RISC-V

Instruction Sets Want to be Free!

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Why Instruction Set Architecture matters

- **Why can’t Intel sell mobile chips?**
  - 99%+ of mobile phones/tablets based on ARM v7/v8 ISA
- **Why can’t ARM partners sell servers?**
  - 99%+ of laptops/desktops/servers based on AMD64 ISA (over 95%+ built by Intel)
- **How can IBM still sell mainframes?**
  - IBM 360, oldest surviving ISA (50+ years)

ISA is most important interface in computer system

where software meets hardware

Open Software/Standards Work!

Field	*Standard*	*Free, Open Impl.*	*Proprietary Impl.*
Networking	Ethernet, TCP/IP	Many	Many
OS	Posix	Linux, FreeBSD	M/S Windows
Compilers	C	gcc, LLVM	Intel icc, ARMcc
Databases	SQL	MySQL, PostgresSQL	Oracle 12C, M/S DB2
Graphics	OpenGL	Mesa3D	M/S DirectX
ISA	??????	-----------	x86, ARM, IBM360

- Why not successful free & open standards and free & open implementations, like other fields
- Dominant proprietary ISAs are not great designs

What is RISC-V?

- Fifth generation of RISC design from UC Berkeley
- A high-quality, license-free, royalty-free RISC ISA specification
- Experiencing rapid uptake in both industry and academia
- Standard maintained by non-profit RISC-V Foundation
- Both proprietary and open-source core implementations
- Supported by growing shared software ecosystem
- Appropriate for all levels of computing system, from microcontrollers to supercomputers

RISC-V Origins

- In 2010, after many years and many projects using MIPS, SPARC, and x86 as basis of research at Berkeley, time to choose ISA for next set of projects
- Obvious choices: x86 and ARM

Intel x86 “AAA” Instruction

- ASCII Adjust After Addition
- AL register is default source and destination

- If the low nibble is > 9 decimal, or the auxiliary carry flag AF = 1, then
  - Add 6 to low nibble of AL and discard overflow
  - Increment high byte of AL
  - Set CF and AF
- Else
  - CF = AF = 0

- Single byte instruction

ARM v7 LDMIAEQ Instruction

```
LDMIAEQ SP!, {R4-R7, PC}
```

- **L**oa**D** **M**ultiple, **I**ncrement-**A**ddress
- Writes to 7 registers from 6 loads
- Only executes if **EQ** condition code is set
- Writes to the PC (a conditional branch)
- Can change instruction sets

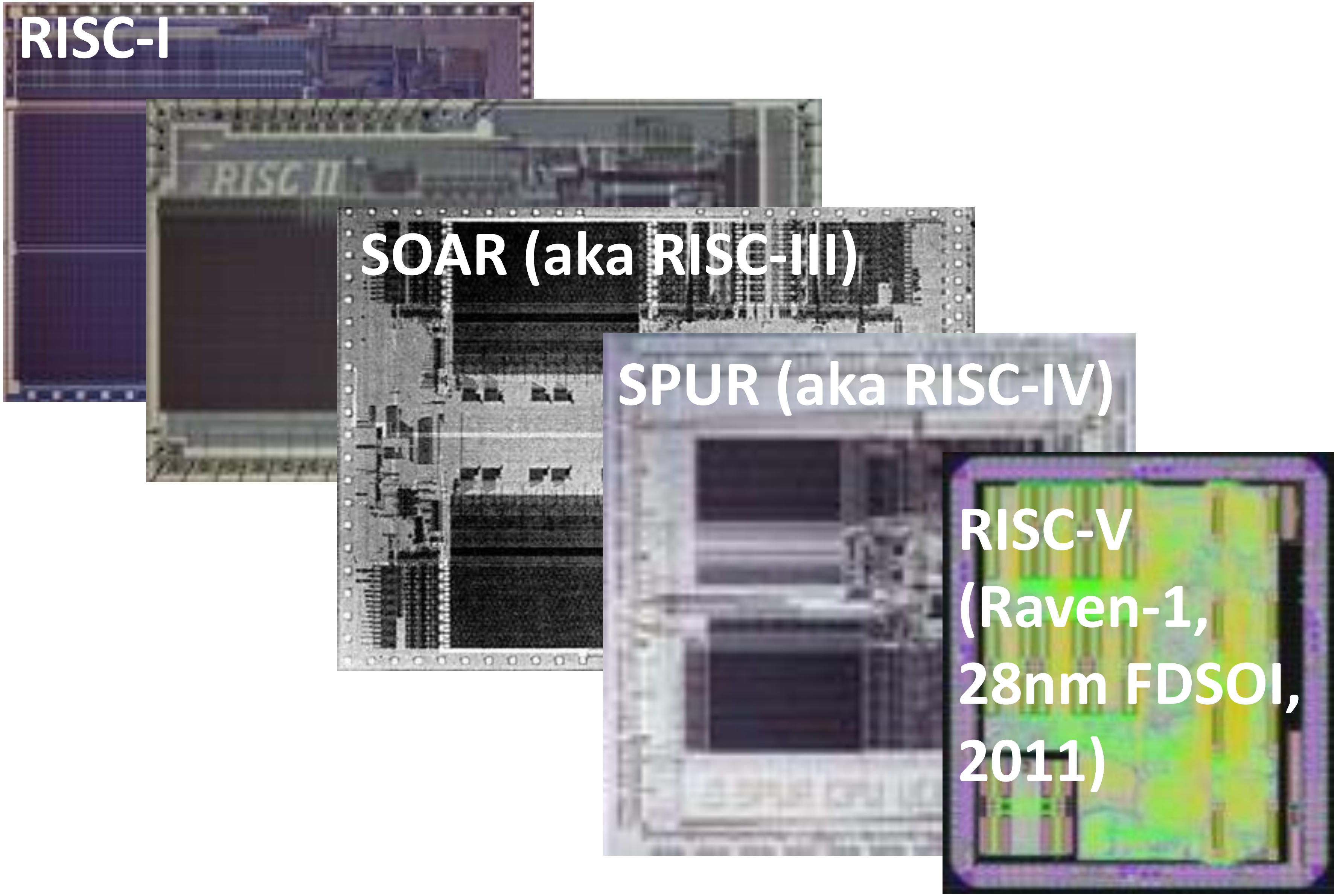
- Idiom for "stack pop and return from a function call"

RISC-V Origin Story

- x86 impossible –IP issues, too complex
- ARM mostly impossible – no 64-bit, IP issues, complex
- So we started "3-month project" in summer 2010 to develop our own clean-slate ISA
  - Andrew Waterman, Yunsup Lee, Dave Patterson, Krste Asanovic principal designers
- Four years later, we released frozen base user spec
  - First public specification released in May 2011
  - Many tapeouts and several publications along the way

Why are outsiders complaining about changes to RISC-V in Berkeley classes?

