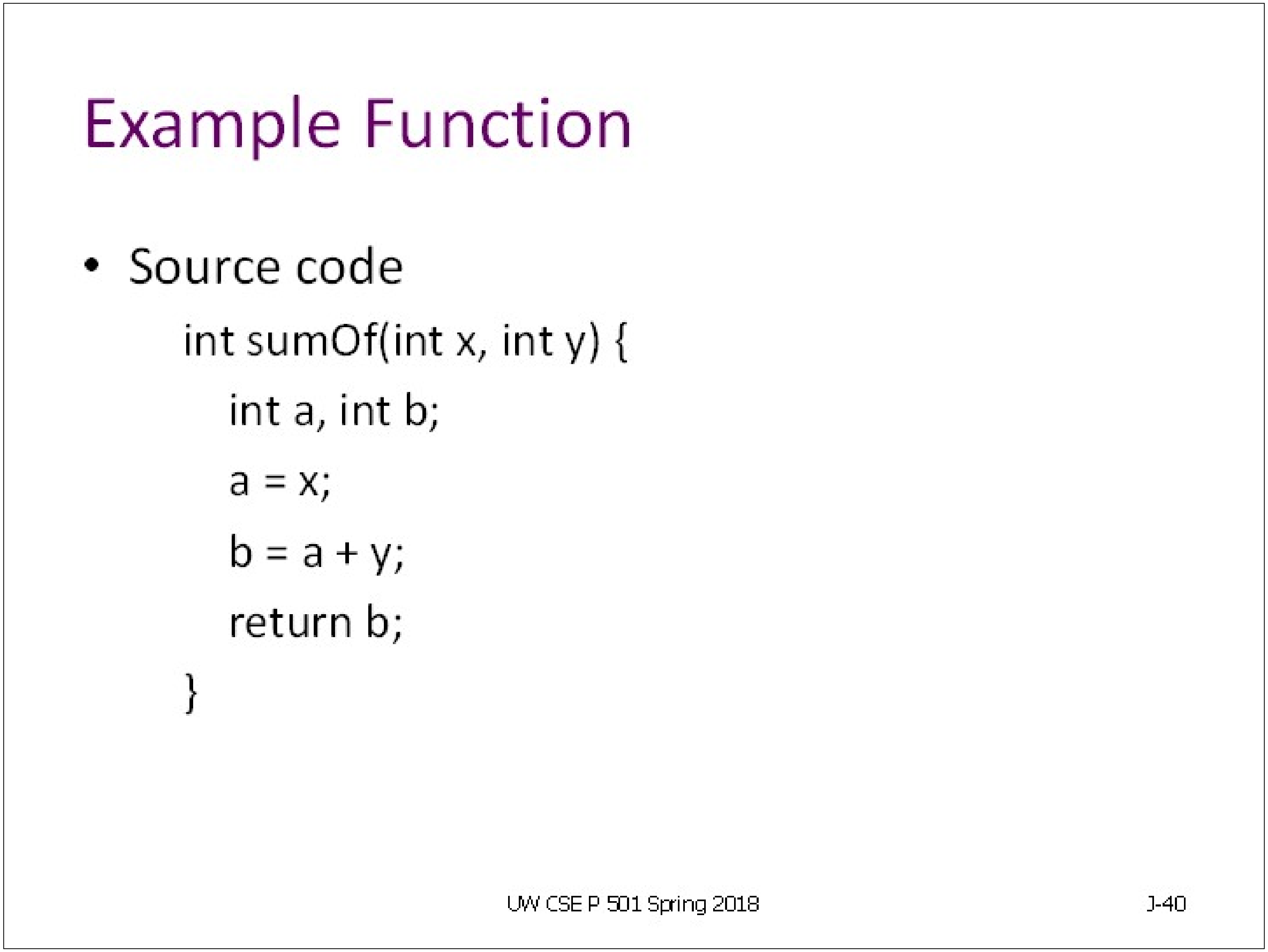
- If caller allocated space for arguments it deallocates as needed



Caller Example

- n = sumOf(17,42)

```
✓ movq   $42,%rsi              # load arguments
✓ movq   $17,%rdi
✓ call   sumOf                 # jump & push ret addr
  movq   %rax,offset_n(%rbp)   # store result
```



Example Function

- Source code

```
int sumOf(int x, int y) {
   int a, int b;
   a = x;
   b = a + y;
   return b;
}
```

