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DI TRIESTE

Restoration and development of Arm's Java-based LEGv8 ISA simulator

Graduating student - Simone Deiana

Supervisor - Alberto Carini

Restoration and development of Arm's Java-based LEGv8 ISA simulator



Restoration and development of Arm's Java-based LEGv8 ISA simulator





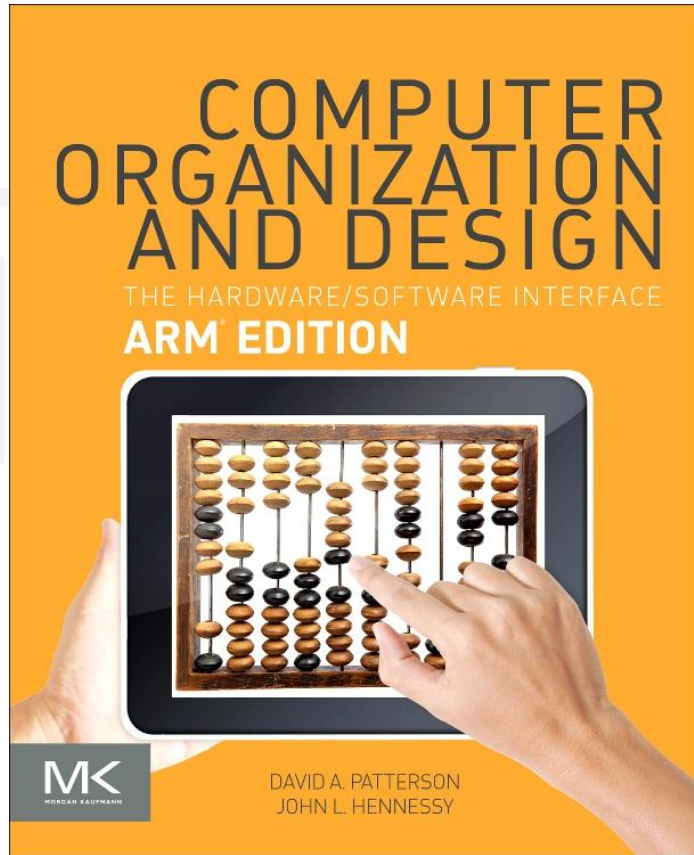
Restoration and development of Arm's Java-based LEGv8 ISA simulator

WHAT IS LEGv8?

Restoration and development of
Arm's Java-based **LEGv8 ISA** simulator

WHAT IS LEGv8?

AN ISA FOR LEARNING COMPUTER ARCHITECTURES



From Computer Organization and Design ARM Edition: The Hardware Software Interface - Patterson, D.A. and Hennessy, J.L.



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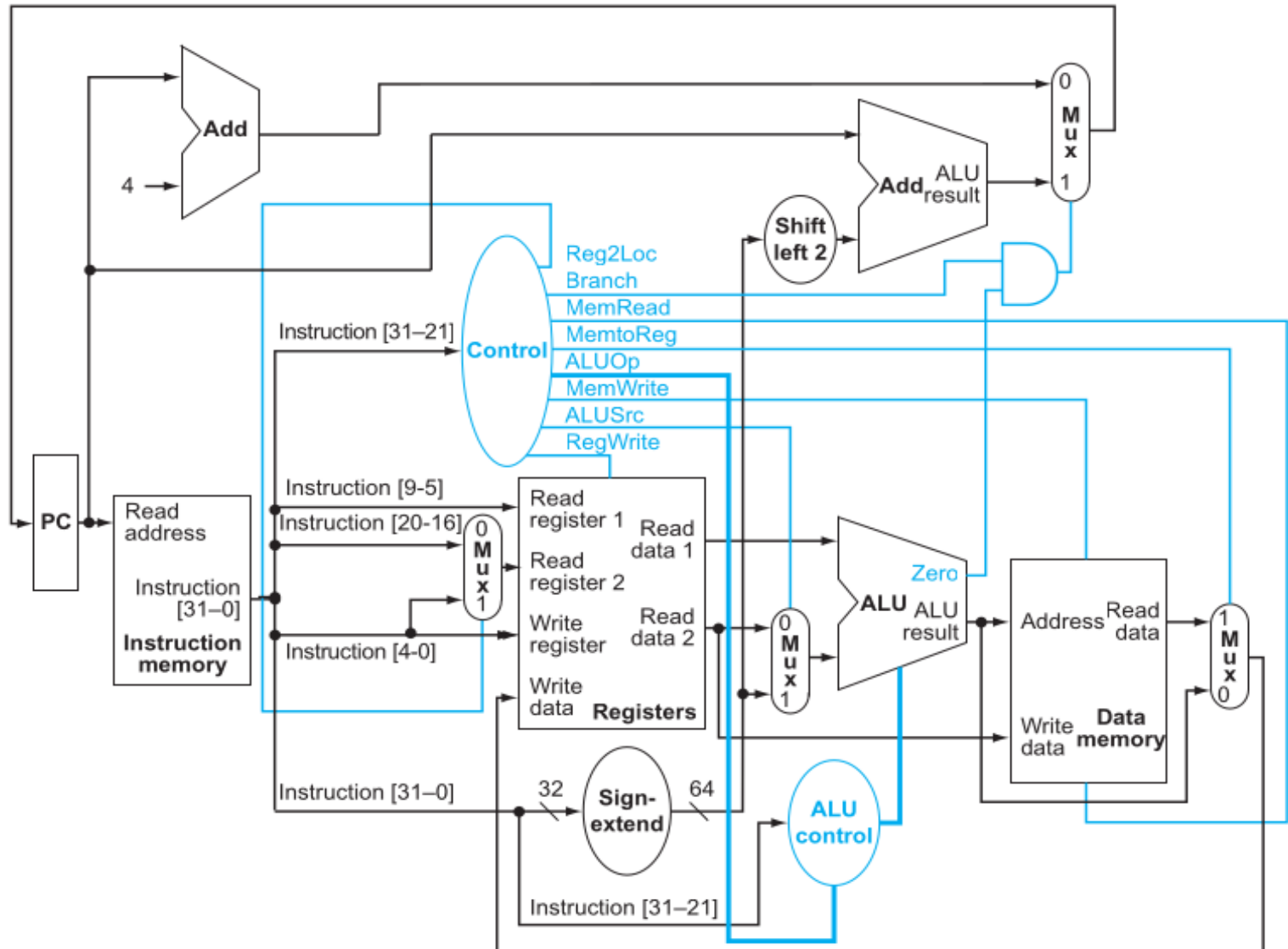
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WHAT IS LEGv8?

- As simple as it can be...
- ... but with a modern design
- Heavily inspired by ARMv8, almost a "subset"
- 64-bit integer and IEEE-754 floating-point arithmetic
- 64-BIT addressed memory (2^{64} BYTES), Harvard model
- Designed for pipelined execution

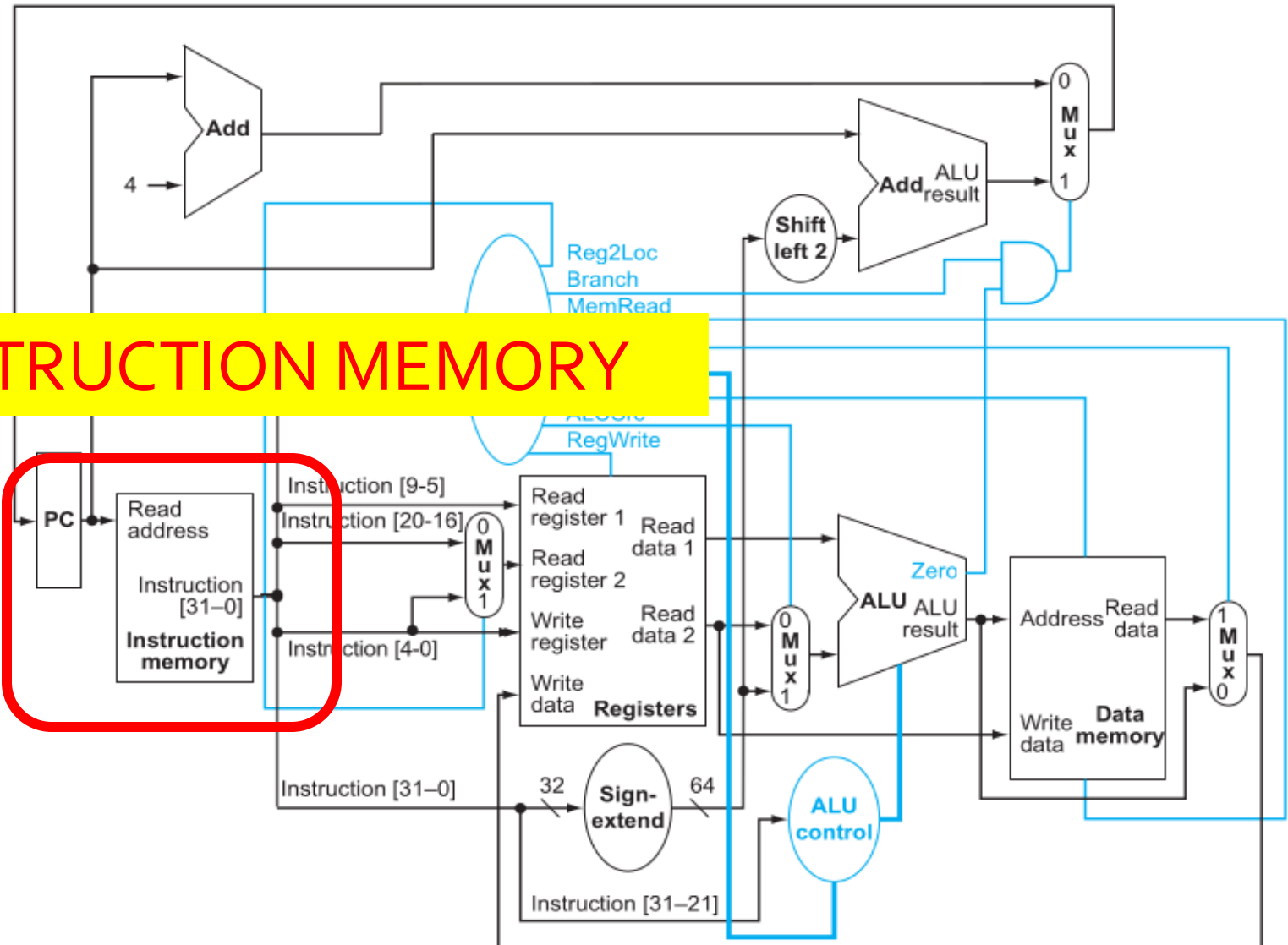
WHAT IS LEGv8?

THE DATAPATH



WHAT IS LEGv8?