Why is name RISC-V?
(pronounced “risk-five”)



RISC-I

SOAR (aka RISC-III)

SPUR (aka RISC-IV)

RISC-V
(Raven-1,
28nm FDSOI,
2011)

Universal ISA Requirements

- Works well with existing software stacks, languages
- Is native hardware ISA, not virtual machine/ANDF
- Suits all sizes of processor, from smallest microcontroller to largest supercomputer
- Suits all implementation technologies, FPGA, ASIC, full-custom, future device technologies…
- Efficient for all microarchitecture styles: microcoded, in-order, decoupled, out-of-order, single-issue, superscalar, …
- Supports extensive specialization to act as base for customized accelerators
- Stable: not changing, not disappearing

Why Didn't Other Open ISAs Take Off?

- ***SPARC V8*** - To its credit, Sun Microsystems made SPARC V8 an IEEE standard in 1994
  - Sun, Gaisler offered open-source cores
  - ISA now owned by Oracle
- ***OpenRISC*** - GNU open-source effort started in 1999, based on DLX from *Computer Architecture: AQA*
  - 64-bit ISA was in progress in 2010
  - Didn't separate Architecture and Implementation

- Competing in microprocessor era – now in SoC era
- Don't meet the needs of a universal ISA

What’s Different about RISC-V?

- *Simple*
  - Far smaller than other commercial ISAs
- *Clean-slate design*
  - Clear separation between user and privileged ISA
  - Avoids µarchitecture or technology-dependent features
- A *modular* ISA
  - Small standard base ISA
  - Multiple standard extensions
- Designed for *extensibility/specialization*
  - Variable-length instruction encoding
  - Vast opcode space available for instruction-set extensions
- *Stable*
  - Base and standard extensions are frozen
  - Additions via optional extensions, not new versions

RISC-V Base Plus Standard Extensions

- Four base integer ISAs
  - RV32E, RV32I, RV64I, RV128I
  - RV32E is 16-register subset of RV32I
  - Only <50 hardware instructions needed for base
- Standard extensions
  - M: Integer multiply/divide
  - A: Atomic memory operations (AMOs + LR/SC)
  - F: Single-precision floating-point
  - D: Double-precision floating-point
  - G = IMAFD, “General-purpose” ISA
  - Q: Quad-precision floating-point
- All the above are a fairly standard RISC encoding in a fixed 32-bit instruction format
- Above user-level ISA components frozen in 2014
  - Supported forever after

RISC-V Standard Base ISA Details

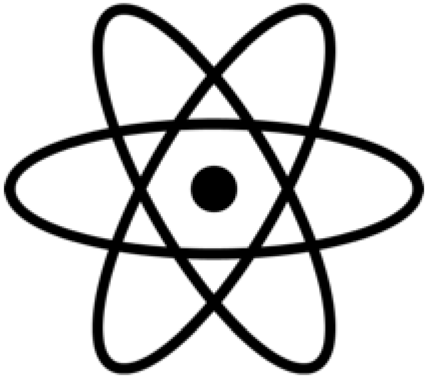
31 25	24 20	19 15	14 12	11 7	6 0	
funct7	rs2	rs1	funct3	rd	opcode	R-type
imm[11:0]		rs1	funct3	rd	opcode	I-type
imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode	S-type
imm[31:12]				rd	opcode	U-type

- 32-bit fixed-width, naturally aligned instructions
- 31 integer registers x1-x31, plus x0 zero register
- rd/rs1/rs2 in fixed location, no implicit registers
- Immediate field (instr[31]) always sign-extended
- Floating-point adds f0-f31 registers plus FP CSR, also fused mul-add four-register format
- Designed to support PIC and dynamic linking

“A”: Atomic Operations Extension

Two classes:

- Atomic Memory Operations (AMO)
    - Fetch-and-op, op=ADD,OR,XOR,MAX,MIN,MAXU,MINU
- Load–Reserved/Store Conditional
    - With forward progress guarantee for short sequences
- All atomic operations can be annotated with two bits (Acquire/Release) to implement release consistency or sequential consistency



- *Current issues in memory model being resolved, will be stronger than pure relaxed model.*