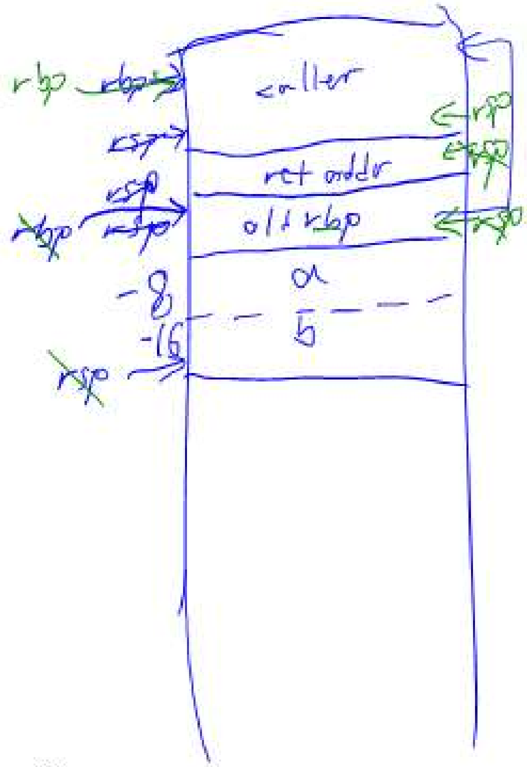
Assembly Language Version

```
              rdi    rsi
# int sumOf(int x, int y) {
#   int a, int b;
sumOf:
prologue  pushq   %rbp      # prologue
    movq    %rsp,%rbp
    subq    $16,%rsp

#   a = x;
    movq    %rdi,-8(%rbp)
```

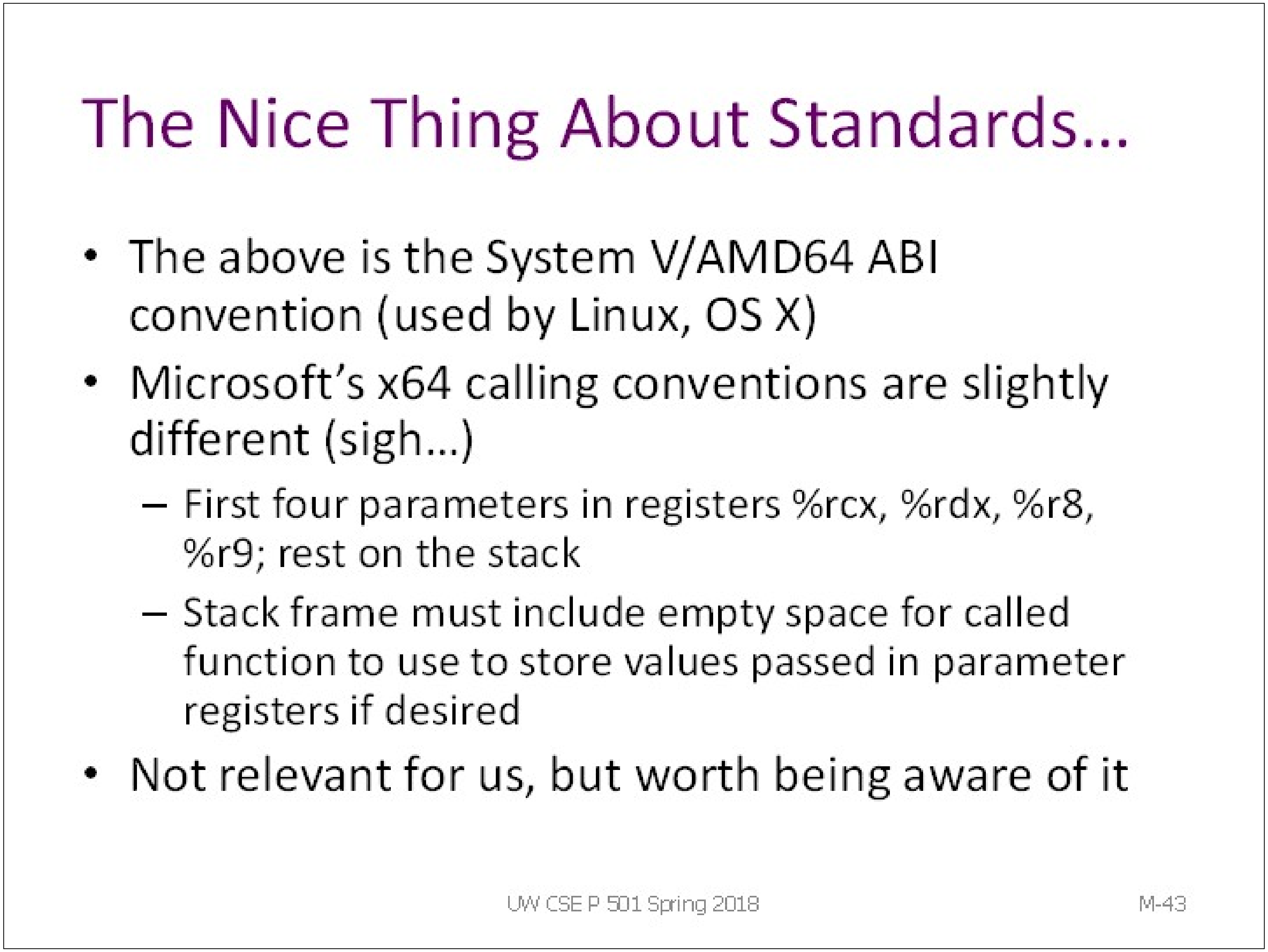
```
#   b = a + y;
                  a
    movq    -8(%rbp),%rax
    addq    %rsi,%rax
    movq    %rax,-16(%rbp)
                a+b

#   return b;
    movq    -16(%rbp),%rax
    movq    %rbp,%rsp
    popq    %rbp
    ret
# }
```