THE DATAPAH

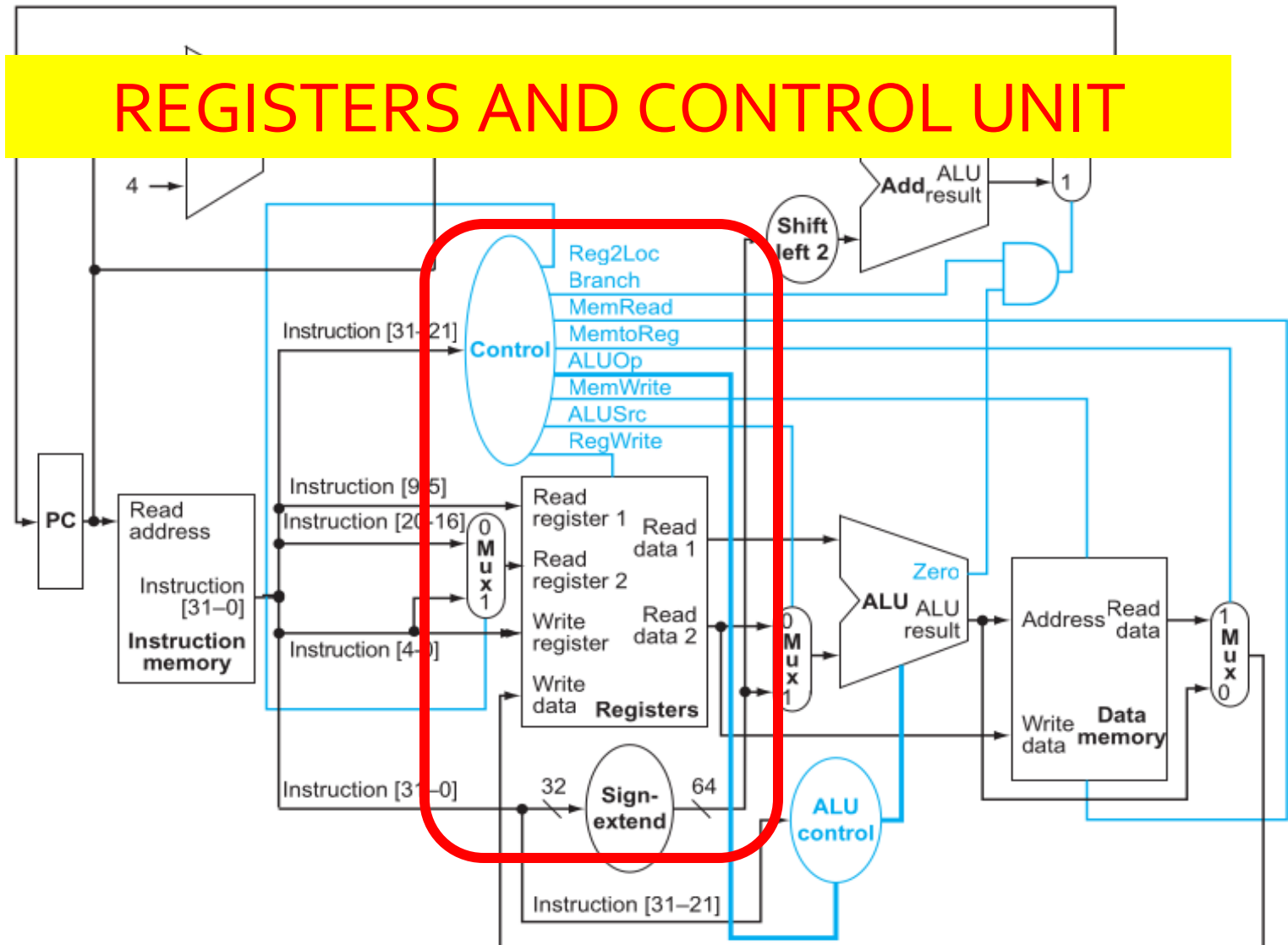


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WHAT IS LEGv8?

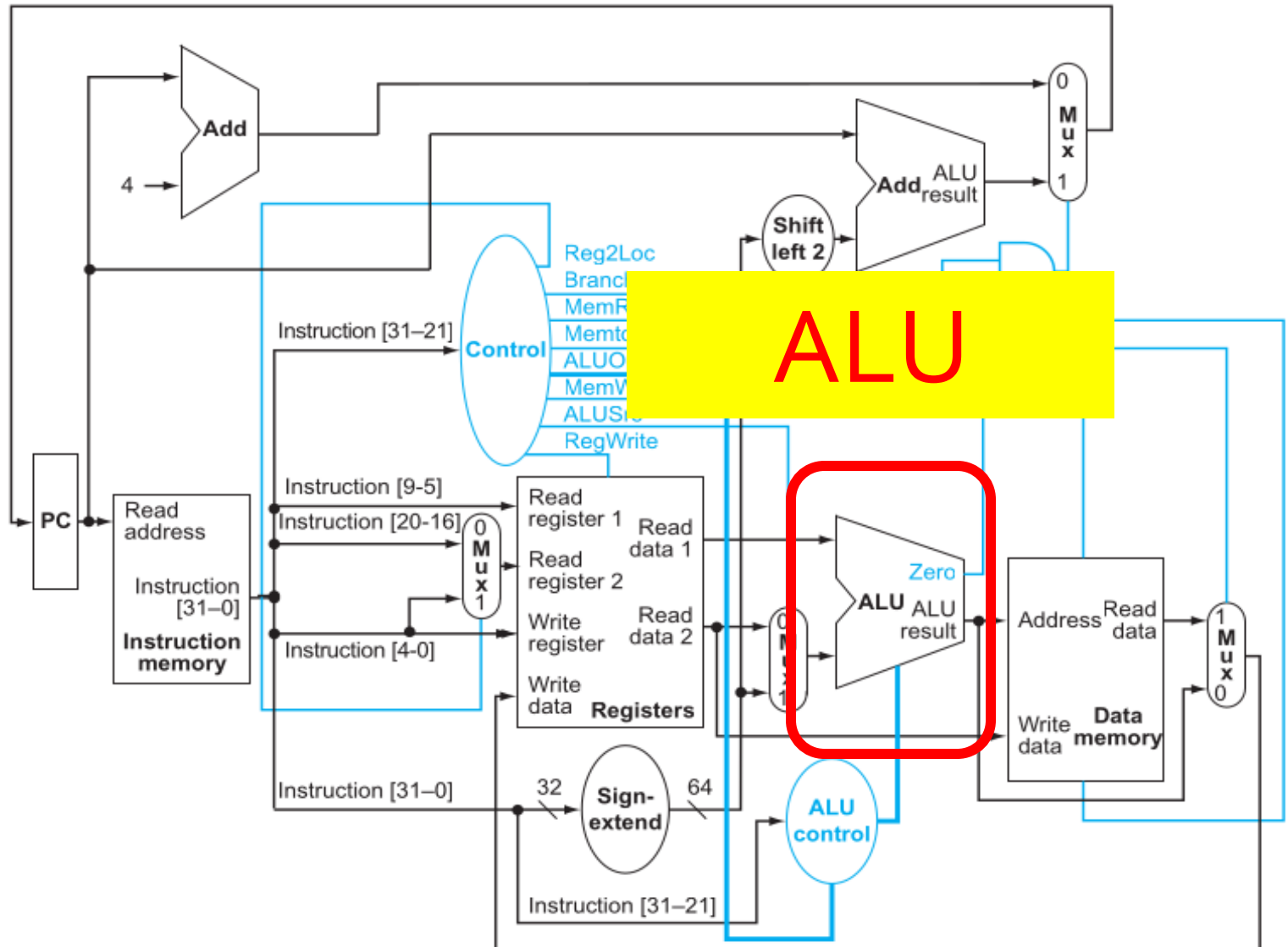
THE DATAPATH

REGISTERS AND CONTROL UNIT



WHAT IS LEGv8?

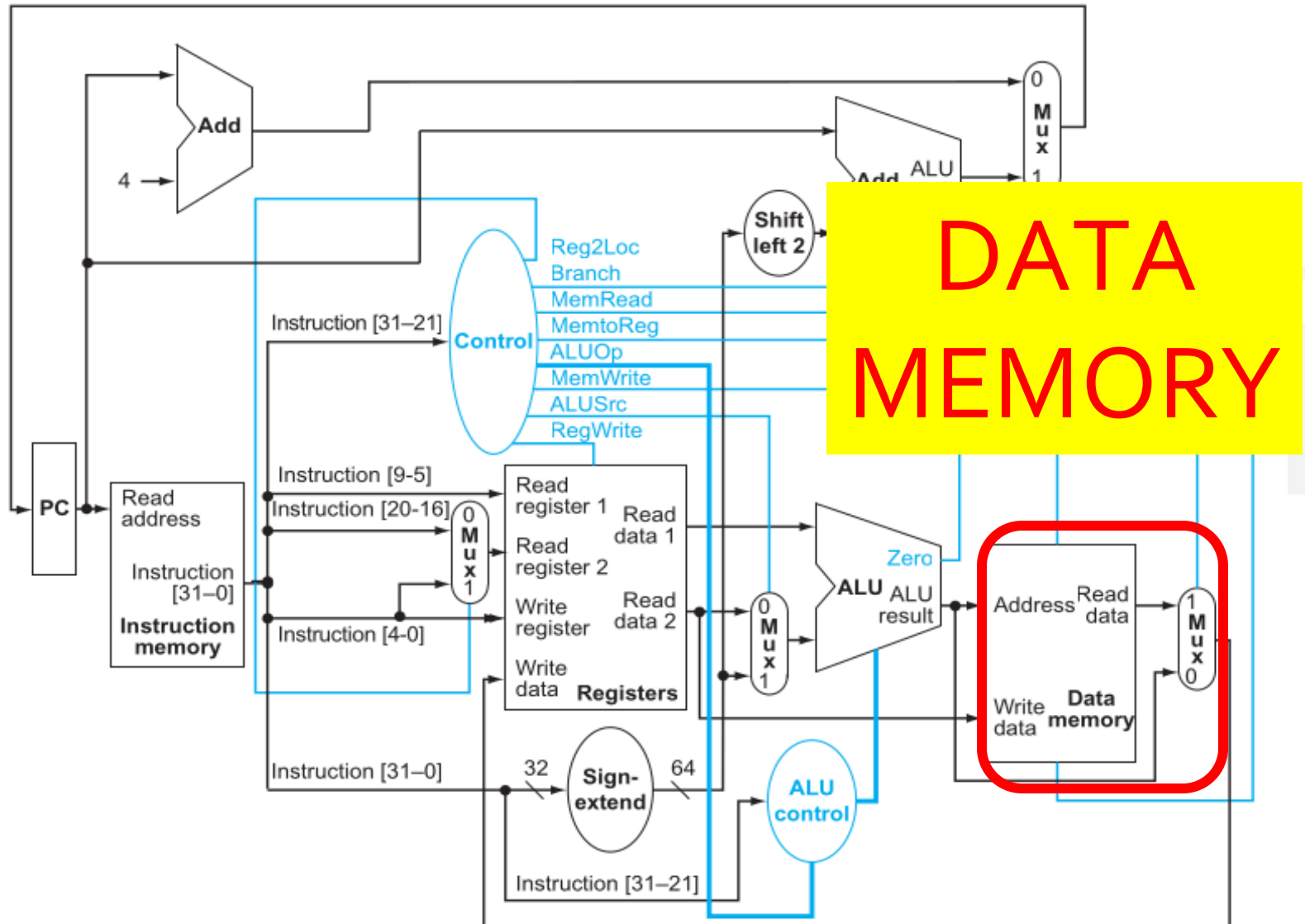
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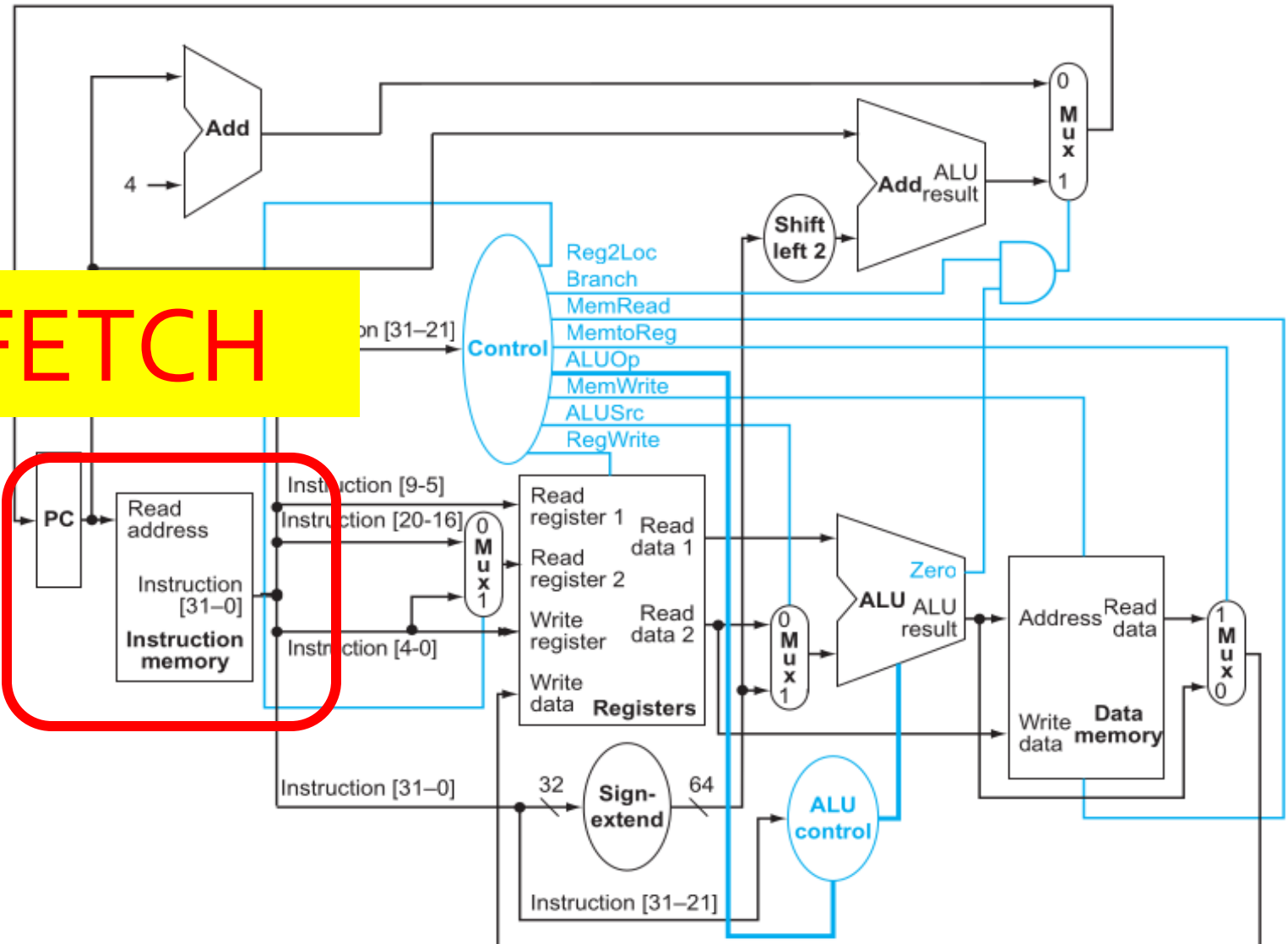
WHAT IS LEGv8?