Variable-Length Encoding

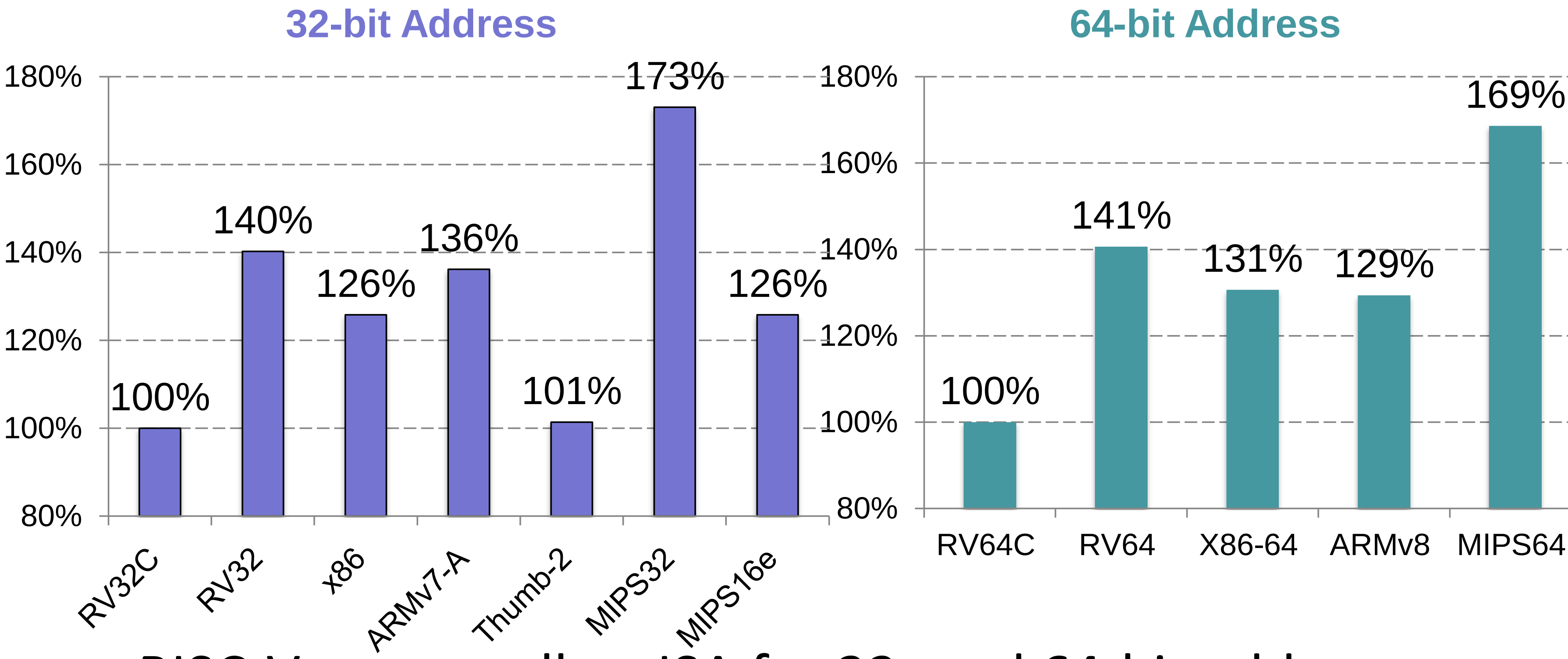
			xxxxxxxxxxxxxxaa	16-bit (aa ≠ 11)
		xxxxxxxxxxxxxxxx	xxxxxxxxxxxbbb11	32-bit (bbb ≠ 111)
	···xxxx	xxxxxxxxxxxxxxxx	xxxxxxxxxx011111	48-bit
	···xxxx	xxxxxxxxxxxxxxxx	xxxxxxxxx0111111	64-bit
	···xxxx	xxxxxxxxxxxxxxxx	xnnnxxxxx1111111	(80+16*nnn)-bit, nnn≠111
	···xxxx	xxxxxxxxxxxxxxxx	x111xxxxx1111111	Reserved for ≥192-bits
Byte Address:	base+4	base+2	base	

- Extensions can use any multiple of 16 bits as instruction length
- Branches/Jumps target 16-bit boundaries even in fixed 32-bit base
  - Consumes 1 extra bit of jump/branch address

“C”: Compressed Instruction Extension

- Compressed code important for:
  - low-end embedded to save static code space
  - high-end commercial workloads to reduce cache footprint
- C extension adds 16-bit compressed instructions
  - 2-address forms with all 32 registers
  - 2/3-address forms with most frequent 8 registers
- 1 compressed instruction expands to 1 base instruction
  - Assembly lang. programmer & compiler oblivious
  - RVC ⇒ RVI decoder only ~700 gates (~2% of small core)
- All original 32-bit instructions retain encoding but now can be 16-bit aligned
- 50%-60% instructions compress ⇒ 25%-30% smaller

SPECint2006 compressed code size with save/restore optimization (relative to "standard" RVC)

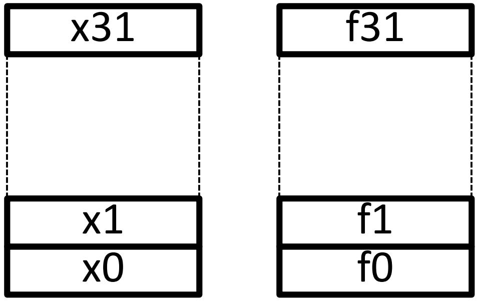


- RISC-V now smallest ISA for 32- and 64-bit addresses
- All results with same GCC compiler and options

Proposed "V" Vector Extension State

Standard RISC-V scalar x and f registers

Up to 32 vector data registers, v0-v31, of at least 4 elements each, with variable bits/element (8,16,32,64,128)



x31

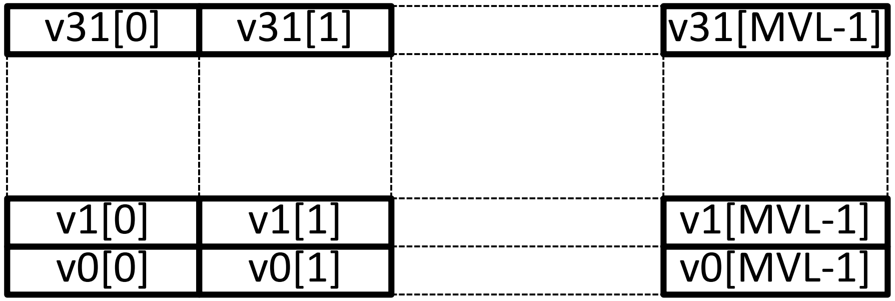
x1

x0

f31

f1

f0



v31[0] v31[1] v31[MVL-1]

