

Instructor: Steven Ho



Layers of abstraction are displayed here.

Great Idea #1: Levels of Representation/Interpretation

Higher-Level Language
Program (e.g. C)

```
temp = v[k];  
v[k] = v[k+1];  
v[k+1] = temp;
```

Compiler

Assembly Language
Program (e.g. RISC-V)

```
lw    t0, 0(x2)  
lw    t1, 4(x2)  
sw    t1, 0(x2)  
sw    t0, 4(x2)
```

We
are
here

Assembler

Machine Language
Program (RISC-V)

```
0000 1001 1100 0110 1010 1111 0101 1000  
1010 1111 0101 1000 0000 1001 1100 0110  
1100 0110 1010 1111 0101 1000 0000 1001  
0101 1000 0000 1001 1100 0110 1010 1111
```

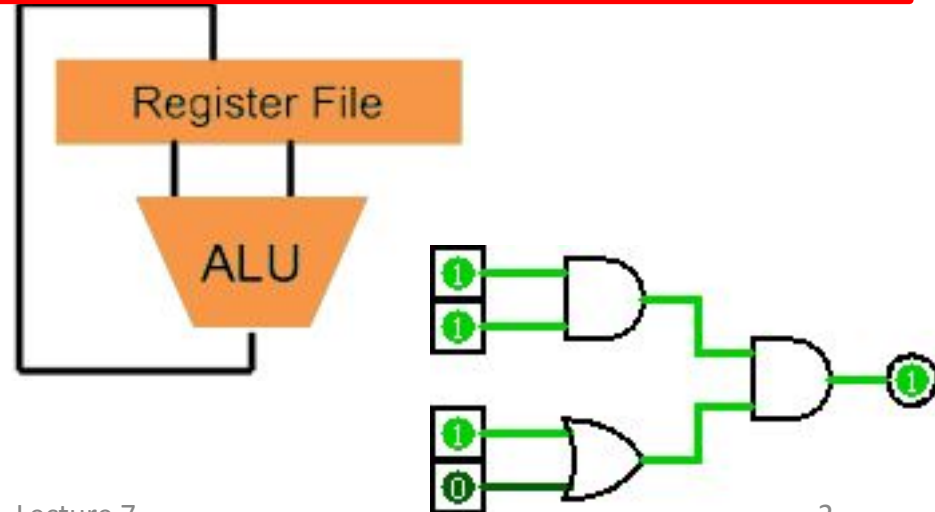
We
are
here

Machine
Interpretation

Hardware Architecture Description
(e.g. block diagrams)

Architecture
Implementation

Logic Circuit Description
(Circuit Schematic Diagrams)



Agenda

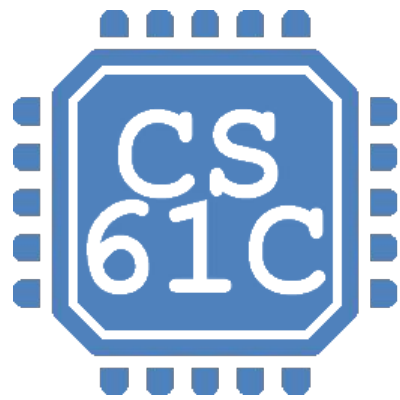
- **Stored-Program Concept**
- R-Format
- I-Format
- Administtrivia
- S-Format
- SB-Format
- U-Format
- UJ-Format



Big Idea: Stored-Program Concept

INSTRUCTIONS ARE DATA

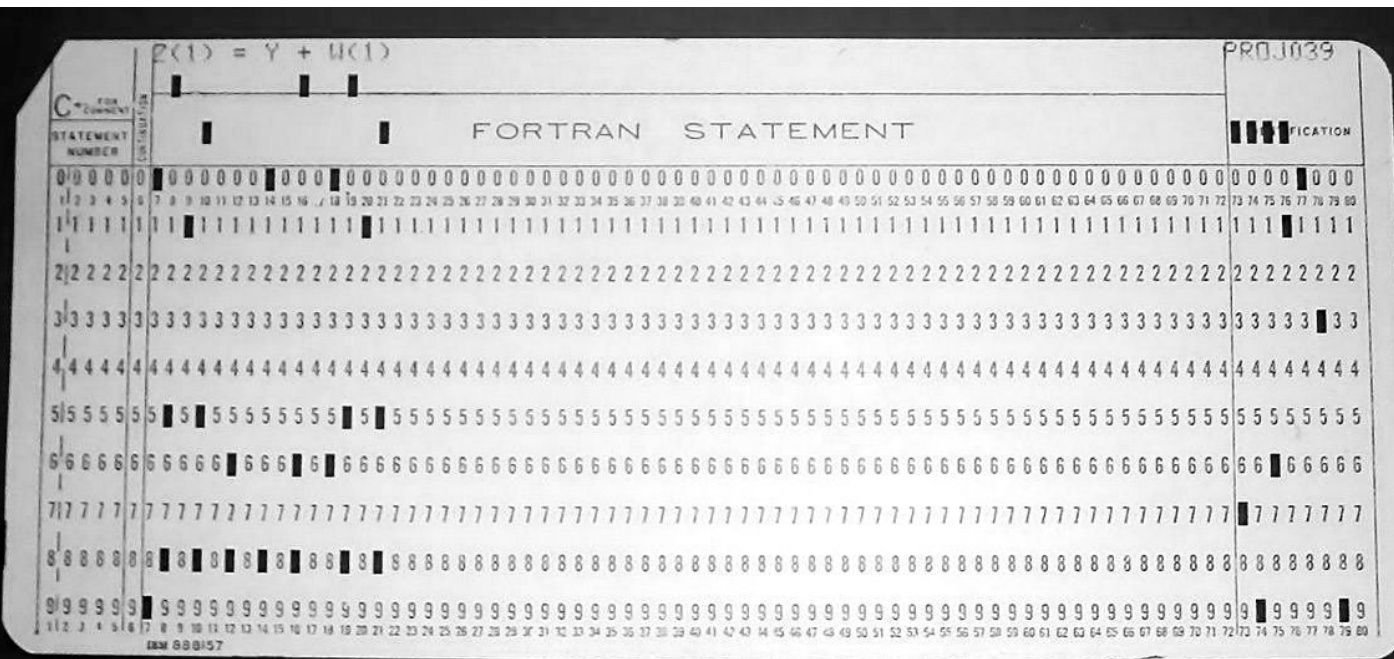
- programs can be stored in memory as numbers
- Before: a number can mean anything
- **Now: make convention for interpreting numbers as instructions**



Great Ideas in Computer Architecture

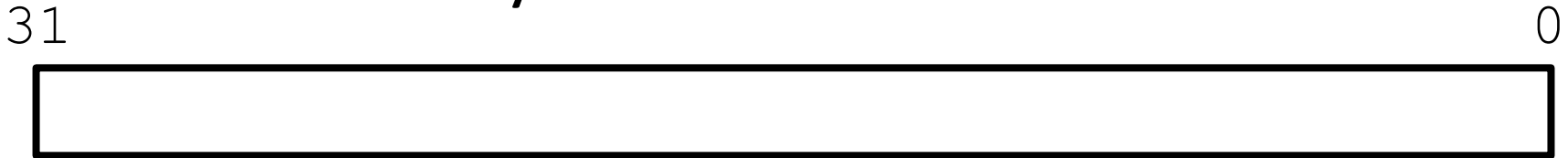
Introduction to Machine Language

Instructor: Steven Ho



Instructions as Numbers

- By convention, RISC-V instructions are each 1 word = 4 bytes = 32 bits



- Divide the 32 bits of an instruction into “fields”
 - regular field sizes → simpler hardware
 - will need some variation....
- Define 6 types of *instruction formats*:
 - R-Format I-Format S-Format U-Format
 - SB-Format UJ-Format

For dividing the instruction into different fields, various formats have been introduced for different types of instructions.