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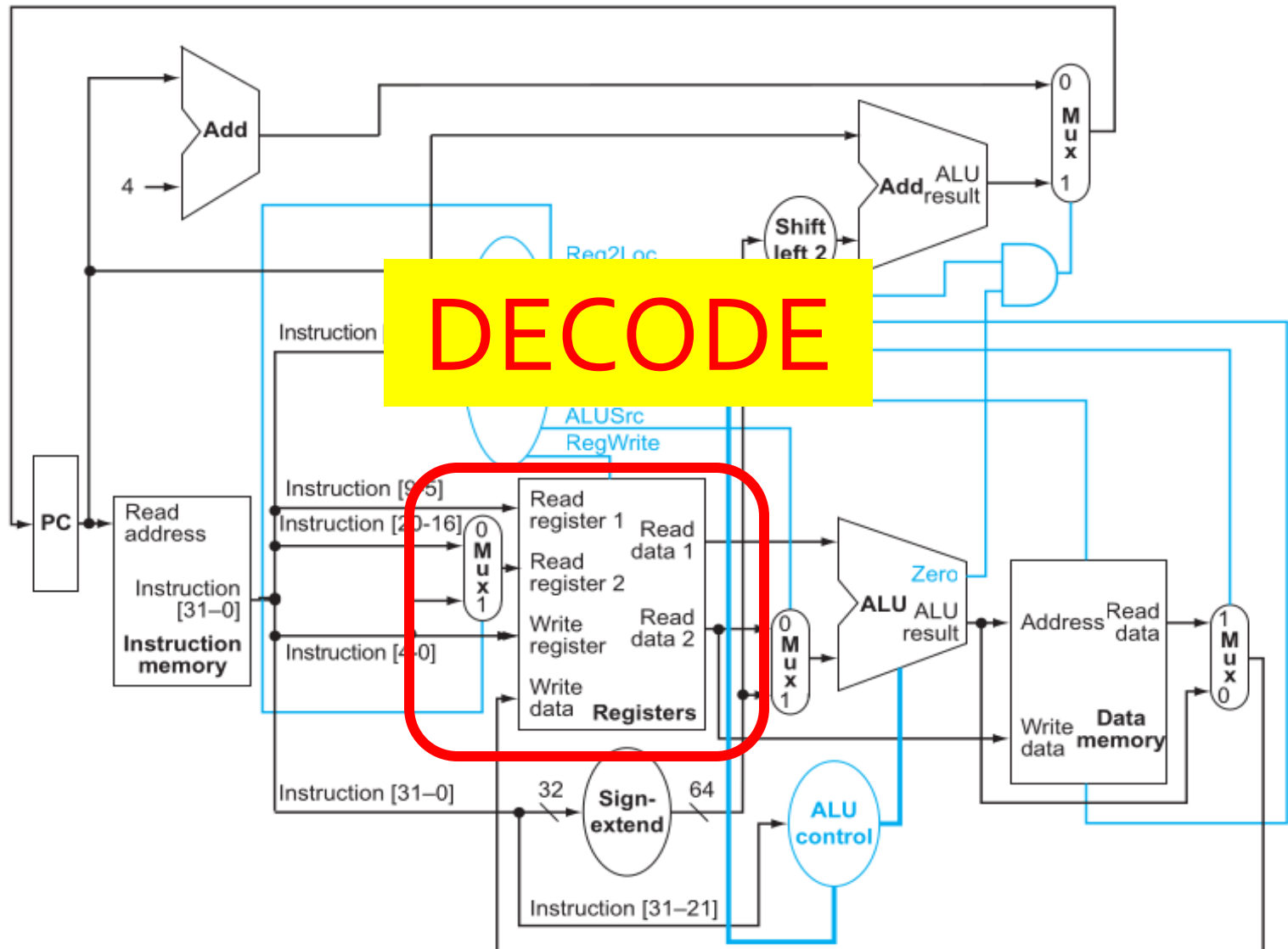
THE STAGES



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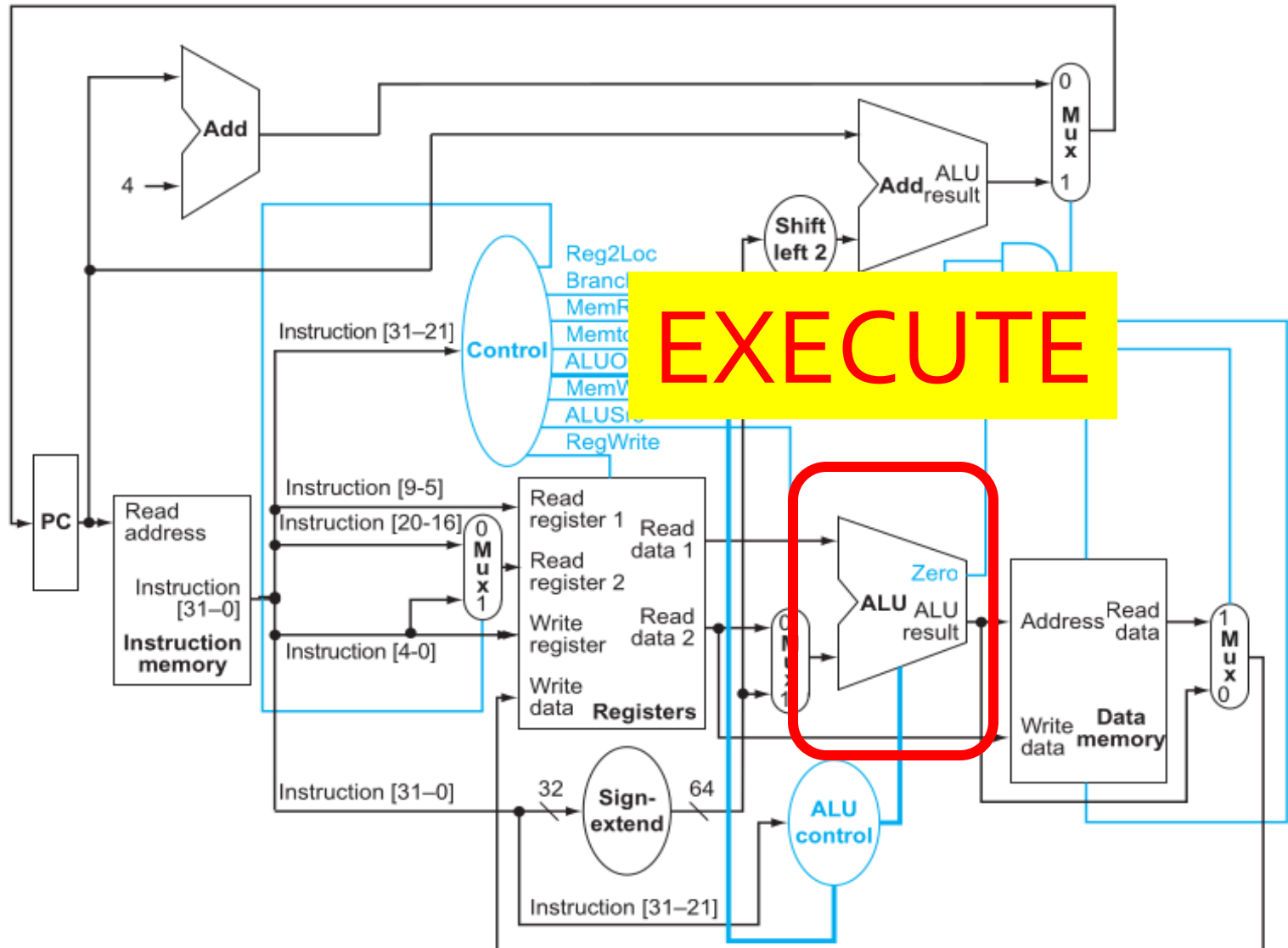
WHAT IS LEGv8?

THE STAGES



WHAT IS LEGv8?