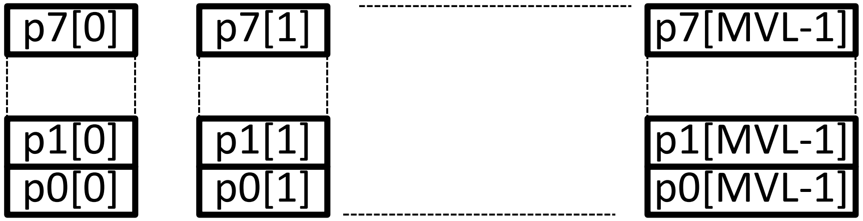
v1[0] v1[1] v1[MVL-1]

v0[0] v0[1] v0[MVL-1]

MVL is maximum vector length, implementation and configuration dependent, but MVL >= 4

Vector configuration CSR vcfg

Vector length CSR vlr



p7[0] p7[1] p7[MVL-1]

p1[0] p1[1] p1[MVL-1]

p0[0] p0[1] p0[MVL-1]

8 vector predicate registers, with 1 bit per element

RISC-V Privileged Architecture

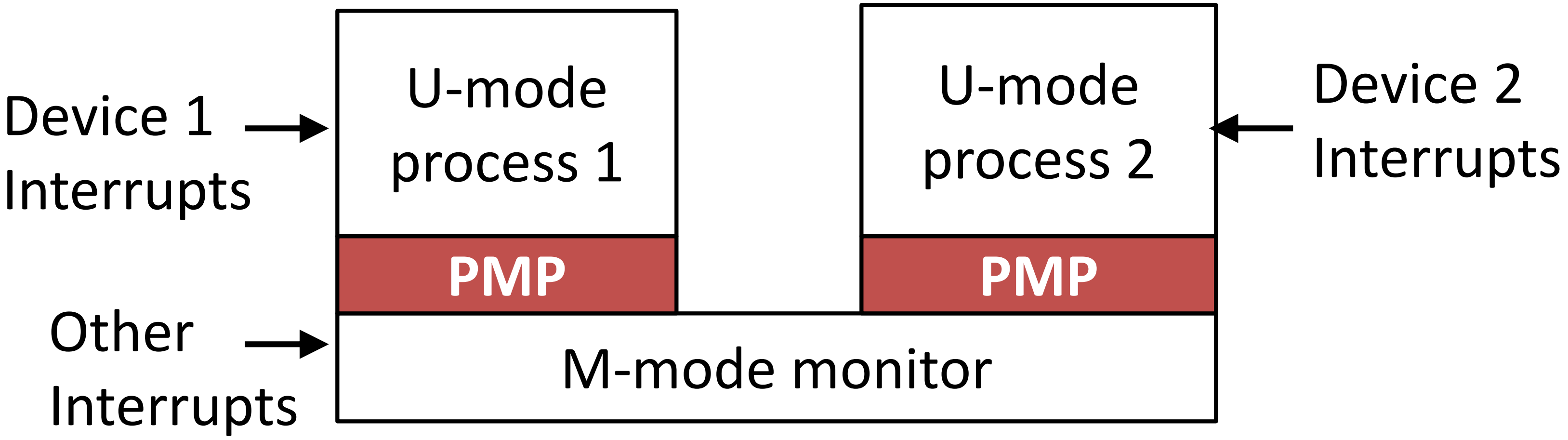
- Three privilege modes
  - User (U-mode)
  - Supervisor (S-mode)
  - Machine (M-mode)
- Supported combinations of modes:
  - M (simple embedded systems)
  - M, U (embedded systems with protection)
  - M, S, U (systems running Unix-style operating systems)
- Hypervisors to be run in modified S mode
  - Prioritize support for Type-2 Hypervisors like KVM
  - Can also support Type-1 Hypervisors in same model

Simple Embedded Systems (M-mode only)

- No address translation/protection
  - "Mbare" bare-metal mode
  - Trap bad physical addresses precisely
- All code inherently trusted
- Low implementation cost
  - 2^7 bits of architectural state (in addition to user ISA)
  - $+2^7$ more bits for timers
  - $+2^7$ more for basic performance counters

Secure Embedded Systems (M, U modes)

- M-mode runs secure boot and runtime monitor
- Embedded code runs in U-mode
- Physical memory protection (PMP) on U-mode accesses
- Interrupt handling can be delegated to U-mode code
  - User-level interrupt support
- Provides arbitrary number of isolated subsystems