The 6 Instruction Formats

- **R-Format:** instructions using 3 register inputs
 - `add, xor, mul` —arithmetic/logical ops
- **I-Format:** instructions with immediates, loads
 - `addi, lw, jalr, slli`
- **S-Format:** store instructions: `sw, sb`
- **SB-Format:** branch instructions: `beq, bge`
- **U-Format:** instructions with upper immediates
 - `lui, auipc` —upper immediate is 20-bits
- **UJ-Format:** jump instructions: `jal`

The 6 Instruction Formats

	31	27	26	25	24	20	19	15	14	12	11	7	6	0
R	funct7				rs2		rs1		funct3		rd		Opcode	
I	imm[11:0]						rs1		funct3		rd		Opcode	
S	imm[11:5]				rs2		rs1		funct3		imm[4:0]		opcode	
SB	imm[12 10:5]				rs2		rs1		funct3		imm[4:1 11]		opcode	
U	imm[31:12]										rd		opcode	
UJ	imm[20 10:1 11 19:12]										rd		opcode	

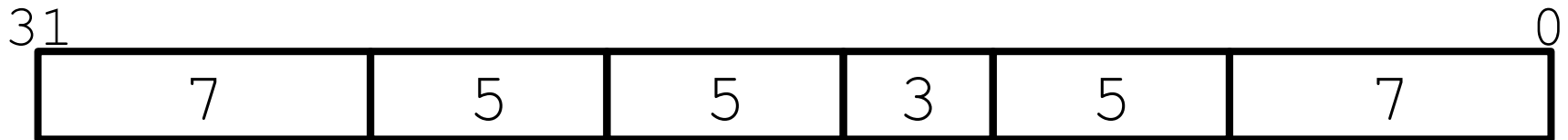
[illegible]

Agenda

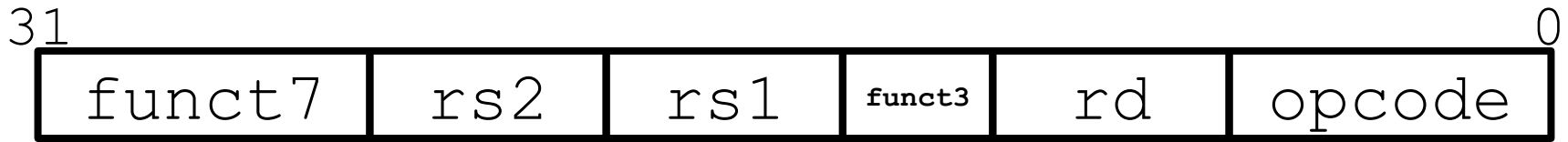
- Stored-Program Concept
- **R-Format**
- I-Format
- Administtrivia
- S-Format
- SB-Format
- U-Format
- UJ-Format

R-Format Instructions (1/3)

- Define “**fields**” of the following number of bits each: $7 + 5 + 5 + 3 + 5 + 7 = 32$



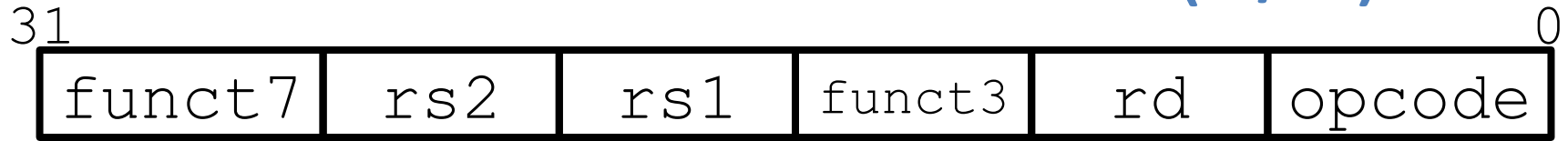
- Each field has a name:



- Each field is viewed as its own unsigned int
 - 5-bit fields can represent any number 0-31, while 7-bit fields can represent any number 0-128, etc.

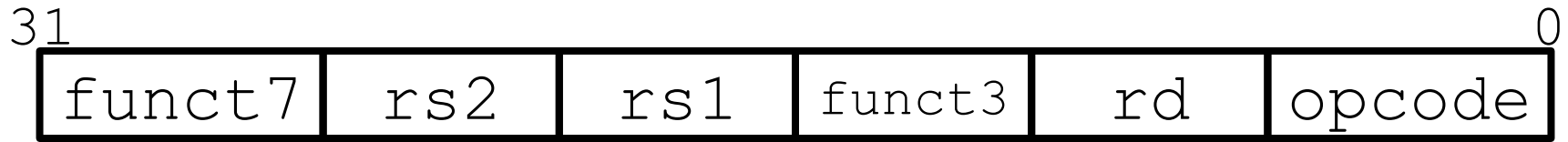
Opcode determines the type of instruction and funct7 and funct3 will actually decide which instruction of that type.

R-Format Instructions (2/3)



- **opcode** (7): partially specifies operation
 - e.g. **R**-types have opcode = 0b0110011,
SB (branch) types have opcode = 0b1100011
- **funct7+funct3** (10): combined with opcode, these two fields describe what operation to perform
- How many R-format instructions can we encode?
 - with opcode fixed at 0b0110011, just funct varies:
 $(2^7) \times (2^3) = (2^{10}) = 1024$

R-Format Instructions (3/3)



- **rs1** (5): 1st operand (“source register 1”)
- **rs2** (5): 2nd operand (second source register)
- **rd** (5): “**d**estination **r**egister” — receives the result of computation
- **Recall:** RISC-V has 32 registers
 - A 5 bit field can represent exactly $2^5 = 32$ things (interpret as the register numbers **x0-x31**)

Reading from the Green Sheet

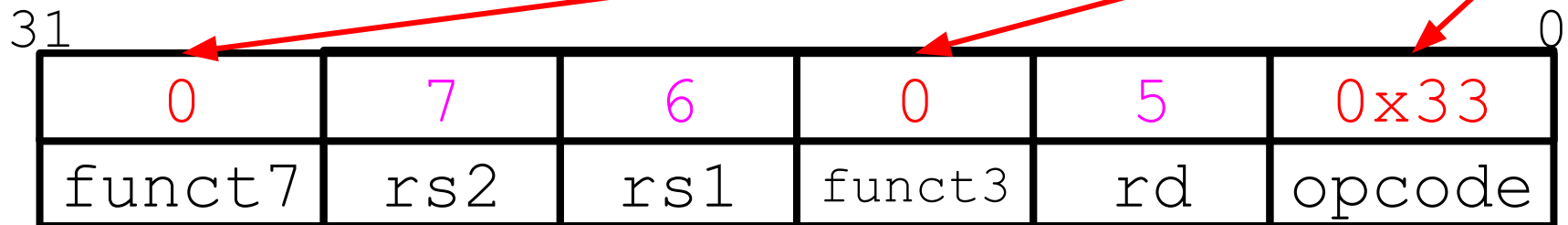
add t0 t1 t2

RV64I BASE INTEGER INSTRUCTIONS, in alphabetical order

MNEMONIC	FMT	NAME	DESCRIPTION (in Verilog)
add, addw	R	ADD (Word)	$R[rd] = R[rs1] + R[rs2]$

OPCODES IN NUMERICAL ORDER BY OPCODE

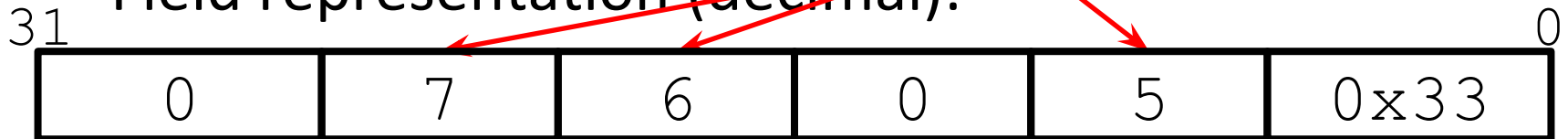
MNEMONIC	FMT	OPCODE	FUNCT3	FUNCT7 OR IMM	HEXADECIMAL
sd	S	0100011	011		23/3
add	R	0110011	000	0000000	33/0/00
sub	R	0110011	000	0100000	33/0/20



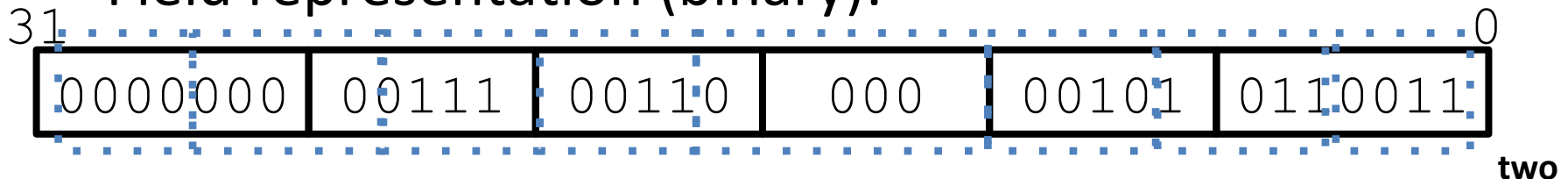
R-Format Example

- RISCV Instruction: `add x5, x6, x7`

Field representation (decimal):



Field representation (binary):



hex representation: `0x 0073 02B3`

decimal representation: `7,537,331`

Called a **Machine Language Instruction**

SUB will do (rs1-rs2).