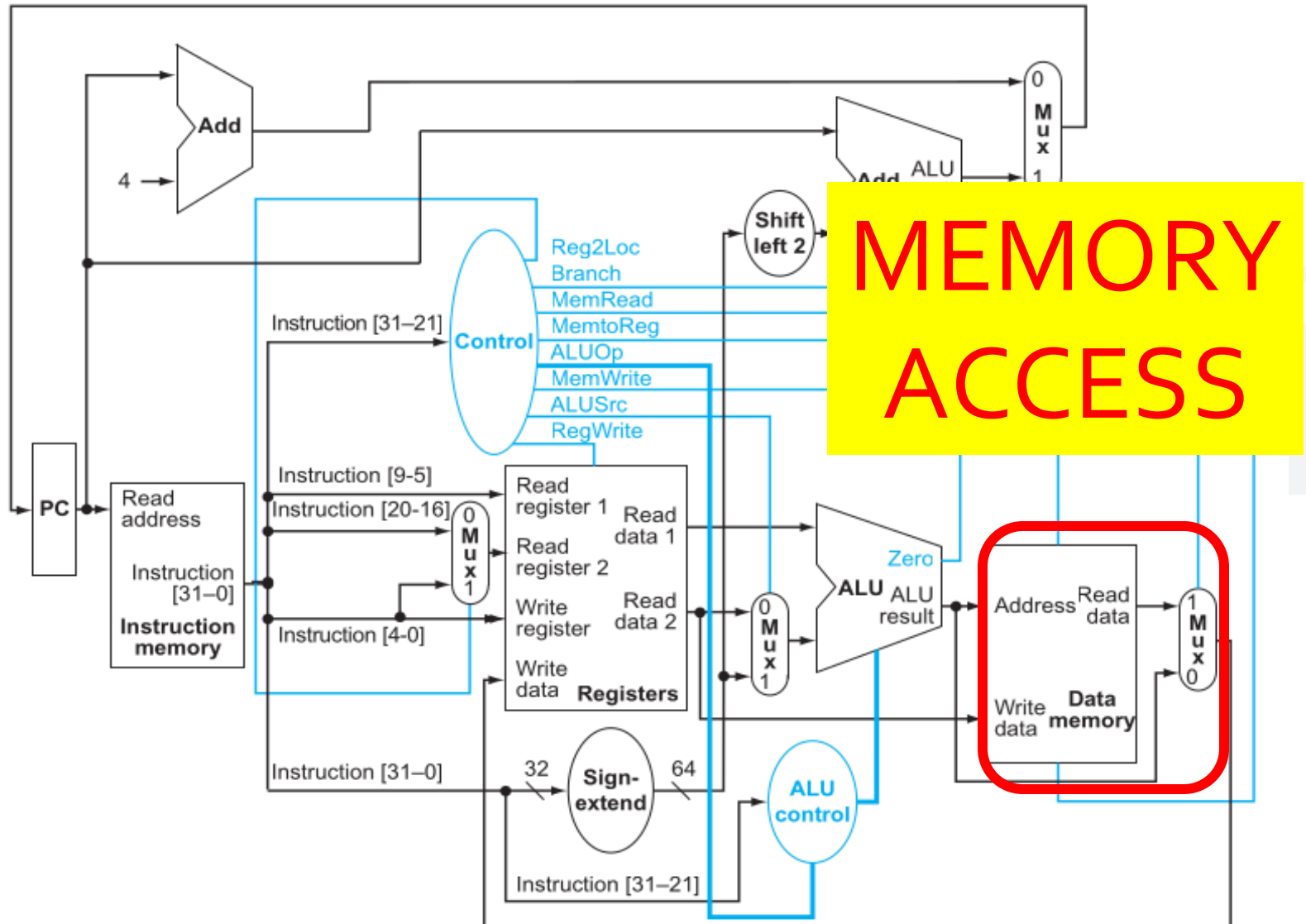
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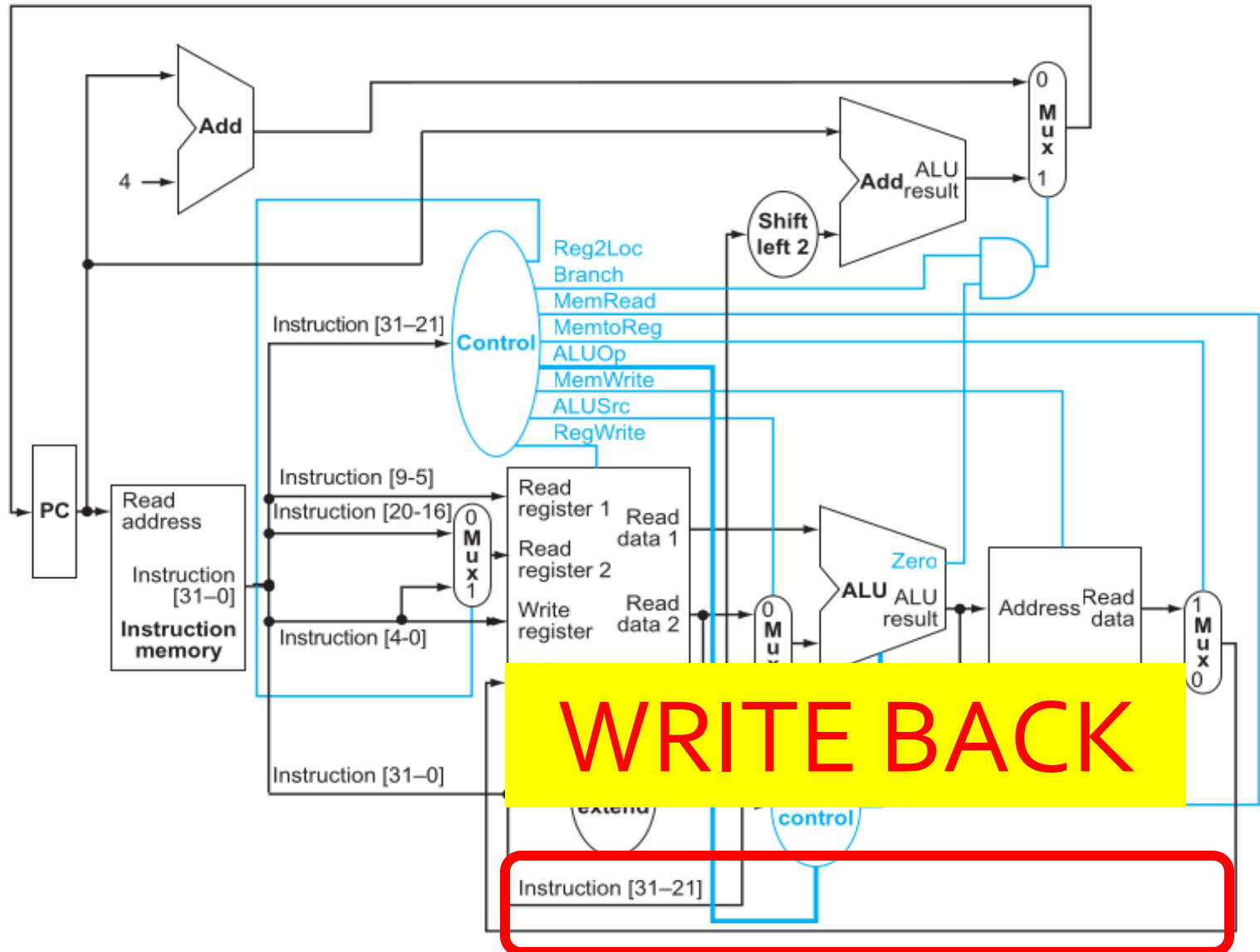
WHAT IS LEGv8?

THE STAGES

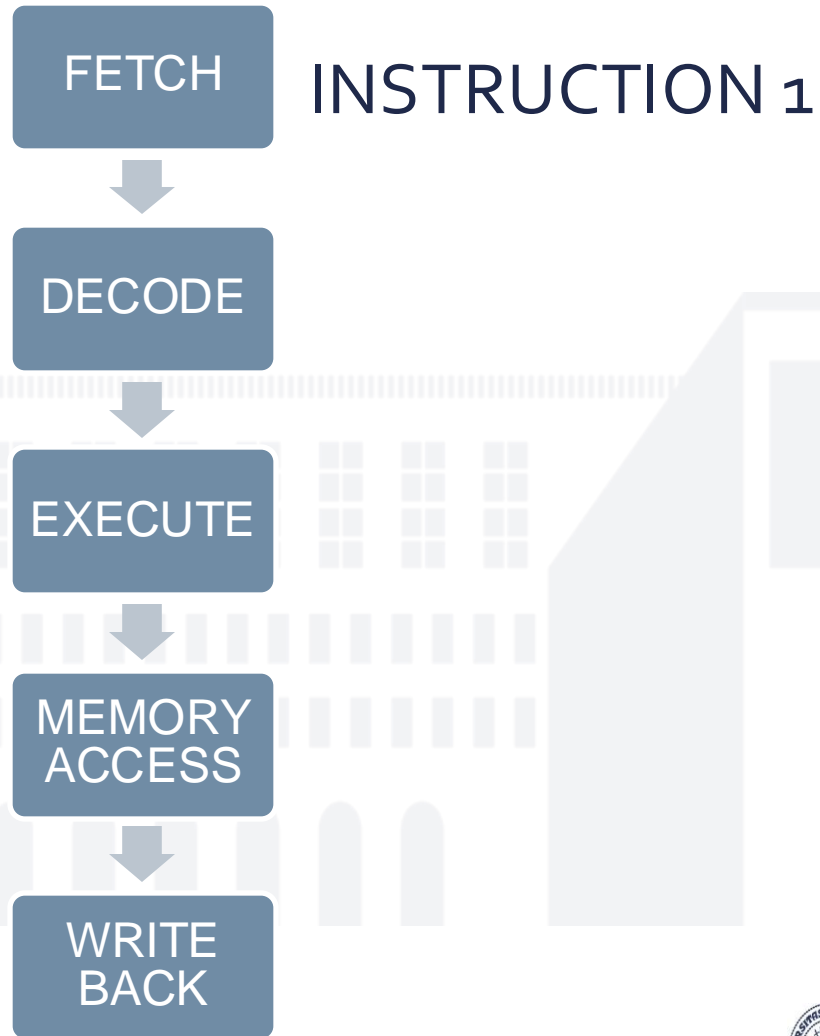


WHAT IS LEGv8?