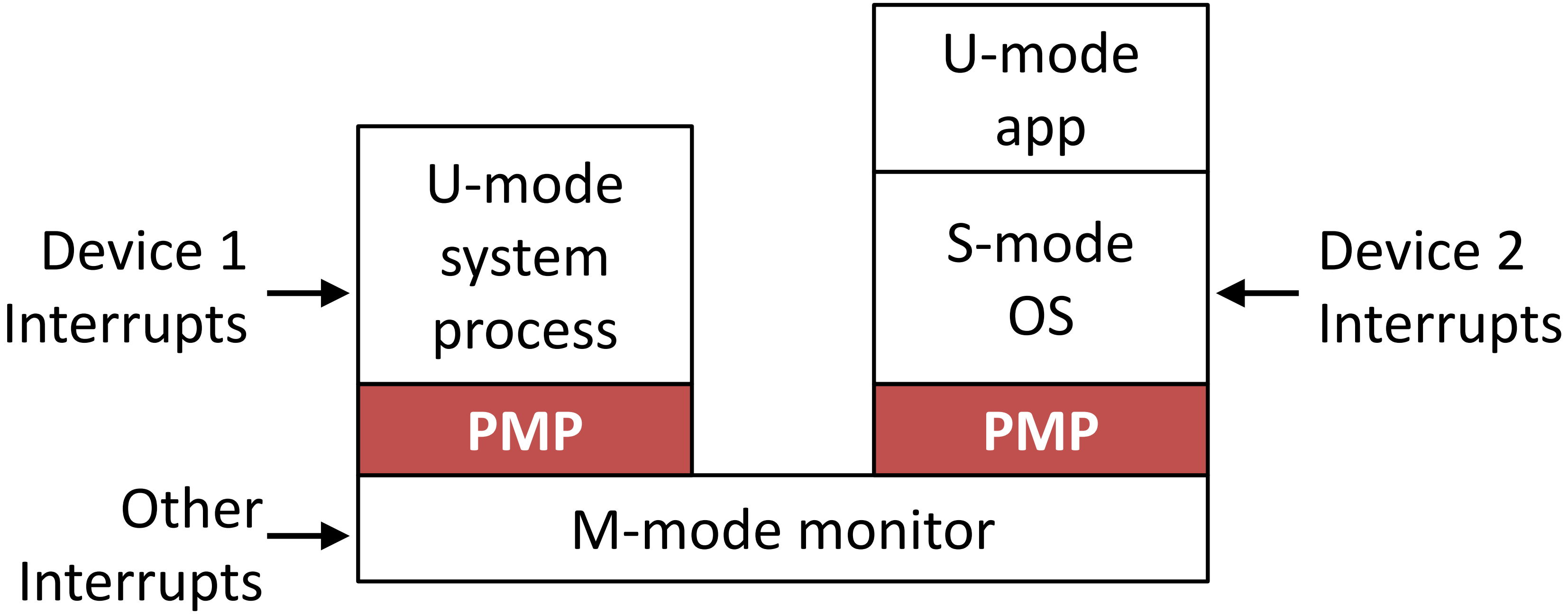


Virtual Memory Architectures (M, S, U modes)

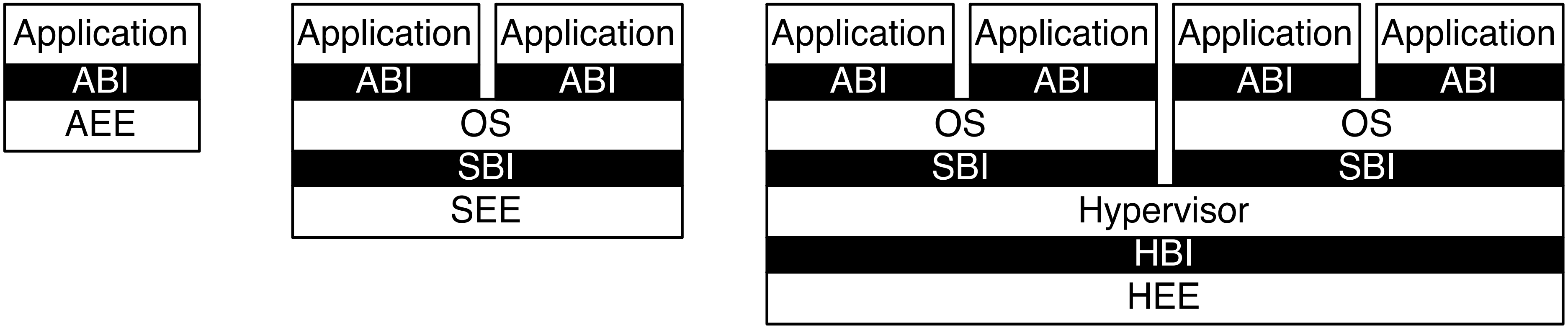
- Designed to support current Unix-style operating systems
- Sv32 (RV32)
  - Demand-paged 32-bit virtual-address spaces
  - 2-level page table
  - 4 KiB pages, 4 MiB megapages
- Sv39 (RV64)
  - Demand-paged 39-bit virtual-address spaces
  - 3-level page table
  - 4 KiB pages, 2 MiB megapages, 1 GiB gigapages
- Sv48, Sv57, Sv64 (RV64)
  - Sv39 + 1/2/3 more page-table levels

S-Mode runs on top of M-mode

- M-mode runs secure boot and monitor
- S-mode runs OS
- U-mode runs application on top of OS or M-mode



RISC-V Virtualization Stacks



Application
ABI
AEE

Application | Application
ABI | ABI
OS
SBI
SEE

Application | Application | Application | Application
ABI | ABI | ABI | ABI
OS | OS
SBI | SBI
Hypervisor
HBI
HEE

- Provide clean split between layers of the software stack
- Application communicates with Application Execution Environment (AEE) via Application Binary Interface (ABI)
- OS communicates via Supervisor Execution Environment (SEE) via System Binary Interface (SBI)
- Hypervisor communicates via Hypervisor Binary Interface to Hypervisor Execution Environment
- All levels of ISA designed to support virtualization

Supervisor Binary Interface

- Platform-specific functionality abstracted behind SBI
  - Query physical memory map
  - Get device info
  - Get hardware thread ID and # of hardware threads
  - Save/restore coprocessor state
  - Query timer properties, set up timer interrupts
  - Send interprocessor interrupts
  - Send TLB shootdowns
  - Reboot/shutdown
- Simplifies hardware acceleration
- Simplifies virtualization

RV32I

RISC-V

RISC-V Reference Card

Base Integer Instructions (32|64|128)