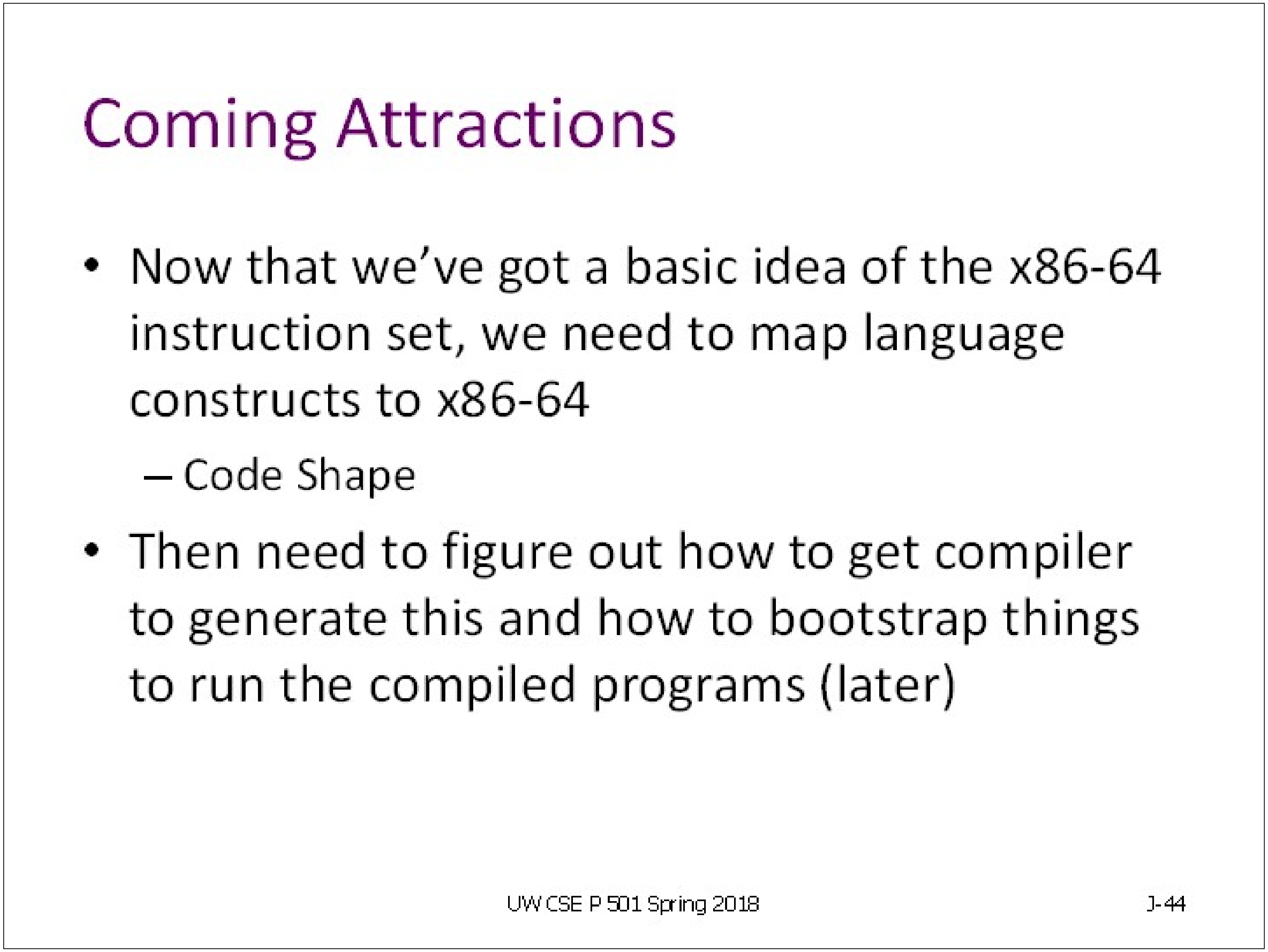
Stack for sumOf

```
int sumOf(int x, int y) {
  int a, int b;
  a = x;
  b = a + y;
  return b;
}
```



The Nice Thing About Standards…

- The above is the System V/AMD64 ABI convention (used by Linux, OS X)
- Microsoft’s x64 calling conventions are slightly different (sigh…)
  - First four parameters in registers %rcx, %rdx, %r8, %r9; rest on the stack
  - Stack frame must include empty space for called function to use to store values passed in parameter registers if desired
- Not relevant for us, but worth being aware of it



Coming Attractions

- Now that we’ve got a basic idea of the x86-64 instruction set, we need to map language constructs to x86-64
  - – Code Shape
- Then need to figure out how to get compiler to generate this and how to bootstrap things to run the compiled programs (later)