All RV32 R-format instructions

0000000	rs2	rs1	000	rd	0110011	ADD
0100000	rs2	rs1	000	rd	0110011	SUB
0000000	rs2	rs1	001	rd	0110011	SLL
0000000	rs2	rs1	010	rd	0110011	SLT
0000000	rs2	rs1	011	rd	0110011	SLTU
0000000	rs2	rs1	100	rd	0110011	XOR
0000000	rs2	rs1	101	rd	0110011	SRL
0100000	rs2	rs1	101	rd	0110011	SRA
0000000	rs2	rs1	110	rd	0110011	OR
0000000	rs2	rs1	111	rd	0110011	AND



Different encoding in funct7 + funct3 selects different operations

Agenda

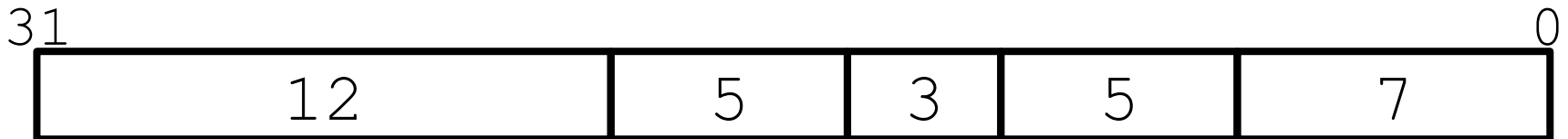
- Stored-Program Concept
- R-Format
- **I-Format**
- Administtrivia
- S-Format
- SB-Format
- U-Format
- UJ-Format

I-Format Instructions (1/4)

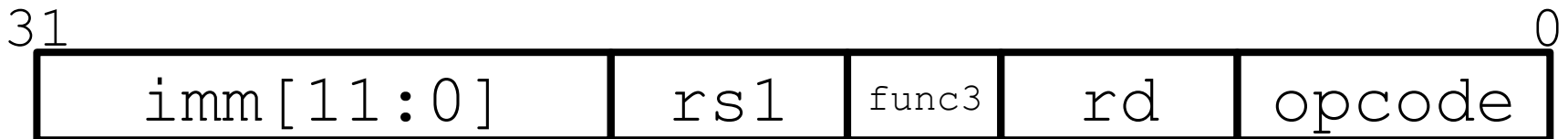
- What about instructions with immediates?
 - 5-bit field too small for most immediates
- Ideally, RISC-V would have only one instruction format (for simplicity)
 - Unfortunately here we need to compromise
- Define new instruction format that is *mostly* consistent with R-Format
 - First notice that, if instruction has immediate, then it uses at most 2 registers (1 src, 1 dst)

I-Format Instructions (2/4)

- Define “fields” of the following number of bits each: $12 + 5 + 3 + 5 + 7 = 32$ bits

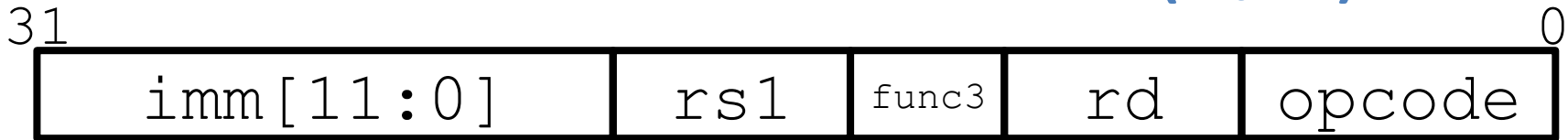


- Field names:



- Key Concept:** Only **imm** field is different from R-format: **rs2** and **funct7** replaced by 12-bit signed immediate, **imm[11:0]**

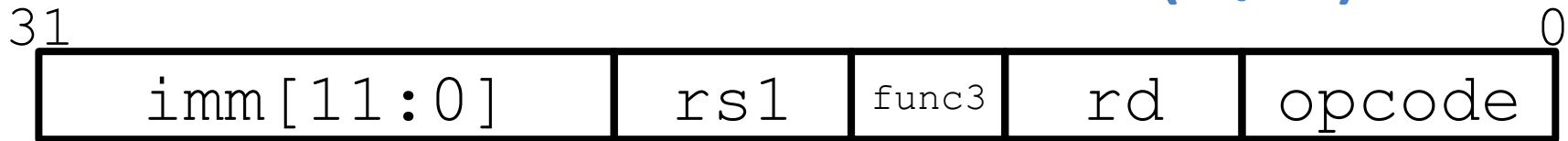
I-Format Instructions (3/4)



- **opcode** (7): uniquely specifies the instruction
- **rs1** (5): specifies a register operand
- **rd** (5): specifies **d**estination **r**egister that receives result of computation

Immediate is taken to be signed here.

I-Format Instructions (4/4)



- **immediate** (12): 12 bit number
 - All computations done in words, so 12-bit immediate must be *extended* to 32 bits
 - **always sign-extended to** 32-bits before use in an arithmetic operation
- Can represent 2^{12} different immediates
 - imm[11:0] can hold values in range $[-2^{11}, +2^{11})$

I-Format Example (1/2)

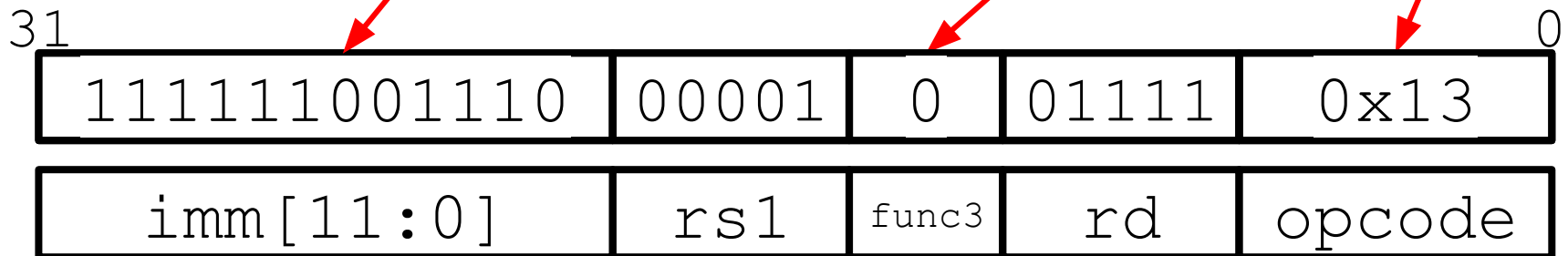
addi x15, x1, -50

OPCODES IN NUMERICAL ORDER BY OPCODE

MNEMONIC	FMT	OPCODE	FUNCT3	FUNCT7 OR IMM	HEXADECIMAL
fence.i	I	0001111	001		0F/1
addi	I	0010011	000		13/0
slli	I	0010011	001	0000000	13/1/00

rd = x15

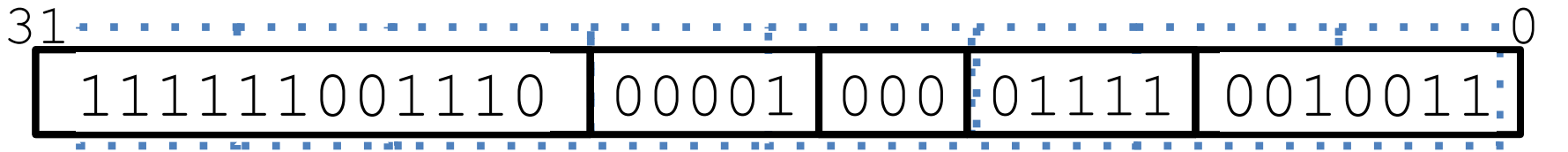
rs1 = x1



I-Format Example (2/2)