Category	*Name*	*Fmt*	*RV{32|64|128)I Base*	
Loads	Load Byte	I	LB	rd,rs1,imm
	Load Halfword	I	LH	rd,rs1,imm
	Load Word	I	L{W|D|Q}	rd,rs1,imm
	Load Byte Unsigned	I	LBU	rd,rs1,imm
	Load Half Unsigned	I	L{H|W|D}U	rd,rs1,imm
Stores	Store Byte	S	SB	rs1,rs2,imm
	Store Halfword	S	SH	rs1,rs2,imm
	Store Word	S	S{W|D|Q}	rs1,rs2,imm
Shifts	Shift Left	R	SLL{|W|D}	rd,rs1,rs2
	Shift Left Immediate	I	SLLI{|W|D}	rd,rs1,shamt
	Shift Right	R	SRL{|W|D}	rd,rs1,rs2
	Shift Right Immediate	I	SRLI{|W|D}	rd,rs1,shamt
	Shift Right Arithmetic	R	SRA{|W|D}	rd,rs1,rs2
	Shift Right Arith Imm	I	SRAI{|W|D}	rd,rs1,shamt
Arithmetic	ADD	R	ADD{|W|D}	rd,rs1,rs2
	ADD Immediate	I	ADDI{|W|D}	rd,rs1,imm
	SUBtract	R	SUB{|W|D}	rd,rs1,rs2
	Load Upper Imm	U	LUI	rd,imm
	Add Upper Imm to PC	U	AUIPC	rd,imm
Logical	XOR	R	XOR	rd,rs1,rs2
	XOR Immediate	I	XORI	rd,rs1,imm
	OR	R	OR	rd,rs1,rs2
	OR Immediate	I	ORI	rd,rs1,imm
	AND	R	AND	rd,rs1,rs2
	AND Immediate	I	ANDI	rd,rs1,imm
Compare	Set <	R	SLT	rd,rs1,rs2
	Set < Immediate	I	SLTI	rd,rs1,imm
	Set < Unsigned	R	SLTU	rd,rs1,rs2
	Set < Imm Unsigned	I	SLTIU	rd,rs1,imm
Branches	Branch =	SB	BEQ	rs1,rs2,imm
	Branch ≠	SB	BNE	rs1,rs2,imm
	Branch <	SB	BLT	rs1,rs2,imm
	Branch ≥	SB	BGE	rs1,rs2,imm
	Branch < Unsigned	SB	BLTU	rs1,rs2,imm
	Branch ≥ Unsigned	SB	BGEU	rs1,rs2,imm
Jump & Link	J&L	UJ	JAL	rd,imm
	Jump & Link Register	I	JALR	rd,rs1,imm
Synch	Synch thread	I	FENCE	
	Synch Instr & Data	I	FENCE.I	
System	System CALL	I	SCALL	
	System BREAK	I	SBREAK	
Counters	ReaD CYCLE	I	RDCYCLE	rd
	ReaD CYCLE upper Half	I	RDCYCLEH	rd
	ReaD TIME	I	RDTIME	rd
	ReaD TIME upper Half	I	RDTIMEH	rd
	ReaD INSTR RETired	I	RDINSTRET	rd
	ReaD INSTR upper Half	I	RDINSTRETH	rd

+14 Privileged

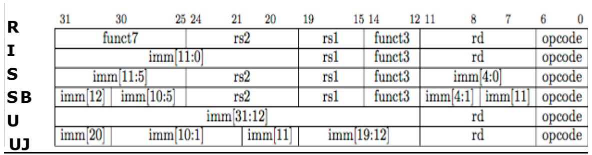
+ 8 for M

+ 11 for A

+ 34 for F, D, Q

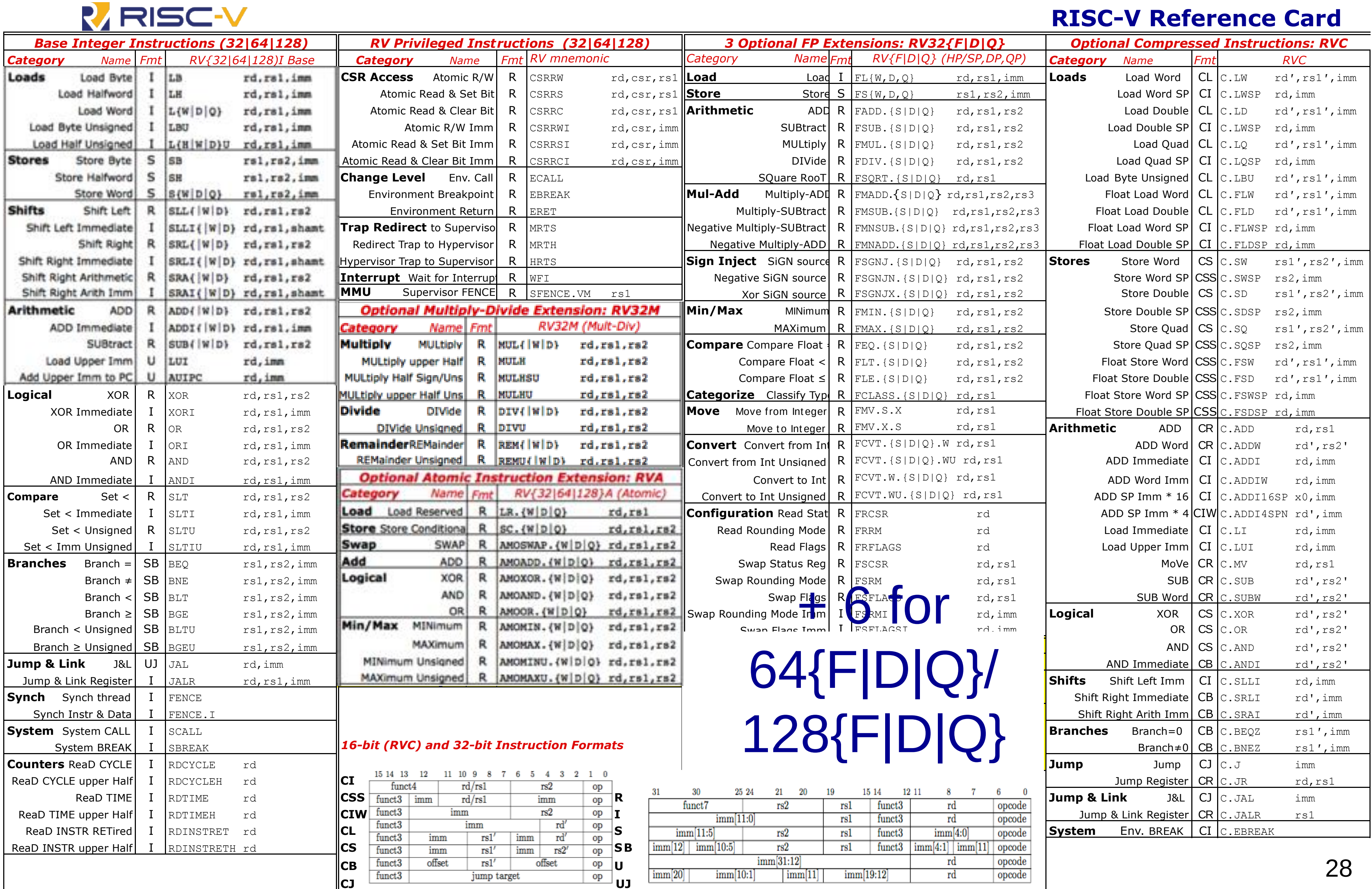
+ 46 for C

32-bit Instruction Formats



	31	30 25	24 21	20	19 15	14 12	11 8	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]	imm[10:5]	rs2		rs1	funct3	imm[4:1]	imm[11]	opcode
U	imm[31:12]						rd		opcode
UJ	imm[20]	imm[10:1]		imm[11]	imm[19:12]		rd		opcode