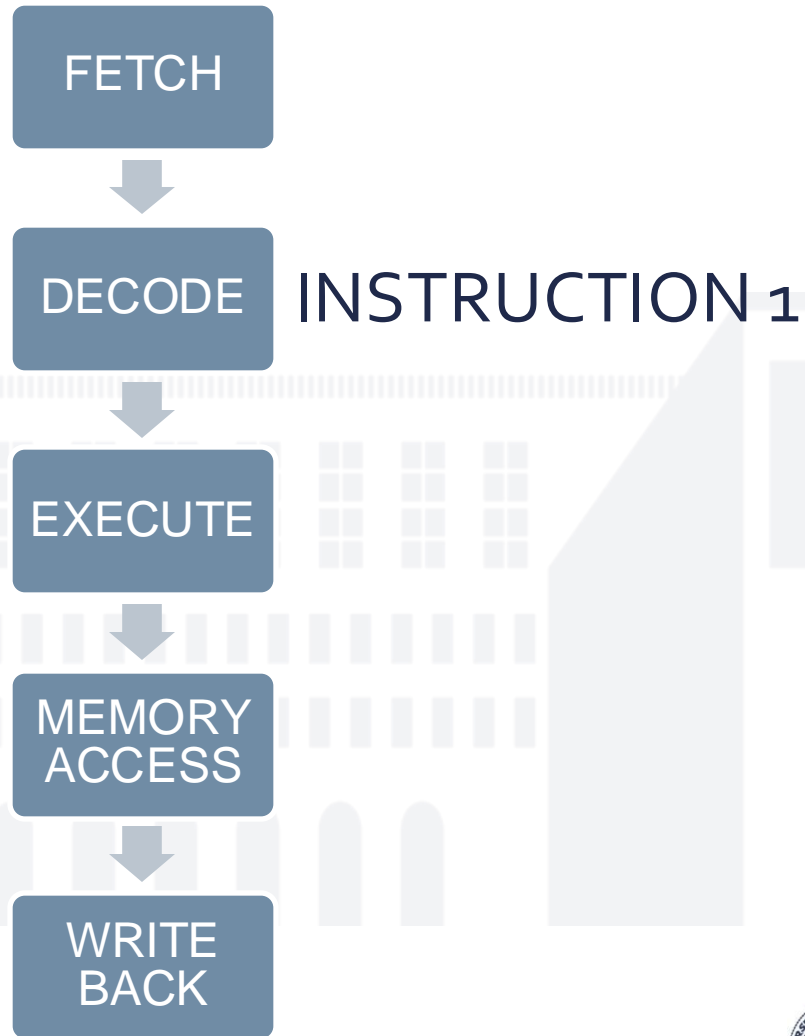
THE STAGES



THE SINGLE CYCLE DATAPATH



THE SINGLE CYCLE DATAPATH



THE SINGLE CYCLE DATAPATH

FETCH



DECODE



EXECUTE

INSTRUCTION 1



MEMORY
ACCESS



WRITE
BACK

THE SINGLE CYCLE DATAPATH

FETCH



DECODE



EXECUTE



MEMORY
ACCESS



WRITE
BACK

INSTRUCTION 1

THE SINGLE CYCLE DATAPATH

FETCH



DECODE



EXECUTE



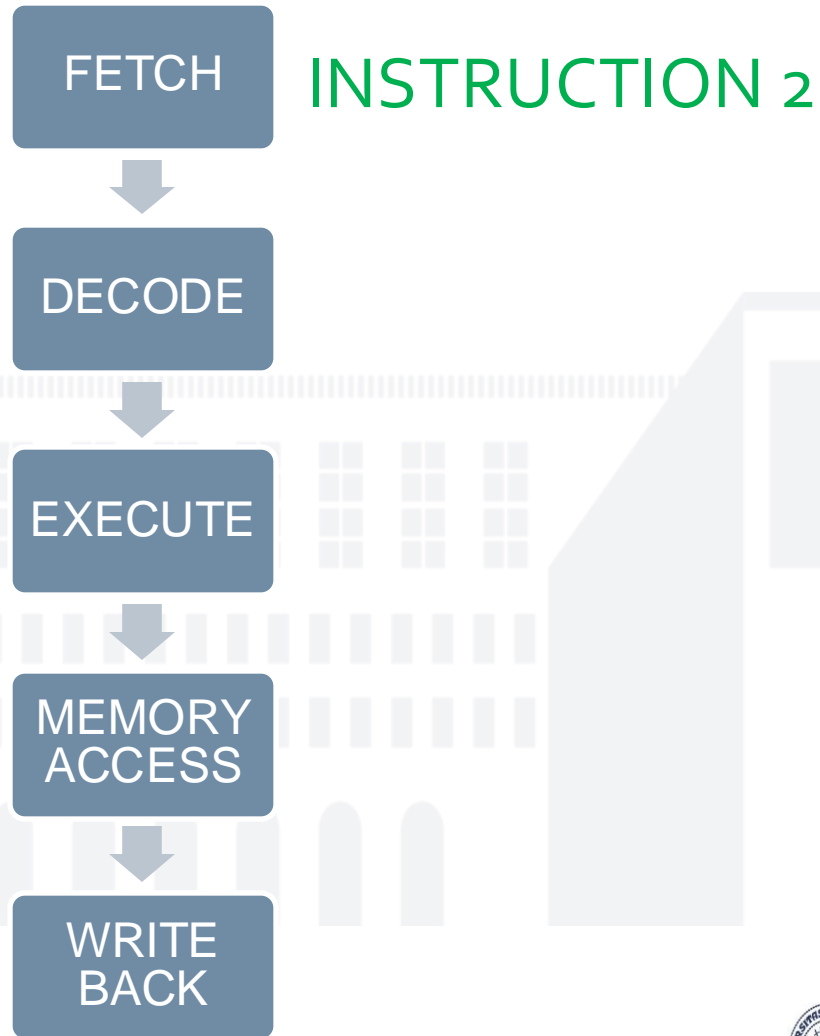
MEMORY
ACCESS



WRITE
BACK

INSTRUCTION 1

THE SINGLE CYCLE DATAPATH



THE SINGLE CYCLE DATAPATH

FETCH



DECODE

INSTRUCTION 2



EXECUTE



MEMORY
ACCESS



WRITE
BACK

THE SINGLE CYCLE DATAPATH

FETCH



DECODE



EXECUTE

INSTRUCTION 2



MEMORY
ACCESS



WRITE
BACK

THE SINGLE CYCLE DATAPATH

FETCH



DECODE



EXECUTE



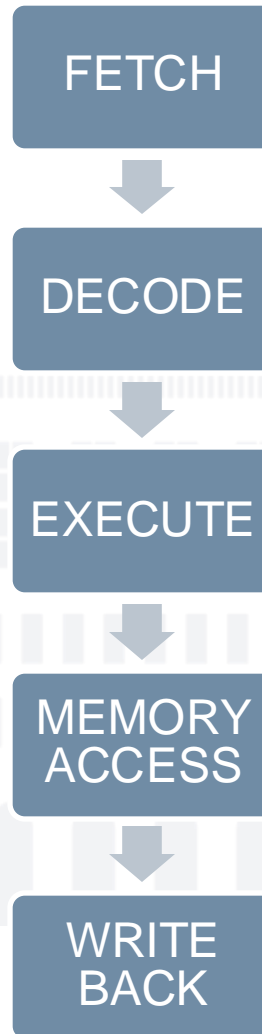
MEMORY
ACCESS



WRITE
BACK

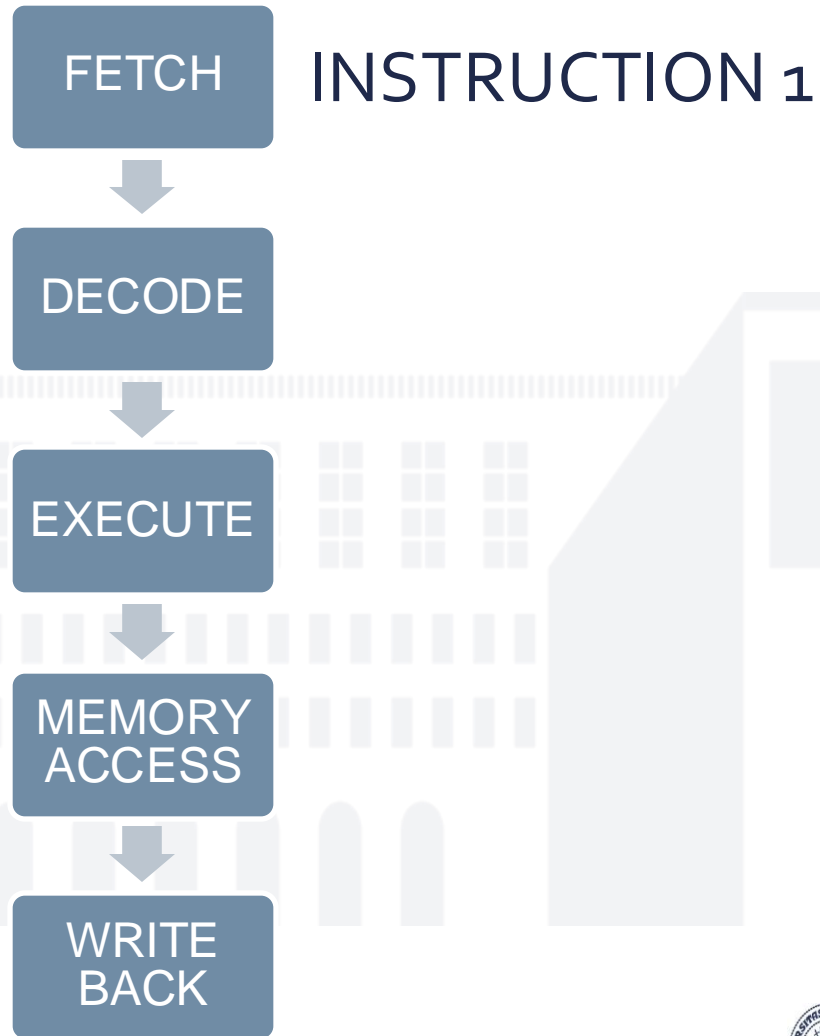
INSTRUCTION 2

THE SINGLE CYCLE DATAPATH

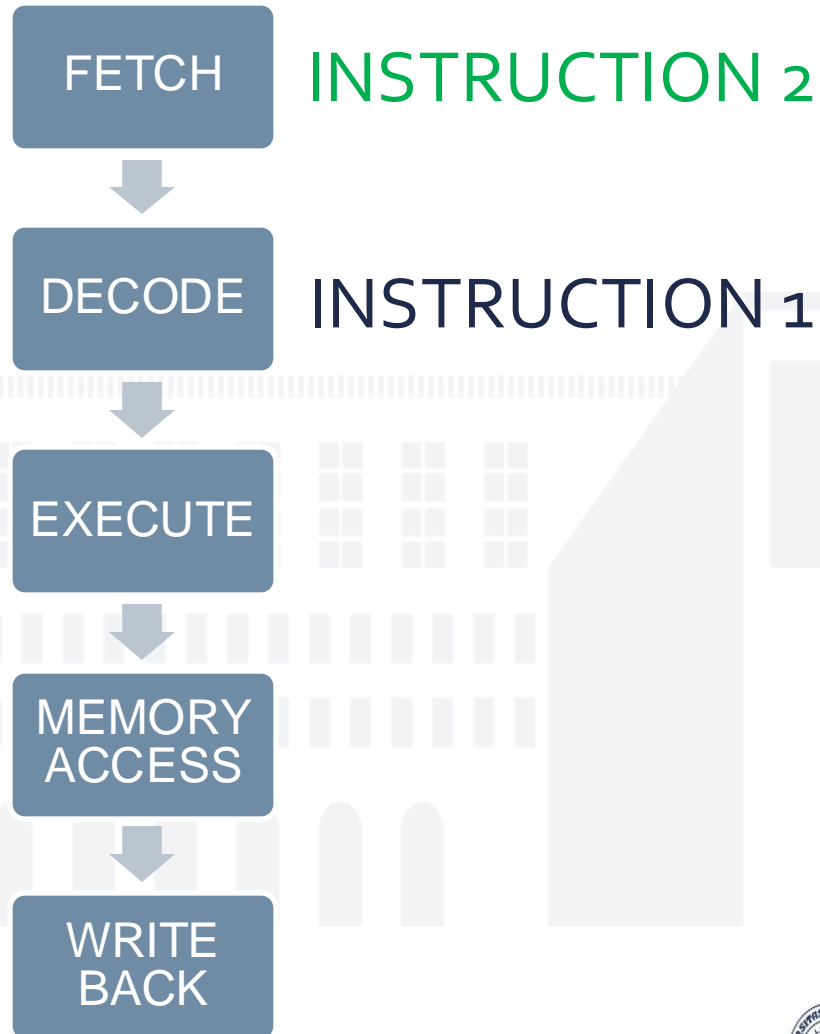


INSTRUCTION 2

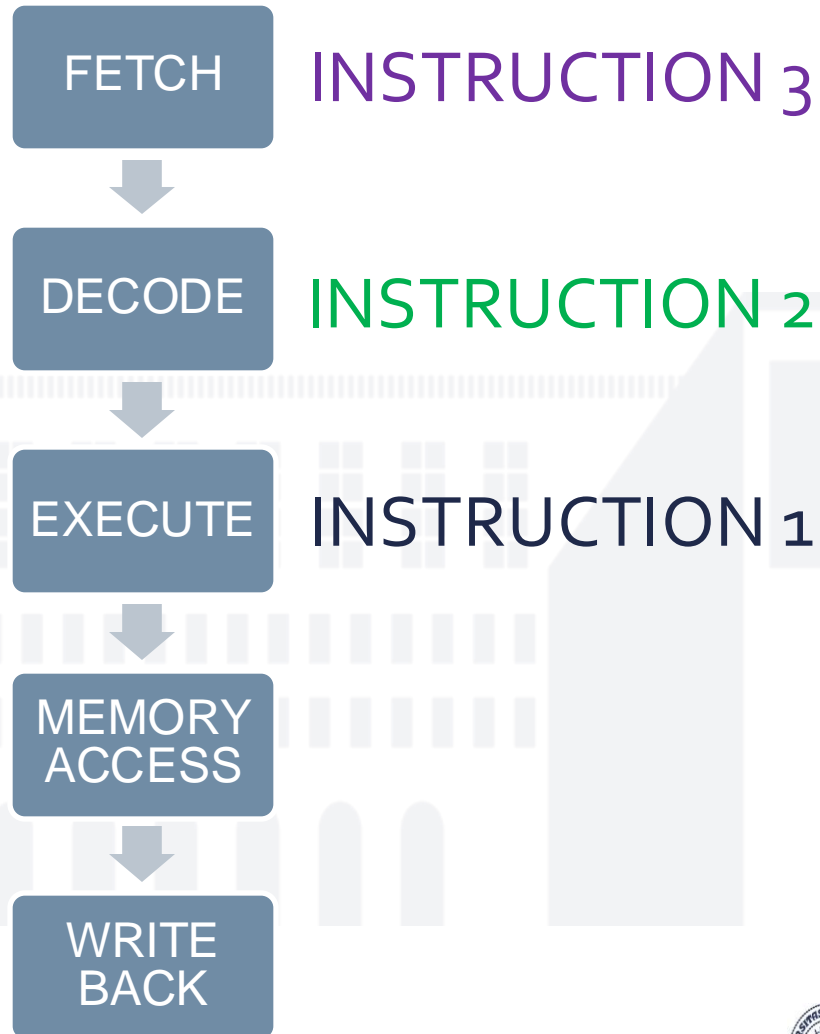