- RISC-V Instruction: `addi x15, x1, -50`

Field representation (binary):



hex representation: `0x FCE0 8793`

two

decimal representation: `4,242,573,203`

All RISC-V I-Type Arithmetic Instructions

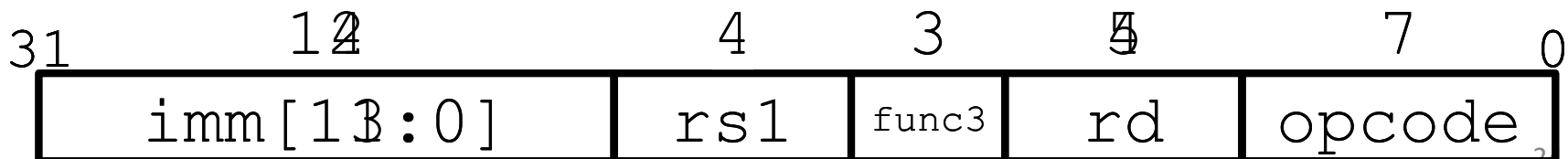
imm[11:0]		rs1	000	rd	0010011	ADDI
imm[11:0]		rs1	010	rd	0010011	SLTI
imm[11:0]		rs1	011	rd	0010011	SLTIU
imm[11:0]		rs1	100	rd	0010011	XORI
imm[11:0]		rs1	110	rd	0010011	ORI
imm[11:0]		rs1	111	rd	0010011	ANDI
0000000	shamt	rs1	001	rd	0010011	LLI
0000000	shamt	rs1	101	rd	0010011	SRLI
0100000	shamt	rs1	101	rd	0010011	SRAI

One of the higher-order immediate bits is used to distinguish “shift right logical” (SRLI) from “shift right arithmetic” (SRAI)

“Shift-by-immediate” instructions only use lower 5 bits of the immediate value for shift amount (can only shift by 0-31 bit positions)

Question: If the number of registers were halved, which statement is true?

- (A) There must be more R-type instructions
- (B) There must be less I-type instructions
- (C) Shift amounts would change to 0-63
- (D) I-type instructions could have 2 more immediate bits



Agenda

- Stored-Program Concept
- R-Format
- I-Format
- **Administrivia**
- S-Format
- SB-Format
- U-Format
- UJ-Format

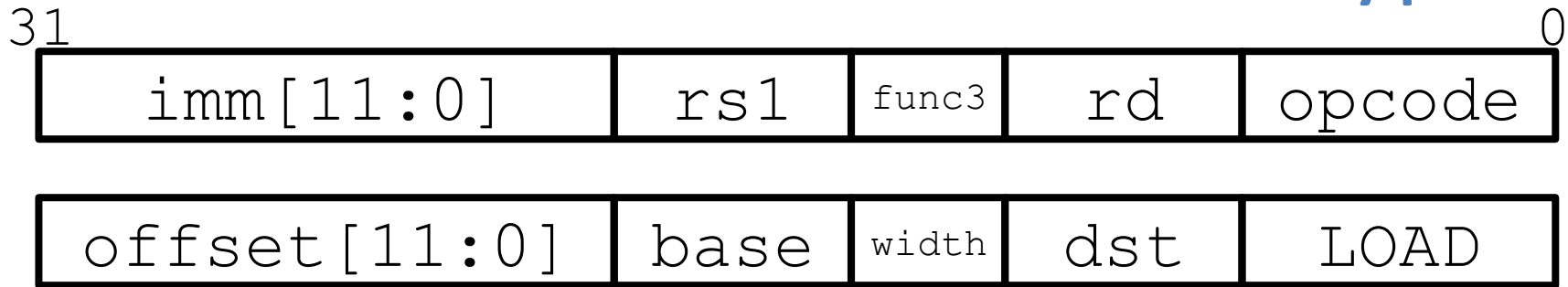
Administrivia

- Guerrilla Session today! 4-6PM, Cory 540AB
- HW1 Due Thursday (6/28)
- Project Due on Friday (6/29)
 - Submission Policy:
 - Testing framework has been released
 - You can do it!! :D
- HW2 Due next Friday (7/06)
- Review Session this Saturday (6/30), 2-4PM
- Guerilla Session part 2, this Sunday (7/01)
2-4PM, Cory 540AB
 - This will also be helpful for the midterm! (That's why we moved it up)

Agenda

- Stored-Program Concept
- R-Format
- **I-Format**
- Administtrivia
- S-Format
- SB-Format
- U-Format
- UJ-Format

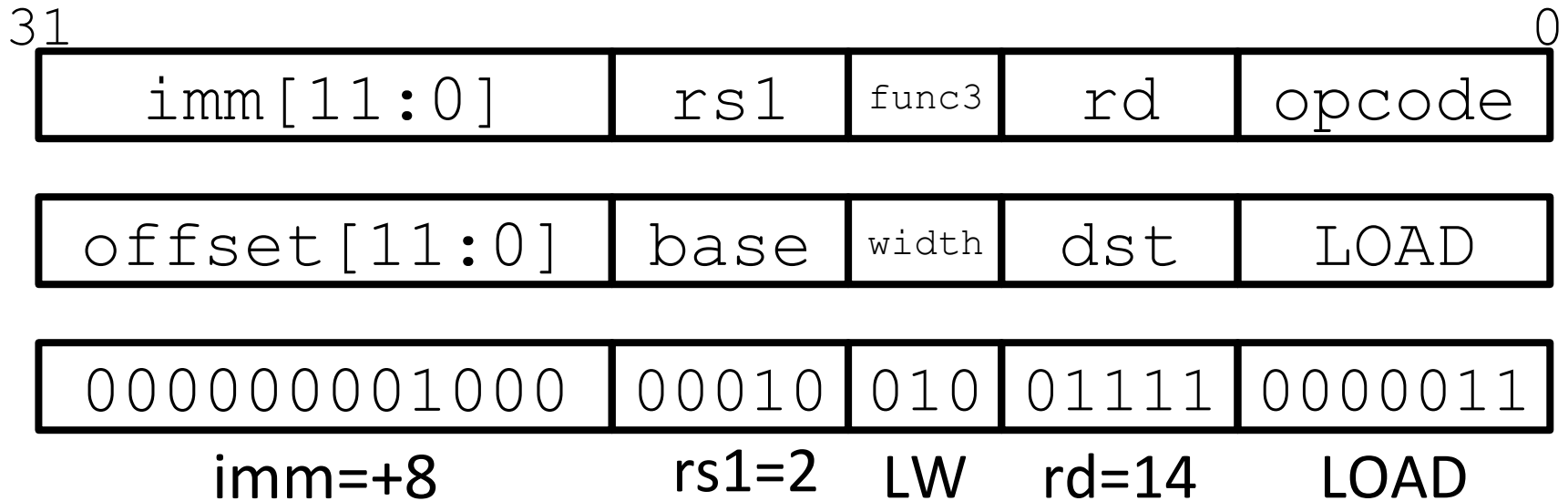
Load Instructions are also I-Type



- The 12-bit signed immediate is added to the base address in register `rs1` to form the memory address
 - This is very similar to the add-immediate operation but used to create address, not to create final result
- Value loaded from memory is stored in `rd`

I-Format Load Example

- **lw x14, 8(x2)**



All RV32 Load Instructions

imm[11:0]	rs1	000	rd	0000011	LB
imm[11:0]	rs1	001	rd	0000011	LH
imm[11:0]	rs1	010	rd	0000011	LW
imm[11:0]	rs1	100	rd	0000011	LBU
imm[11:0]	rs1	101	rd	0000011	LHU