RV32I / RV64I / RV128I + M, A, F, D, Q, C



RISC-V Reference Card

Category	Name	Fmt	RV{32|64|128}I Base
Loads	Load Byte	I	LB rd,rs1,imm
	Load Halfword	I	LH rd,rs1,imm
	Load Word	I	L{W|D|Q} rd,rs1,imm
	Load Byte Unsigned	I	LBU rd,rs1,imm
	Load Half Unsigned	I	L{H|W|D}U rd,rs1,imm
Stores	Store Byte	S	SB rs1,rs2,imm
	Store Halfword	S	SH rs1,rs2,imm
	Store Word	S	S{W|D|Q} rs1,rs2,imm
Shifts	Shift Left	R	SLL{|W|D} rd,rs1,rs2
	Shift Left Immediate	I	SLLI{|W|D} rd,rs1,shamt
	Shift Right	R	SRL{|W|D} rd,rs1,rs2
	Shift Right Immediate	I	SRLI{|W|D} rd,rs1,shamt
	Shift Right Arithmetic	R	SRA{|W|D} rd,rs1,rs2
	Shift Right Arith Imm	I	SRAI{|W|D} rd,rs1,shamt
Arithmetic	ADD	R	ADD{|W|D} rd,rs1,rs2
	ADD Immediate	I	ADDI{|W|D} rd,rs1,imm
	SUBtract	R	SUB{|W|D} rd,rs1,rs2
	Load Upper Imm	U	LUI rd,imm
	Add Upper Imm to PC	U	AUIPC rd,imm
Logical	XOR	R	XOR rd,rs1,rs2
	XOR Immediate	I	XORI rd,rs1,imm
	OR	R	OR rd,rs1,rs2
	OR Immediate	I	ORI rd,rs1,imm
	AND	R	AND rd,rs1,rs2
	AND Immediate	I	ANDI rd,rs1,imm
Compare	Set <	R	SLT rd,rs1,rs2
	Set < Immediate	I	SLTI rd,rs1,imm
	Set < Unsigned	R	SLTU rd,rs1,rs2
	Set < Imm Unsigned	I	SLTIU rd,rs1,imm
Branches	Branch =	SB	BEQ rs1,rs2,imm
	Branch ≠	SB	BNE rs1,rs2,imm
	Branch <	SB	BLT rs1,rs2,imm
	Branch ≥	SB	BGE rs1,rs2,imm
	Branch < Unsigned	SB	BLTU rs1,rs2,imm
	Branch ≥ Unsigned	SB	BGEU rs1,rs2,imm
Jump & Link	J&L	UJ	JAL rd,imm
	Jump & Link Register	I	JALR rd,rs1,imm
Synch	Synch thread	I	FENCE
	Synch Instr & Data	I	FENCE.I
System	System CALL	I	SCALL
	System BREAK	I	SBREAK
Counters	ReaD CYCLE	I	RDCYCLE rd
	ReaD CYCLE upper Half	I	RDCYCLEH rd
	ReaD TIME	I	RDTIME rd
	ReaD TIME upper Half	I	RDTIMEH rd
	ReaD INSTR RETired	I	RDINSTRET rd
	ReaD INSTR upper Half	I	RDINSTRETH rd

Category	Name	Fmt	RV mnemonic
CSR Access	Atomic R/W	R	CSRRW rd,csr,rs1
	Atomic Read & Set Bit	R	CSRRS rd,csr,rs1
	Atomic Read & Clear Bit	R	CSRRC rd,csr,rs1
	Atomic R/W Imm	R	CSRRWI rd,csr,imm
	Atomic Read & Set Bit Imm	R	CSRRSI rd,csr,imm
	Atomic Read & Clear Bit Imm	R	CSRRCI rd,csr,imm
Change Level	Env. Call	R	ECALL
	Environment Breakpoint	R	EBREAK
	Environment Return	R	ERET
Trap Redirect	to Superviso	R	MRTS
	Redirect Trap to Hypervisor	R	MRTH
	Hypervisor Trap to Supervisor	R	HRTS
Interrupt	Wait for Interrup	R	WFI
MMU	Supervisor FENCE	R	SFENCE.VM rs1

Category	Name	Fmt	RV32M (Mult-Div)
Multiply	MULtiply	R	MUL{|W|D} rd,rs1,rs2
	MULtiply upper Half	R	MULH rd,rs1,rs2
	MULtiply Half Sign/Uns	R	MULHSU rd,rs1,rs2
	MULtiply upper Half Uns	R	MULHU rd,rs1,rs2
Divide	DIVide	R	DIV{|W|D} rd,rs1,rs2
	DIVide Unsigned	R	DIVU rd,rs1,rs2
Remainder	REMainder	R	REM{|W|D} rd,rs1,rs2
	REMainder Unsigned	R	REMU{|W|D} rd,rs1,rs2