THE PIPELINED DATAPATH



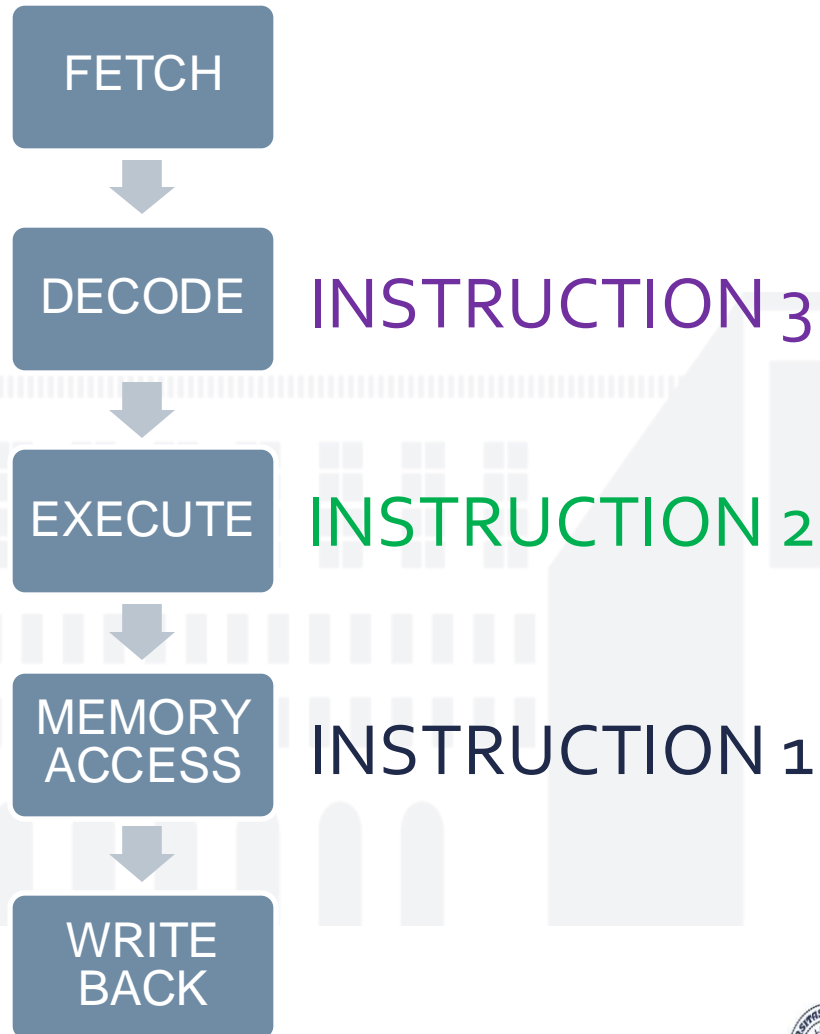
THE PIPELINED DATAPATH



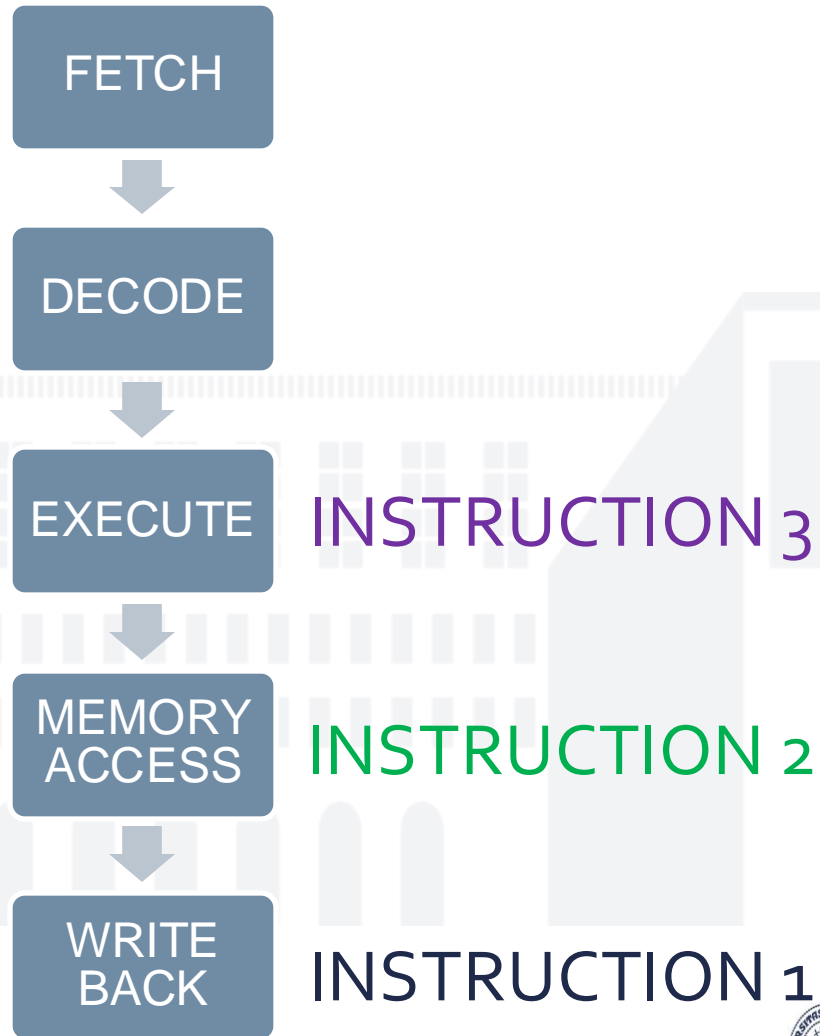
THE PIPELINED DATAPATH



THE PIPELINED DATAPATH



THE PIPELINED DATAPATH



THE PIPELINED DATAPATH

FETCH



DECODE



EXECUTE



MEMORY
ACCESS

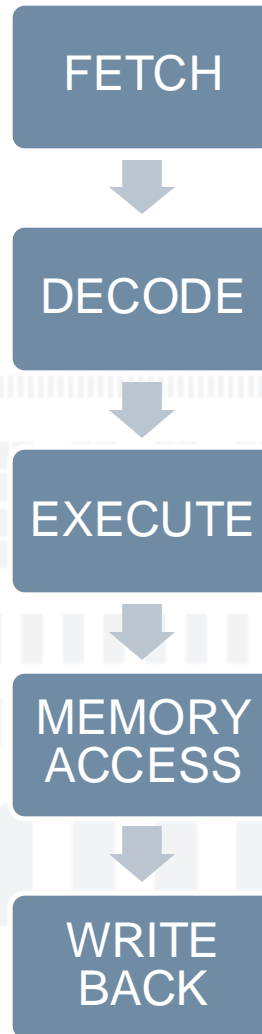


WRITE
BACK

INSTRUCTION 3

INSTRUCTION 2

THE PIPELINED DATAPATH



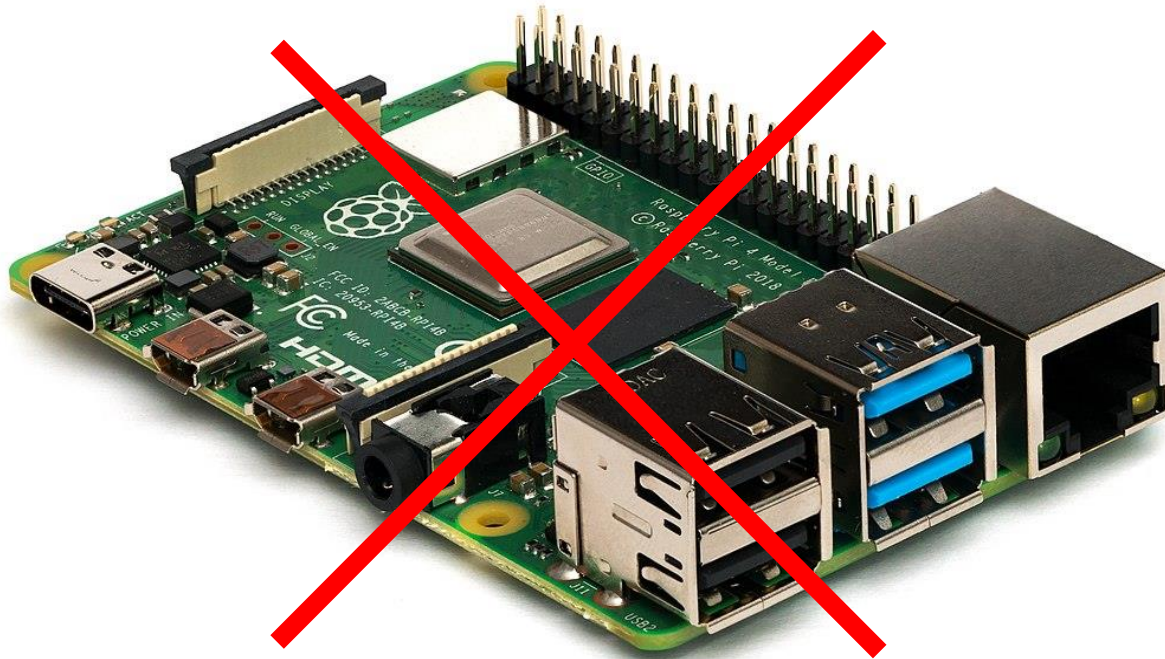
INSTRUCTION 3

WHAT SIMULATOR, AND WHY?

Restoration and development of
Arm's Java-based LEGv8 ISA simulator

WHAT SIMULATOR, AND WHY?

NO HARDWARE FOR LEGv8 => NEED A SIMULATOR



Michael H. („Laserlicht“) / Wikimedia Commons

WHAT SIMULATOR, AND WHY?

BUT WHICH ONE?



LEGv8

197 results

THE PROBLEM:

NO SOFTWARE CAN YET
SIMULATE THE ENTIRE
LEGv8 ISA!

THE SOLUTION:

- Write one from scratch
- OR (BETTER)
- Improve one that already exists

ARM HAS OFFICIALLY MADE A LEGv8 SIMULATOR

GOOD!

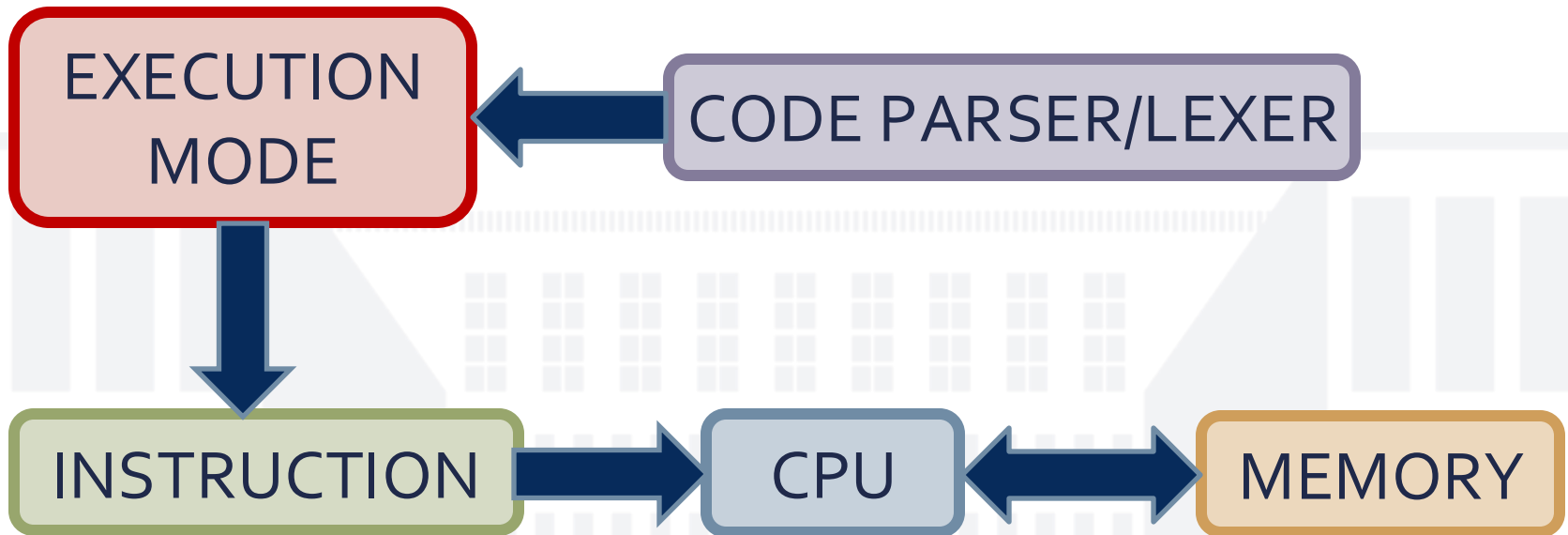
IT'S INCOMPLETE
AND BROKEN

BAD!