↑
funct3 field encodes size and
signedness of load data

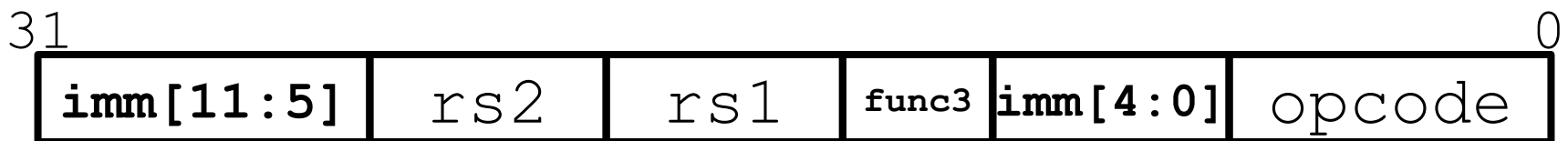
- LBU is “load unsigned byte”
- LH is “load halfword”, which loads 16 bits (2 bytes) and sign-extends to fill destination 32-bit register
- LHU is “load unsigned halfword”, which zero-extends 16 bits to fill destination 32-bit register
- There is no LWU in RV32, because there is no sign/zero extension needed when copying 32 bits from a memory location into a 32-bit register

Agenda

- Stored-Program Concept
- R-Format
- I-Format
- Administritivia
- **S-Format**
- SB-Format
- U-Format
- UJ-Format

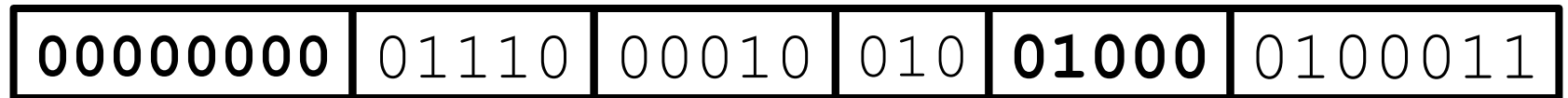
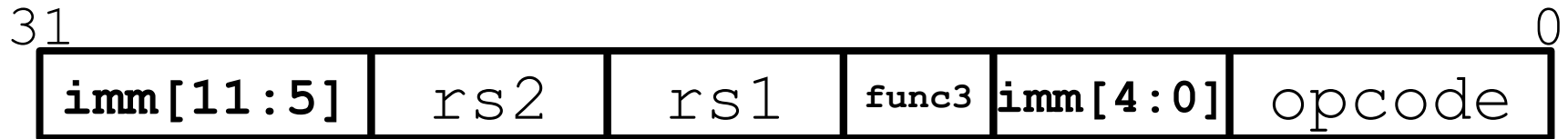
S-Format Used for Stores

- Store needs to read two registers, `rs1` for base memory address, and `rs2` for data to be stored, as well as need immediate offset!
- Can't have both `rs2` and immediate in same place as other instructions!
- Note: stores don't write a value to the register file, no `rd`!
- RISC-V design decision is **move low 5 bits of immediate** to where `rd` field was in other instructions – keep `rs1/rs2` fields in same place
- register names more critical than immediate bits in hardware design

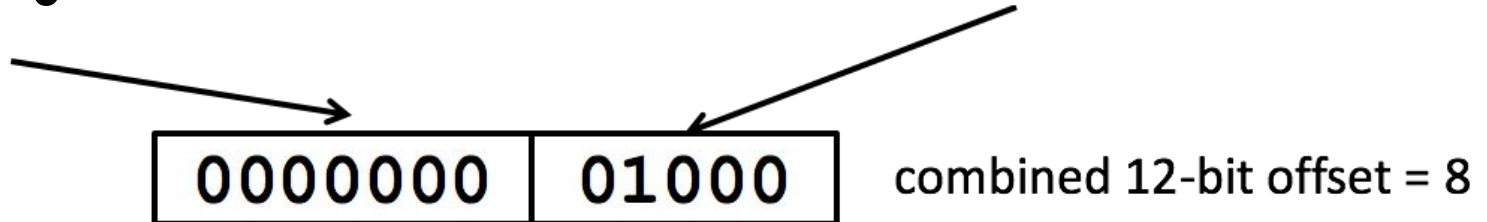


S-Format Example

sw x14, 8(x2)



off[11:5] = 0 rs2=14 rs1=2 SW off[4:0] = 8 STORE



All RV32 Store Instructions

imm[11:5]	rs2	rs1	000	imm[4:0]	0100011	SB
imm[11:5]	rs2	rs1	001	imm[4:0]	0100011	SH
imm[11:5]	rs2	rs1	010	imm[4:0]	0100011	SW

Agenda

- Stored-Program Concept
- R-Format
- I-Format
- Administritivia
- S-Format
- **SB-Format**
- U-Format
- UJ-Format

Branching Instructions

- beq, bne, bge, blt
 - Need to specify an **address** to go to
 - Also take **two** registers to compare
 - Doesn't write into a register (similar to stores)
- How to encode label, i.e., where to branch to?

Branching Instruction Usage

- Branches typically used for loops (`if-else`, `while`, `for`)
 - Loops are generally small (< 50 instructions)
- **Recall:** Instructions stored in a localized area of memory (Code/Text)
 - Largest branch distance limited by size of code
 - Address of current instruction stored in the program counter (PC)

PC-Relative Addressing

- **PC-Relative Addressing:** Use the `immediate` field as a two's complement offset to PC
 - Branches generally change the PC by a small amount
 - Can specify $\pm 2^{11}$ **addresses** from the PC
- Why not use byte address offset from PC as the `immediate`?

Branching Reach

- **Recall:** RISC-V uses 32-bit addresses, and memory is **byte-addressed**
- Instructions are “***word-aligned***”: Address is always a multiple of 4 (in bytes)
- PC ALWAYS points to an instruction
 - PC is *typed* as a pointer to a word
 - can do C-like pointer arithmetic
- **Let immediate specify #words instead of #bytes**
 - Instead of specifying $\pm 2^{11}$ **bytes** from the PC, we will now specify $\pm 2^{11}$ **words** = $\pm 2^{13}$ **byte addresses around PC**

Branch Calculation

- If we **don't** take the branch:

$$PC = PC + 4 = \text{next instruction}$$

- If we **do** take the branch:

$$PC = PC + (\text{immediate} * 4)$$

- **Observations:**

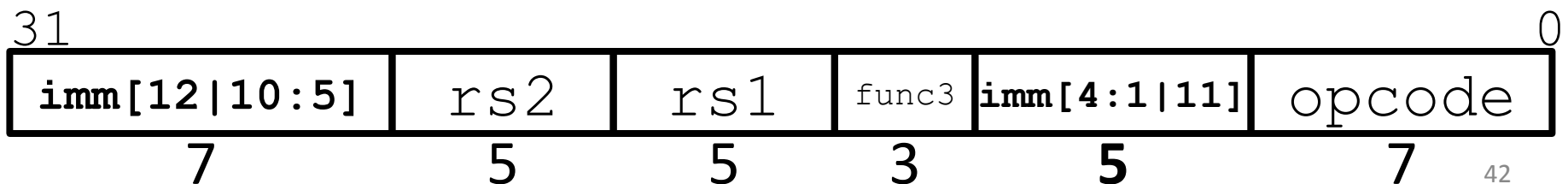
- `immediate` is number of instructions to move (remember, specifies words) either forward (+) or backwards (–)

RISC-V Feature, $n \times 16$ -bit instructions

- Extensions to RISC-V base ISA support 16-bit compressed instructions and also variable-length instructions that are multiples of 16-bits in length
- 16-bit = half-word
- To enable this, RISC-V scales the branch offset to be **half-words** even when there are no 16-bit instructions
- Reduces branch reach by half and means that $\frac{1}{2}$ of possible targets will be errors on RISC-V processors that only support 32-bit instructions (as used in this class)
- RISC-V conditional branches can only reach $\pm 2^{10} \times 32$ -bit instructions either side of PC