WHAT STANDS OUT:

- Written in Java (high level, extensible)
- Distributed as a web application
- Nice, functional UI
- Closely follows the textbook

STRUCTURE OF THE SIMULATOR



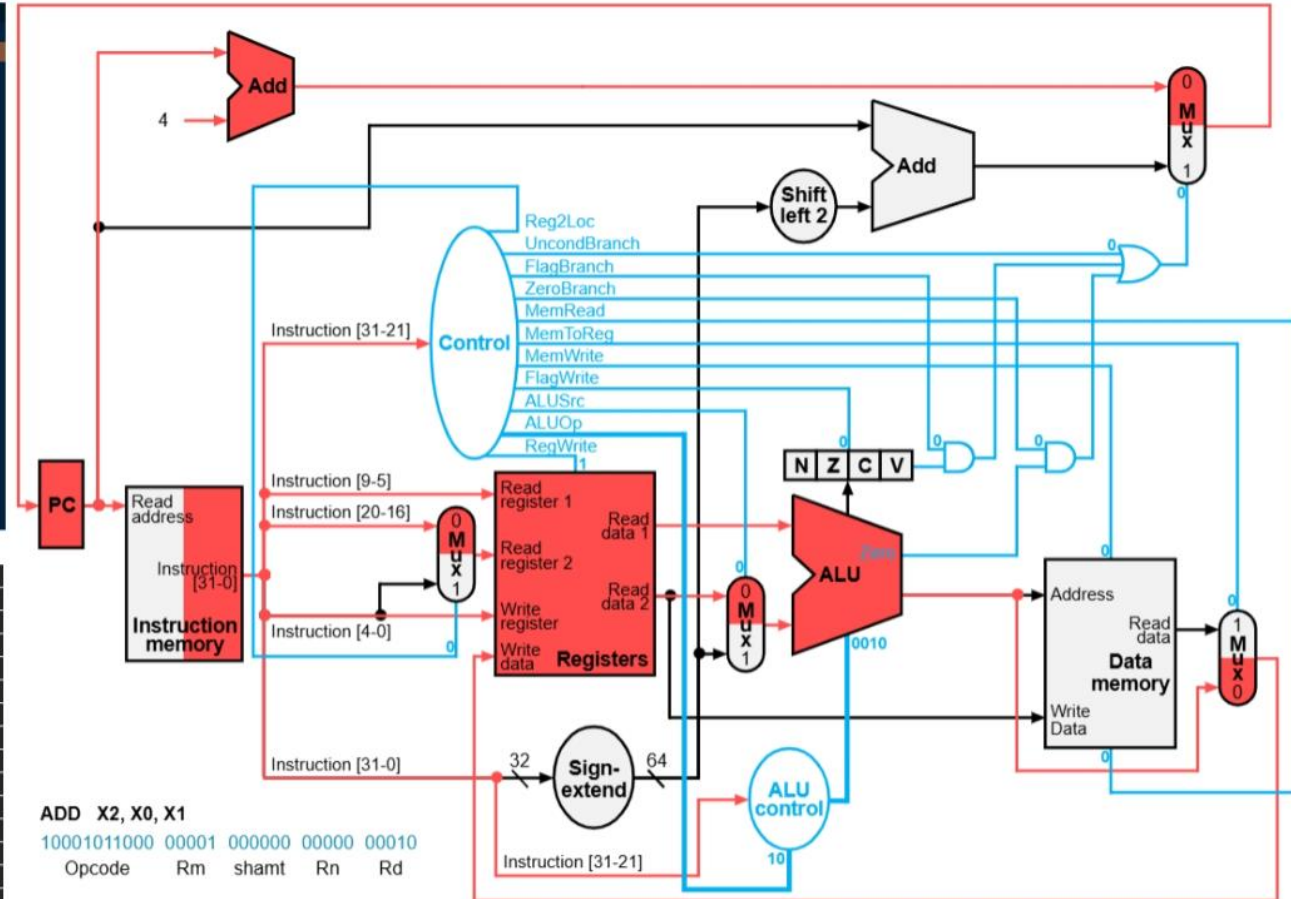
WHAT SIMULATOR, AND WHY?

LEGv8 Simulator

Execution Mode: **Single Cycle** Assemble Execute Instruction Help

```
1 ADDI X0, XZR, #53
2 ADDI X1, XZR, #75
3 ADD X2, X0, X1
4 CMP X2, X0
5 B.LE if
6 if: SUBIS X3, X2, #9
7 MOV X4, X3
8
```

PC	0x40000c	Hex	Dec	Z	0	N	0	C	0	V	0
X0	0x35	Hex	Dec	X16	0x0	Hex	Dec	X16	0x0	Hex	Dec
X1	0x4b	Hex	Dec	X17	0x0	Hex	Dec	X17	0x0	Hex	Dec
X2	0x80	Hex	Dec	X18	0x0	Hex	Dec	X18	0x0	Hex	Dec
X3	0x0	Hex	Dec	X19	0x0	Hex	Dec	X19	0x0	Hex	Dec
X4	0x0	Hex	Dec	X20	0x0	Hex	Dec	X20	0x0	Hex	Dec
X5	0x0	Hex	Dec	X21	0x0	Hex	Dec	X21	0x0	Hex	Dec
X6	0x0	Hex	Dec	X22	0x0	Hex	Dec	X22	0x0	Hex	Dec
X7	0x0	Hex	Dec	X23	0x0	Hex	Dec	X23	0x0	Hex	Dec
X8	0x0	Hex	Dec	X24	0x0	Hex	Dec	X24	0x0	Hex	Dec
X9	0x0	Hex	Dec	X25	0x0	Hex	Dec	X25	0x0	Hex	Dec
X10	0x0	Hex	Dec	X26	0x0	Hex	Dec	X26	0x0	Hex	Dec
X11	0x0	Hex	Dec	X27	0x0	Hex	Dec	X27	0x0	Hex	Dec
X12	0x0	Hex	Dec	SP	0x7ffffffc	Hex	Dec	SP	0x7ffffffc	Hex	Dec
X13	0x0	Hex	Dec	FP	0x0	Hex	Dec	FP	0x0	Hex	Dec
X14	0x0	Hex	Dec	LR	0x0	Hex	Dec	LR	0x0	Hex	Dec
X15	0x0	Hex	Dec	XZR	0x0	Hex	Dec	XZR	0x0	Hex	Dec



WHERE'S THE CATCH?

- Integer comparisons are broken
- Subroutine calls are broken
- Even if fixed: nobody knows how to compile the project!

=> **BASICALLY UNUSABLE**

FIXING AND RESTORING THE SIMULATOR

Restoration and development of
Arm's Java-based LEGv8 ISA simulator

COMPARISONS DON'T WORK!

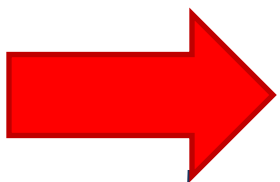
- No "if-else" conditionals
- No "switch-case" conditionals
- No "while" loops
- No "for" loops

THE COMPARISON BUG

```
1      ADDI    X0, XZR, #1
2      ADDI    X1, XZR, #2
3      CMP     X0, X1
4      B.LE    should_jump
5      ADD     X2, X0, X1
6  should_jump:  ADDI    X2, XZR, #16
7
```

X0 = 1, X1 = 2

PC	0x400008	Hex	Dec	Z	0	N	0	C	0	V	0
X0	0x1	Hex	Dec	X16			0x0			Hex	Dec
X1	0x2	Hex	Dec	X17			0x0			Hex	Dec
X2	0x0	Hex	Dec	X18			0x0			Hex	Dec

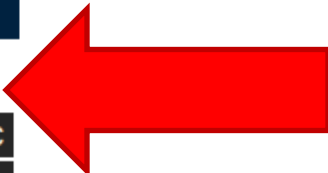


THE COMPARISON BUG

```
1 |      ADDI      X0, XZR, #1
2 |      ADDI      X1, XZR, #2
3 | CMP          X0, X1
4 |      B.LE      should_jump
5 |      ADD       X2, X0, X1
6 | should_jump:   ADDI      X2, XZR, #16
7 |
```

COMPARE X0 WITH X1

PC	0x40000c	Hex	Dec	Z	0	N	1	C	0	V	1
X0	0x1	Hex	Dec	X16			0x0			Hex	Dec
X1	0x2	Hex	Dec	X17			0x0			Hex	Dec
X2	0x0	Hex	Dec	X18			0x0			Hex	Dec



THE COMPARISON BUG

```
1 |      ADDI      X0, XZR, #1
2 |      ADDI      X1, XZR, #2
3 |      CMP       X0, X1
4 |      B.LE      should_jump
5 |      ADD       X2, X0, X1
6 |  should_jump:  ADDI      X2, XZR, #16
7 |
```

1 <= 2 ?

OF COURSE, LET'S JUMP!

PC	0x400010	Hex	Dec	Z	0	N	1	C	0	V	1
X0	0x1	Hex	Dec	X16			0x0	Hex	Dec		
X1	0x2	Hex	Dec	X17			0x0	Hex	Dec		
X2	0x0	Hex	Dec	X18			0x0	Hex	Dec		

THE COMPARISON BUG

```
1 |      ADDI      X0, XZR, #1
2 |      ADDI      X1, XZR, #2
3 |      CMP       X0, X1
4 |      B.LE      should_jump
5 |      ADD       X2, X0, X1
6 | should_jump:   ADDI      X2, XZR, #16
7 |
```

...OR NOT

PC	0x400014	Hex	Dec	Z	0	N	1	C	0	V	1
X0	0x1	Hex	Dec	X16			0x0			Hex	Dec
X1	0x2	Hex	Dec	X17			0x0			Hex	Dec
X2	0x3	Hex	Dec	X18			0x0			Hex	Dec

THE FLAGS ARE SET WRONG!

HOW THEY SHOULD BE

\leq	B.LE	$\sim(Z=0 \ \& \ N=V)$
--------	------	------------------------

HOW THEY ARE

Z	0	N	1	C	0	V	1
---	---	---	---	---	---	---	---

$\neg(Z=0 \ \wedge \ N=V) = \neg(\text{TRUE} \ \wedge \ \text{TRUE}) = \text{FALSE}$

BRANCH AND LINKS DON'T WORK!

~~*void subroutine(arg1, ...)*~~
~~*float function(arg1, ...)*~~

CAN'T REUSE CODE

THE BRANCH AND LINK BUG

```
1      ADDI      X0, XZR, #1
2      BL        subroutine
3      B         exit
4
5  subroutine:
6      ADDI      X0, X0, #16
7      BR        LR
8  exit:
9
```

PROGRAM COUNTER: 0x0

RETURN ADDRESS: 0x0

THE BRANCH AND LINK BUG

```
1      ADDI      X0, XZR, #1
2      BL        subroutine
3      B         exit
4
5  subroutine:
6      ADDI      X0, X0, #16
7      BR        LR
8  exit:
9
```

PROGRAM COUNTER: 0x4

RETURN ADDRESS: 0x0

THE BRANCH AND LINK BUG

```
1      ADDI      X0, XZR, #1
2      BL        subroutine
3      B         exit
4
5  subroutine:
6      ADDI      X0, X0, #16
7      BR        LR
8  exit:
9
```

PROGRAM COUNTER: 0xC

RETURN ADDRESS: 0xC

THE BRANCH AND LINK BUG

```
1      ADDI      X0, XZR, #1
2      BL        subroutine
3      B         exit
4
5  subroutine:
6      ADDI      X0, X0, #16
7      BR        LR
8  exit:
9
```

PROGRAM COUNTER: 0x10

RETURN ADDRESS: 0xC

THE BRANCH AND LINK BUG

```
1      ADDI      X0, XZR, #1
2      BL        subroutine
3      B         exit
4
5  subroutine:
6      ADDI      X0, X0, #16
7      BR        LR
8  exit:
9
```

IT DOESN'T GO BACK!

IT SHOULD GO HERE!

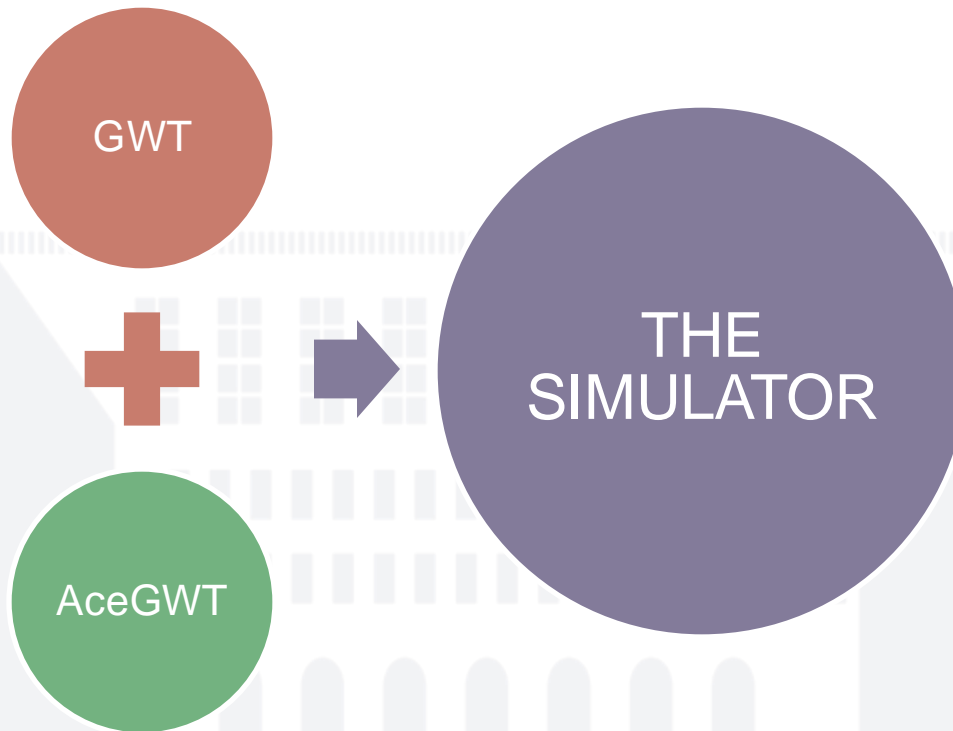
1	ADDI	X0, XZR, #1	
2	BL	subroutine	
3	B	exit	ADDRESS: 0x8
4			
5	subroutine:		
6	ADDI	X0, X0, #16	
7	BR	LR	
8	exit:		
9			

PROGRAM COUNTER: 0xC

RETURN ADDRESS: 0xC

ALL FIXED? NOW WHAT?