RISC-V B-Format for Branches

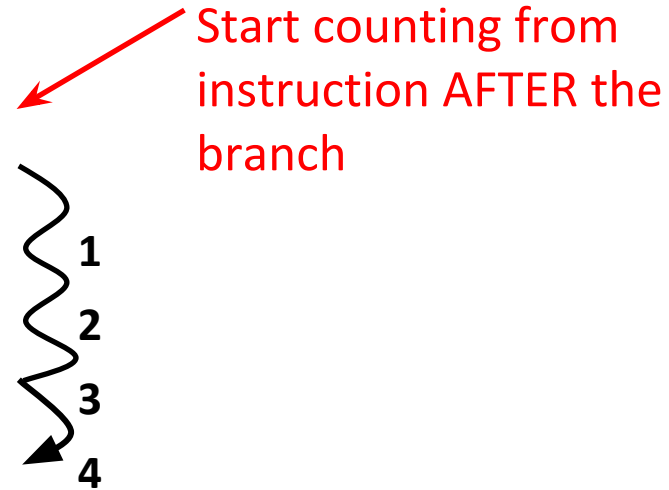
- B-format is mostly same as S-Format, with two register sources ($rs1 / rs2$) and a 12-bit immediate
- But now immediate represents values -2^{12} to $+2^{12}-2$ in 2-byte increments
- The 12 immediate bits encode even 13-bit signed byte offsets (lowest bit of offset is always zero, so no need to store it)



Branch Example (1/2)

- RISC-V Code:

```
Loop: beq x19, x10, End
      add x18, x18, x10
      addi x19, x19, -1
      j Loop
End: <target instr>
```



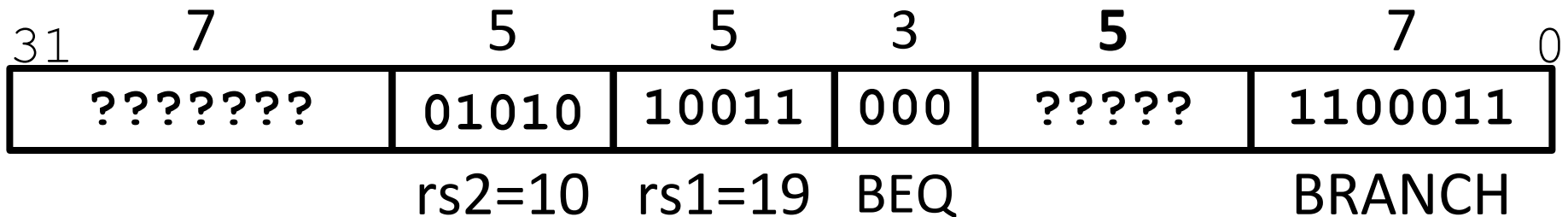
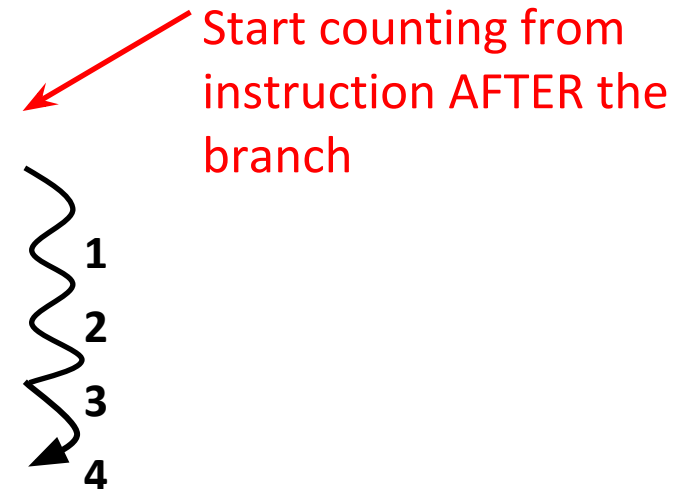
- Branch offset = $4 \times 32\text{-bit instructions} = 16\text{ bytes}$
- (Branch with offset of 0, branches to itself)

Branch Example (1/2)

- RISCV Code:

```

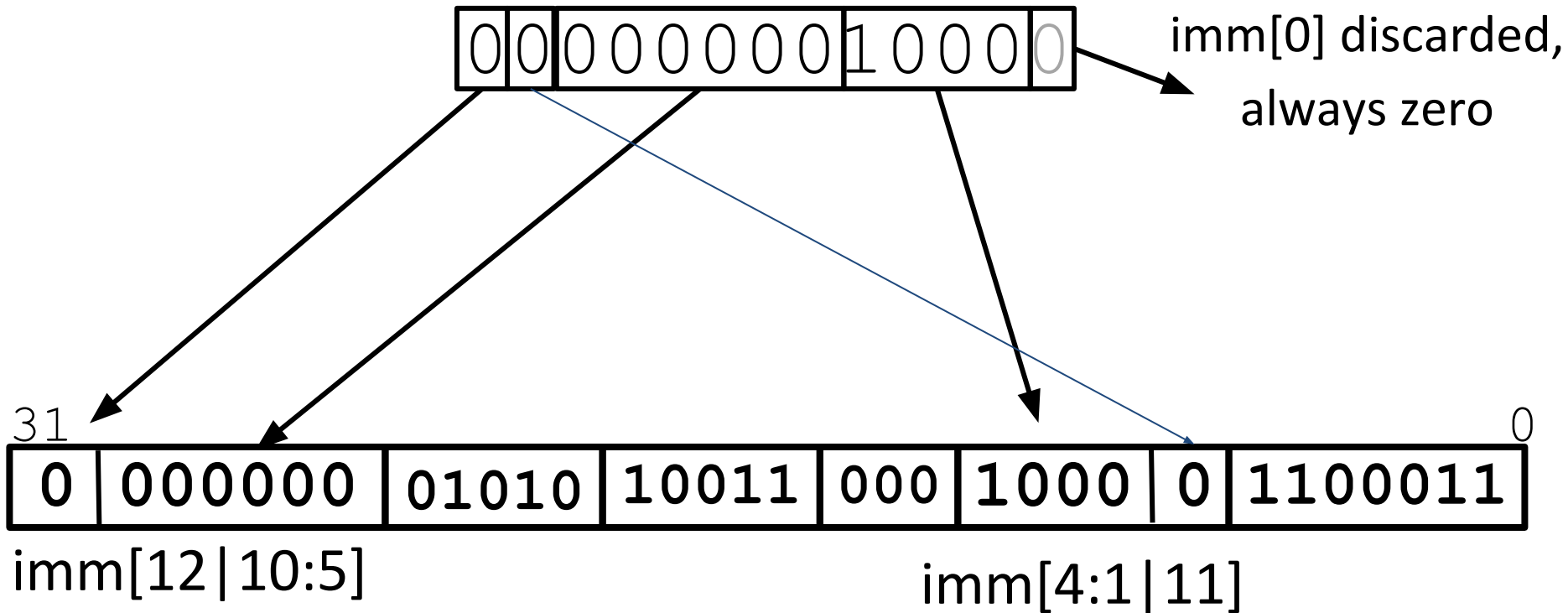
Loop: beq x19, x10, End
      add x18, x18, x10
      addi x19, x19, -1
      j Loop
End:  <target instr>
    
```



Branch Example (1/2)

beq **x19,x10,offset = 16 bytes**

13-bit immediate, imm[12:0], with value 16



RISC-V Immediate Encoding

- Why is it so confusing?!?!

Instruction Encodings, inst[31:0]

31	30	25	24	21	20	19	15	14	12	11	8	7	6	0	
funct7				rs2			rs1		funct3		rd			opcode	R-type
imm[11:0]							rs1		funct3		rd			opcode	I-type
imm[11:5]				rs2			rs1		funct3		imm[4:0]			opcode	S-type
imm[12]	imm[10:5]			rs2			rs1		funct3		imm[4:1]	imm[11]	opcode	B-type	

32-bit immediates produced, imm[31:0]

31	30	20	19	12	11	10	5	4	1	0	
— inst[31] —						inst[30:25]		inst[24:21]		inst[20]	I-immediate
— inst[31] —						inst[30:25]		inst[11:8]		inst[7]	S-immediate
— inst[31] —						inst[7]		inst[30:25]		inst[11:8]	0 B-immediate

Upper bits sign-extended from inst[31] always

Only bit 7 of instruction changes role in immediate between S and B

All RISC-V Branch Instructions

imm[12 10:5]	rs2	rs1	000	imm[4:1 11]	1100011	BEQ
imm[12 10:5]	rs2	rs1	001	imm[4:1 11]	1100011	BNE
imm[12 10:5]	rs2	rs1	100	imm[4:1 11]	1100011	BLT
imm[12 10:5]	rs2	rs1	101	imm[4:1 11]	1100011	BGE
imm[12 10:5]	rs2	rs1	110	imm[4:1 11]	1100011	BLTU
imm[12 10:5]	rs2	rs1	111	imm[4:1 11]	1100011	BGEU