THE PROJECT'S LIBRARIES



GWT

- Framework (formerly) from Google
- Generates web applications (client-server, client only) from Java
- Emulates Java's JVM with JavaScript

GWT

- Old, outdated, barely supported
- Convoluted custom build tools
- Limited emulation of JVM
- Basically needs Eclipse plug-in for real development

AceGWT

- Provides GWT bindings for the Ace editor
- Can be used like normal GWT component
- Also old, outdated, and unsupported

TO BUILD THE PROJECT:

- Need old version of Eclipse, and Eclipse GWT plug-in
- Reverse engineer the dependencies and where they are needed
- Configure the project to stop failing

FILLING THE GAPS

Restoration and **development** of
Arm's Java-based LEGv8 ISA simulator

WHAT IS THE SIMULATOR MISSING?

- Incomplete integer arithmetic
- No IEEE-754 arithmetic and data instructions
- No visualization for the stack memory

THE MISSING INTEGER-BASED INSTRUCTIONS

- **MUL** — LOWER 64 BITS OF THE MULTIPLICATION
- **SMULH** — HIGHER 64 BITS OF THE SIGNED MULTIPLICATION
- **UMULH** — HIGHER 64 BITS OF THE UNSIGNED MULTIPLICATION
- **SDIV** — SIGNED DIVISION
- **UDIV** — UNSIGNED DIVISION
- **LDA** — LOAD ADDRESS OF A LABEL IN A REGISTER

UMULH: A CASE STUDY

- Takes two 64-bit unsigned integer values
- Extends them to 128 bits unsigned
- Performs 128-bit product
- Saves higher 64 bits to destination

PROBLEM 1

- Java does not have primitive 128-bit integer types
- Product of 64-bit integers truncated
- The BigInteger library exists
- GWT 2.7 doesn't emulate it (2.8 does)

PROBLEM 2

- Primitive integers are signed
- BigInteger also signed
- Bitmask converts 64-bit unsigned integers to 65-bit signed, perform signed multiplication, take the higher bits

CAN'T SEE THE STACK

- Fundamental for testing and debugging complex programs (now we can write them)
- Useful to understanding LEGv8 and stack management
- Visible in most simulators

THE INTEGER REGISTERS VIEW

X0	0x0	Hex	Dec	X16	0x0	Hex	Dec
X1	0x0	Hex	Dec	X17	0x0	Hex	Dec
X2	0x0	Hex	Dec	X18	0x0	Hex	Dec
X3	0x0	Hex	Dec	X19	0x0	Hex	Dec
X4	0x0	Hex	Dec	X20	0x0	Hex	Dec
X5	0x0	Hex	Dec	X21	0x0	Hex	Dec
X6	0x0	Hex	Dec	X22	0x0	Hex	Dec
X7	0x0	Hex	Dec	X23	0x0	Hex	Dec
X8	0x0	Hex	Dec	X24	0x0	Hex	Dec
X9	0x0	Hex	Dec	X25	0x0	Hex	Dec
X10	0x0	Hex	Dec	X26	0x0	Hex	Dec
X11	0x0	Hex	Dec	X27	0x0	Hex	Dec
X12	0x0	Hex	Dec	SP	0x7fffffff	Hex	Dec
X13	0x0	Hex	Dec	FP	0x0	Hex	Dec
X14	0x0	Hex	Dec	LR	0x0	Hex	Dec
X15	0x0	Hex	Dec	XZR	0x0	Hex	Dec

THE NEW STACK VIEW

0x8000000000:	0x0	Hex	0x7fffffff80:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff78:	0x0	Hex
0x7fffffff0:	0x0	Hex	0x7fffffff70:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff68:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff60:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff58:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff50:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff48:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff40:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff38:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff30:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff28:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff20:	0x0	Hex
0x7fffffff8:	0x0	Hex	0x7fffffff18:	0x0	Hex
0x7fffffff80:	0x0	Hex	0x7fffffff10:	0x0	Hex
0x7fffffff88:	0x0	Hex	0x7fffffff08:	0x0	Hex

ADDING FLOATING-POINT SUPPORT

- **FADDS, FADDD** — ADD TWO IEEE-754 VALUES
- **FSUBS, FSUBD** - SUBTRACT TWO IEEE-754 VALUES
- **FMULS, FMULD** - MULTIPLY TWO IEEE-754 VALUES
- **FDIVS, FDIVD** — DIVIDE TWO IEEE-754 VALUES
- **LDURS, LDURD** — LOAD IEEE-754 VALUE FROM MEMORY
- **STURS, STURD** - STORE IEEE-754 VALUE TO MEMORY
- **FCMPS, FCMPPD** — COMPARE TWO IEEE-754 VALUES

ARITHMETICAL INSTRUCTIONS (FADDD, FDIVS, ...)

- Native Java support for IEEE-754 with float and double types
- Native Java support for IEEE-754 arithmetical operations
- Straight forward implementation

MEMORY ACCESS INSTRUCTIONS (LDURS, STURD, ...)

- Simulator uses long values to store bits in memory
- Use existing *longs* and *ints* as raw bits
- Use Java *Double.longBitsToDouble* and *Double.doubleToLongBits* to convert before memory

COMPARISON INSTRUCTIONS (FCMPS, FCMPD)

- LEGv8 does not specify flag-setting conditions for IEEE-754 comparisons
- Use ARMv8's ones

IEEE-754 Relationship	ARM APSR Flags			
	N	Z	C	V
Equal	0	1	1	0
Less Than	1	0	0	0
Greater Than	0	0	1	0
Unordered (<i>At least one argument was NaN.</i>)	0	0	1	1

INTEGER REGISTERS

X0	0xc	Hex	Dec
X0	12	Hex	Dec

FLOATING-POINT REGISTERS

S0	0xc00a0000	Hex	Dec
S0	-2.15625	Hex	Dec

THE FINAL VIEW

1	MOVK	X0, #192	0x800000000:	0x0	Hex	0x7fffffff80:	0x0	Hex
2	LSL	X0, X0, #8	0x7fffffff8:	0x0	Hex	0x7fffffff78:	0x0	Hex
3	MOVK	X0, #10	0x7fffffff0:	0xc00a0000	Hex	0x7fffffff70:	0x0	Hex
4	LSL	X0, X0, #16	0x7ffffffe8:	0x0	Hex	0x7ffffff68:	0x0	Hex
5	SUBI	SP, SP, #16	0x7ffffffe0:	0x0	Hex	0x7ffffff60:	0x0	Hex
6	STUR	X0, [SP, #0]	0x7ffffffd8:	0x0	Hex	0x7ffffff58:	0x0	Hex
7	LDURS	S0, [SP, #0]	0x7ffffffd0:	0x0	Hex	0x7ffffff50:	0x0	Hex
8			0x7ffffffc8:	0x0	Hex	0x7ffffff48:	0x0	Hex
			0x7ffffffc0:	0x0	Hex	0x7ffffff40:	0x0	Hex
			0x7ffffffb8:	0x0	Hex	0x7ffffff38:	0x0	Hex
			0x7ffffffb0:	0x0	Hex	0x7ffffff30:	0x0	Hex
			0x7ffffffa8:	0x0	Hex	0x7ffffff28:	0x0	Hex
			0x7ffffffa0:	0x0	Hex	0x7ffffff20:	0x0	Hex
			0x7ffffff98:	0x0	Hex	0x7ffffff18:	0x0	Hex
			0x7ffffff90:	0x0	Hex	0x7ffffff10:	0x0	Hex
			0x7ffffff88:	0x0	Hex	0x7ffffff08:	0x0	Hex

PC	0x40001c	Z	0	N	0	C	0	V	0	D0	0xc00a0000	D16	0x0	S0	-2.15625	S16	0x0
X0	0xc00a0000	Hex	Dec	X16	0x0	Hex	Dec	D1	0x0	Hex	Dec	D17	0x0	Hex	Dec	S17	0x0
X1	0x0	Hex	Dec	X17	0x0	Hex	Dec	D2	0x0	Hex	Dec	D18	0x0	Hex	Dec	S18	0x0
X2	0x0	Hex	Dec	X18	0x0	Hex	Dec	D3	0x0	Hex	Dec	D19	0x0	Hex	Dec	S19	0x0
X3	0x0	Hex	Dec	X19	0x0	Hex	Dec	D4	0x0	Hex	Dec	D20	0x0	Hex	Dec	S20	0x0
X4	0x0	Hex	Dec	X20	0x0	Hex	Dec	D5	0x0	Hex	Dec	D21	0x0	Hex	Dec	S21	0x0
X5	0x0	Hex	Dec	X21	0x0	Hex	Dec	D6	0x0	Hex	Dec	D22	0x0	Hex	Dec	S22	0x0
X6	0x0	Hex	Dec	X22	0x0	Hex	Dec	D7	0x0	Hex	Dec	D23	0x0	Hex	Dec	S23	0x0
X7	0x0	Hex	Dec	X23	0x0	Hex	Dec	D8	0x0	Hex	Dec	D24	0x0	Hex	Dec	S24	0x0
X8	0x0	Hex	Dec	X24	0x0	Hex	Dec	D9	0x0	Hex	Dec	D25	0x0	Hex	Dec	S25	0x0
X9	0x0	Hex	Dec	X25	0x0	Hex	Dec	D10	0x0	Hex	Dec	D26	0x0	Hex	Dec	S26	0x0
X10	0x0	Hex	Dec	X26	0x0	Hex	Dec	D11	0x0	Hex	Dec	D27	0x0	Hex	Dec	S27	0x0
X11	0x0	Hex	Dec	X27	0x0	Hex	Dec	D12	0x0	Hex	Dec	D28	0x0	Hex	Dec	S28	0x0
X12	0x0	Hex	Dec	SP	0x7fffffff0	Hex	Dec	D13	0x0	Hex	Dec	D29	0x0	Hex	Dec	S29	0x0
X13	0x0	Hex	Dec	FP	0x0	Hex	Dec	D14	0x0	Hex	Dec	D30	0x0	Hex	Dec	S30	0x0
X14	0x0	Hex	Dec	LR	0x0	Hex	Dec	D15	0x0	Hex	Dec	D31	0x0	Hex	Dec	S31	0x0
X15	0x0	Hex	Dec	XZR	0x0	Hex	Dec										

THE CHERRY ON TOP: MODERNIZING THE BUILD SYSTEM

- Opens the doors to effortless collaboration
- Decouples project from Eclipse IDE
- Use updated libraries

INTEGRATING MAVEN

- Latest GWT and AceGWT support Maven
- Integrated Maven into the simulator
- Can now use other IDEs,
Java 21, GWT 2.11
- To develop, download the code and run *mvn package*. That's it.

CONCLUSIONS

- Arm's LEGv8 simulator finally working
- Only one to implement every LEGv8 instruction
- Can now be developed with modern tools, set-up and build in seconds

SOME FUTURE DEVELOPMENTS

- Refactor codebase with modern practices
- Improve pipelined execution
- Improve UI, make it responsive
- Find modern replacements for GWT, AceGWT
- Get the changes to the official repos

THANK YOU FOR
YOUR ATTENTION

THESIS AVAILABLE HERE

SIMULATOR AVAILABLE HERE