Questions on PC-addressing

- Does the value in branch immediate field change if we move the code?
 - If moving individual lines of code, then yes
 - If moving all of code, then no (why?)
- What do we do if destination is $> 2^{10}$ instructions away from branch?
 - Other instructions save us:

```
beq x10, x0, far          bne x10, x0, next
# next instr              →   j    far
                           next: # next instr
```

Meet the \$taff

	Sukrit	Suvansh
Roadside Sign	"Help, can't find my roadsign"	"Do not sushi enter" (put picture)
Greatest Weakness	Committing to too many things	Binging TV
Favorite artist	Kanye West	Joshua Radin
Favorite meme of all time	All Spongebob memes	Avocado kid



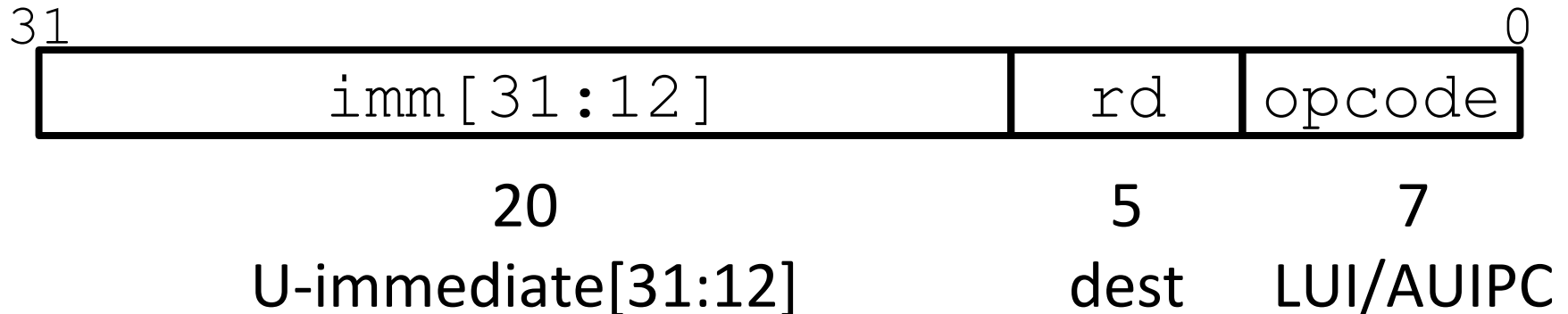
Agenda

- Stored-Program Concept
- R-Format
- I-Format
- Administritivia
- S-Format
- SB-Format
- **U-Format**
- UJ-Format

Dealing With Large Immediates

- How do we deal with 32-bit immediates?
 - Our I-type instructions only give us 12 bits
- **Solution:** Need a new instruction format for dealing with the rest of the 20 bits.
- This instruction should deal with:
 - a destination register to put the 20 bits into
 - the immediate of 20 bits
 - the instruction opcode

U-Format for “Upper Immediate” instructions



- Has 20-bit immediate in upper 20 bits of 32-bit instruction word
- One destination register, `rd`
- Used for two instructions
 - LUI – Load Upper Immediate
 - AUIPC – Add Upper Immediate to PC

LUI to create long immediates

- `lui` writes the upper 20 bits of the destination with the immediate value, and clears the lower 12 bits
- Together with an `addi` to set low 12 bits, can create any 32-bit value in a register using two instructions (`lui/addi`).

```
lui x10, 0x87654          # x10 = 0x87654000
addi x10, x10, 0x321      # x10 = 0x87654321
```

Corner Case

- How to set 0xDEADBEEF?

```
lui x10, 0xDEADB      # x10 = 0xDEADB000
addi x10, x10, 0xEEF   # x10 = 0xDEADAEEF
```

addi 12-bit immediate is always sign-extended!

- if top bit of the 12-bit immediate is a 1, it will subtract -1 from upper 20 bits

Solution

- How to set 0xDEADBEEF?

```
lui x10, 0xDEADC      # x10 = 0xDEADC000
addi x10, x10, 0xEEF   # x10 = 0xDEADBEEF
```

Pre-increment value placed in upper 20 bits, if sign bit will be set on immediate in lower 12 bits.

Assembler pseudo-op handles all of this:

```
li x10, 0xDEADBEEF # Creates two instructions
```

AUIPC

- Adds upper immediate value to PC and places result in destination register
- Used for PC-relative addressing
- `Label: auipc x10, 0`
 - Puts address of label into x10

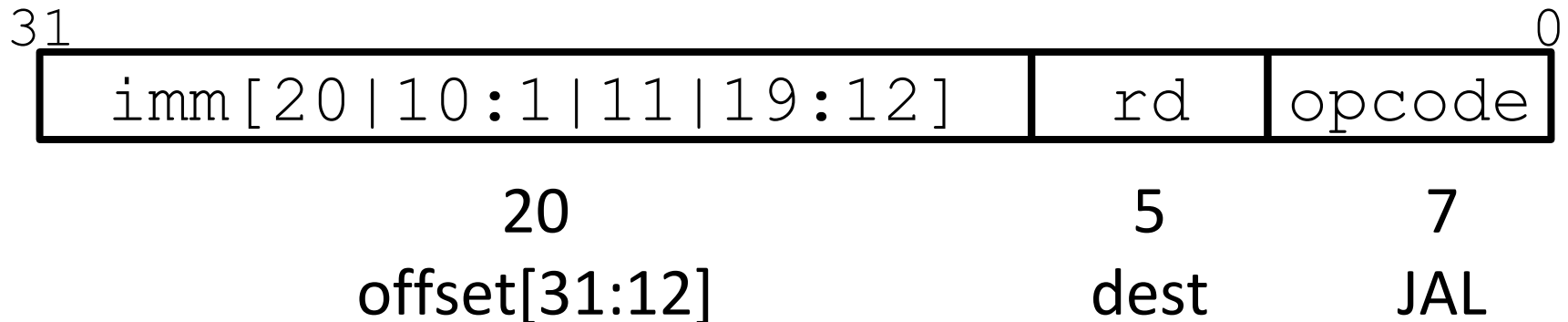
Agenda

- Stored-Program Concept
- R-Format
- I-Format
- Administtrivia
- S-Format
- SB-Format
- U-Format
- **UJ-Format**

UJ-Format Instructions (1/3)

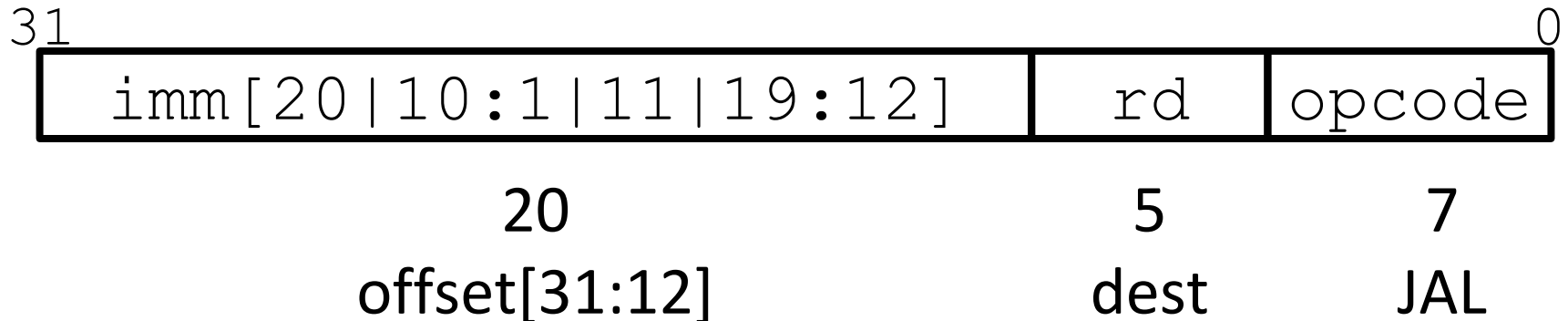
- For branches, we assumed that we won't want to branch too far, so we can specify a *change* in the PC
- For general jumps (`jal`), we may jump to *anywhere* in code memory
 - Ideally, we would specify a 32-bit memory address to jump to
 - Unfortunately, we can't fit both a 7-bit `opcode` and a 32-bit address into a single 32-bit word
 - Also, when linking we must write to an `rd` register

UJ-Format Instructions (2/3)



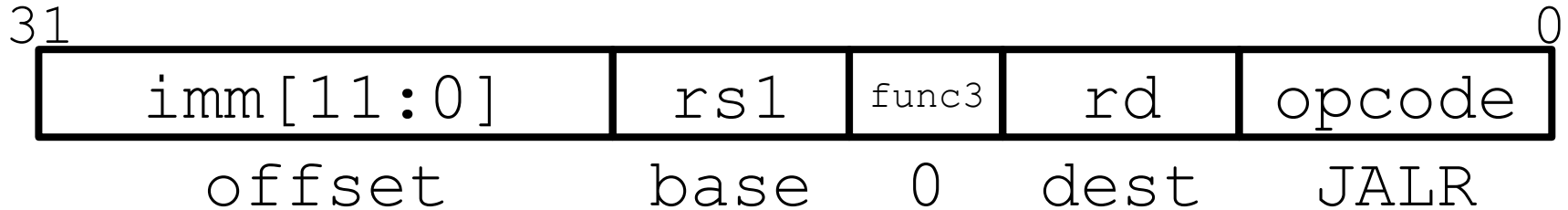
- `jal` saves PC+4 in register `rd` (the return address)
- Set PC = PC + offset (PC-relative jump)
- Target somewhere within $\pm 2^{19}$ locations, 2 bytes apart
- $\pm 2^{18}$ 32-bit instructions
- Reminder: “j” jump is a pseudo-instruction—the assembler will instead use `jal` but sets `rd=x0` to discard return address
- Immediate encoding optimized similarly to branch instruction to reduce hardware cost

UJ-Format Instructions (2/3)



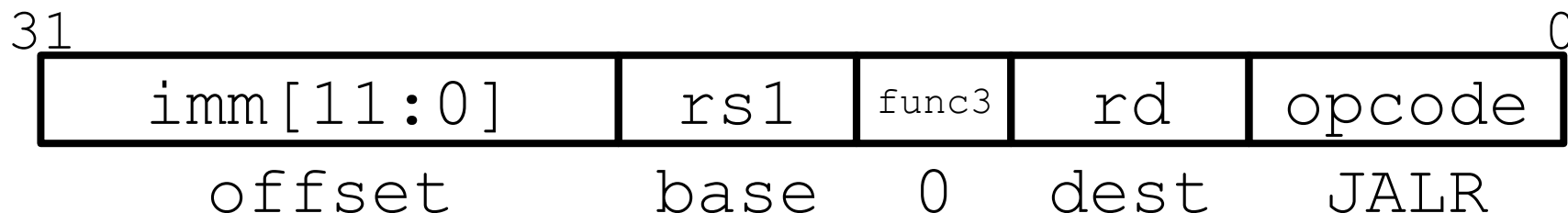
- `# j pseudo-instruction`
- `j Label = jal x0, Label` # Discard return address
- `# Call function within 2^{18} instructions of PC`
- `jal ra, FuncName`
- Why is the immediate so funky?
 - Similar reasoning as for branch immediates

jalr Instruction (I-Format)



- `jalr rd, rs1, offset`
- Writes PC+4 to `rd` (return address)
- Sets `PC = rs1 + offset`
- Uses same immediates as arithmetic & loads
 - **no** multiplication by 2 bytes

Uses of jalr



ret and jr psuedo-instructions

```
ret = jr ra = jalr x0, ra, 0
```

Call function at any 32-bit absolute address

```
lui x1, <hi 20 bits>
```

```
jalr ra, x1, <lo 12 bits>
```

Jump PC-relative with 32-bit offset

```
auipc x1, <hi 20 bits>
```

```
jalr x0, x1, <lo 12 bits>
```

Question: When combining two C files into one executable, we can compile them independently and then merge them together.

When merging two or more binaries:

- 1) **Jump** instructions don't require any changes
- 2) **Branch** instructions don't require any changes

	1	2
(A)	F	F
(B)	F	T
(C)	T	F
(D)	T	T

Summary of RISC-V Instruction Formats

31	30	25	24	21	20	19	15	14	12	11	8	7	6	0				
funct7				rs2			rs1		funct3		rd			opcode		R-type		
imm[11:0]						rs1		funct3		rd			opcode		I-type			
imm[11:5]				rs2			rs1		funct3		imm[4:0]			opcode		S-type		
imm[12]		imm[10:5]			rs2			rs1		funct3		imm[4:1]		imm[11]		opcode		B-type
imm[31:12]										rd			opcode		U-type			
imm[20]		imm[10:1]				imm[11]		imm[19:12]			rd			opcode		J-type		

Summary

- The Stored Program concept is very powerful
 - Instructions can be treated and manipulated the same way as data in both hardware and software
- RISC-V Machine Language Instructions:

imm[31:12]					rd	0110111	LUI
imm[31:12]					rd	0010111	AUIPC
imm[20:10:11:19:12]					rd	1101111	JAL
imm[11:0]			rs1	000	rd	1100111	JALR
imm[12:10:5]		rs2	rs1	000	imm[4:1:11]	1100011	BEQ
imm[12:10:5]		rs2	rs1	001	imm[4:1:11]	1100011	BNE
imm[12:10:5]		rs2	rs1	100	imm[4:1:11]	1100011	BLT
imm[12:10:5]		rs2	rs1	101	imm[4:1:11]	1100011	BGE
imm[12:10:5]		rs2	rs1	110	imm[4:1:11]	1100011	BLTU
imm[12:10:5]		rs2	rs1	111	imm[4:1:11]	1100011	BGEU
imm[11:0]			rs1	000	rd	0000011	LB
imm[11:0]			rs1	001	rd	0000011	LH
imm[11:0]			rs1	010	rd	0000011	LW
imm[11:0]			rs1	100	rd	0000011	LBU
imm[11:0]			rs1	101	rd	0000011	LHU
imm[11:5]		rs2	rs1	000	imm[4:0]	0100011	SB
imm[11:5]		rs2	rs1	001	imm[4:0]	0100011	SH
imm[11:5]		rs2	rs1	010	imm[4:0]	0100011	SW
imm[11:0]			rs1	000	rd	0010011	ADDI
imm[11:0]			rs1	010	rd	0010011	SLTI
imm[11:0]			rs1	011	rd	0010011	SLTIU
imm[11:0]			rs1	100	rd	0010011	XORI
imm[11:0]			rs1	110	rd	0010011	ORI
imm[11:0]			rs1	111	rd	0010011	ANDI

0000000	shamt	rs1	001	rd	0010011	SLLI	
0000000	shamt	rs1	101	rd	0010011	SRLI	
0100000	shamt	rs1	101	rd	0010011	SRAI	
0000000	rs2	rs1	000	rd	0110011	ADD	
0100000	rs2	rs1	000	rd	0110011	SUB	
0000000	rs2	rs1	001	rd	0110011	SLL	
0000000	rs2	rs1	010	rd	0110011	SLT	
0000000	rs2	rs1	011	rd	0110011	SLTU	
0000000	rs2	rs1	100	rd	0110011	XOR	
0000000	rs2	rs1	101	rd	0110011	SRL	
0100000	rs2	rs1	101	rd	0110011	SRA	
0000000	rs2	rs1	110	rd	0110011	OR	
0000000	rs2	rs1	111	rd	0110011	AND	
0000	pred	succ	00000	000	00000	0001111	FENCE
0000	0000	0000	00000	001	00000	0001111	FENCE.I
00000000000000			00000	000	00000	1110011	ECALL
00000000000001			00000	000	00000	1110011	EBREAK
csr		rs1	001	rd	1110011	CSRRW	
csr		rs1	010	rd	1110011	CSRRS	
csr		rs1	011	rd	1110011	CSRRC	
csr		zimm	101	rd	1110011	CSRRWI	
csr		zimm	110	rd	1110011	CSRRSI	
csr		zimm	111	rd	1110011	CSRRCI	