Category	Name	Fmt	RV{32|64|128}A (Atomic)
Load	Load Reserved	R	LR.{W|D|Q} rd,rs1
Store	Store Conditiona	R	SC.{W|D|Q} rd,rs1,rs2
Swap	SWAP	R	AMOSWAP.{W|D|Q} rd,rs1,rs2
Add	ADD	R	AMOADD.{W|D|Q} rd,rs1,rs2
Logical	XOR	R	AMOXOR.{W|D|Q} rd,rs1,rs2
	AND	R	AMOAND.{W|D|Q} rd,rs1,rs2
	OR	R	AMOOR.{W|D|Q} rd,rs1,rs2
Min/Max	MINimum	R	AMOMIN.{W|D|Q} rd,rs1,rs2
	MAXimum	R	AMOMAX.{W|D|Q} rd,rs1,rs2
	MINimum Unsigned	R	AMOMINU.{W|D|Q} rd,rs1,rs2
	MAXimum Unsigned	R	AMOMAXU.{W|D|Q} rd,rs1,rs2

Category	Name	Fmt	RV{F|D|Q} (HP/SP,DP,QP)
Load	Load	I	FL{W,D,Q} rd,rs1,imm
Store	Store	S	FS{W,D,Q} rs1,rs2,imm
Arithmetic	ADD	R	FADD.{S|D|Q} rd,rs1,rs2
	SUBtract	R	FSUB.{S|D|Q} rd,rs1,rs2
	MULtiply	R	FMUL.{S|D|Q} rd,rs1,rs2
	DIVide	R	FDIV.{S|D|Q} rd,rs1,rs2
	SQuare RooT	R	FSQRT.{S|D|Q} rd,rs1
Mul-Add	Multiply-ADD	R	FMADD.{S|D|Q} rd,rs1,rs2,rs3
	Multiply-SUBtract	R	FMSUB.{S|D|Q} rd,rs1,rs2,rs3
	Negative Multiply-SUBtract	R	FMNSUB.{S|D|Q} rd,rs1,rs2,rs3
	Negative Multiply-ADD	R	FMNADD.{S|D|Q} rd,rs1,rs2,rs3
Sign Inject	SiGN source	R	FSGNJ.{S|D|Q} rd,rs1,rs2
	Negative SiGN source	R	FSGNJN.{S|D|Q} rd,rs1,rs2
	Xor SiGN source	R	FSGNJX.{S|D|Q} rd,rs1,rs2
Min/Max	MINimum	R	FMIN.{S|D|Q} rd,rs1,rs2
	MAXimum	R	FMAX.{S|D|Q} rd,rs1,rs2
Compare	Compare Float	R	FEQ.{S|D|Q} rd,rs1,rs2
	Compare Float <	R	FLT.{S|D|Q} rd,rs1,rs2
	Compare Float ≤	R	FLE.{S|D|Q} rd,rs1,rs2
Categorize	Classify Typ	R	FCLASS.{S|D|Q} rd,rs1
Move	Move from Integer	R	FMV.S.X rd,rs1
	Move to Integer	R	FMV.X.S rd,rs1
Convert	Convert from Int	R	FCVT.{S|D|Q}.W rd,rs1
	Convert from Int Unsigned	R	FCVT.{S|D|Q}.WU rd,rs1
	Convert to Int	R	FCVT.W.{S|D|Q} rd,rs1
	Convert to Int Unsigned	R	FCVT.WU.{S|D|Q} rd,rs1
Configuration	Read Stat	R	FRCSR rd
	Read Rounding Mode	R	FRRM rd
	Read Flags	R	FRFLAGS rd
	Swap Status Reg	R	FSCSR rd,rs1
	Swap Rounding Mode	R	FSRM rd,rs1
	Swap Flags	R	FSFLAGS rd,rs1
	Swap Rounding Mode Imm	I	FSRMI rd,imm
	Swap Flags Imm	I	FSFLAGSI rd,imm

Category	Name	Fmt	RVC
Loads	Load Word	CL	C.LW rd′,rs1′,imm
	Load Word SP	CI	C.LWSP rd,imm
	Load Double	CL	C.LD rd′,rs1′,imm
	Load Double SP	CI	C.LWSP rd,imm
	Load Quad	CL	C.LQ rd′,rs1′,imm
	Load Quad SP	CI	C.LQSP rd,imm
	Load Byte Unsigned	CL	C.LBU rd′,rs1′,imm
	Float Load Word	CL	C.FLW rd′,rs1′,imm
	Float Load Double	CL	C.FLD rd′,rs1′,imm
	Float Load Word SP	CI	C.FLWSP rd,imm
	Float Load Double SP	CI	C.FLDSP rd,imm
Stores	Store Word	CS	C.SW rs1′,rs2′,imm
	Store Word SP	CSS	C.SWSP rs2,imm
	Store Double	CS	C.SD rs1′,rs2′,imm
	Store Double SP	CSS	C.SDSP rs2,imm
	Store Quad	CS	C.SQ rs1′,rs2′,imm
	Store Quad SP	CSS	C.SQSP rs2,imm
	Float Store Word	CSS	C.FSW rd′,rs1′,imm
	Float Store Double	CSS	C.FSD rd′,rs1′,imm
	Float Store Word SP	CSS	C.FSWSP rd,imm
	Float Store Double SP	CSS	C.FSDSP rd,imm
Arithmetic	ADD	CR	C.ADD rd,rs1
	ADD Word	CR	C.ADDW rd′,rs2′
	ADD Immediate	CI	C.ADDI rd,imm
	ADD Word Imm	CI	C.ADDIW rd,imm
	ADD SP Imm * 16	CI	C.ADDI16SP x0,imm
	ADD SP Imm * 4	CIW	C.ADDI4SPN rd′,imm
	Load Immediate	CI	C.LI rd,imm
	Load Upper Imm	CI	C.LUI rd,imm
	MoVe	CR	C.MV rd,rs1
	SUB	CR	C.SUB rd′,rs2′
	SUB Word	CR	C.SUBW rd′,rs2′
Logical	XOR	CS	C.XOR rd′,rs2′
	OR	CS	C.OR rd′,rs2′
	AND	CS	C.AND rd′,rs2′
	AND Immediate	CB	C.ANDI rd′,rs2′
Shifts	Shift Left Imm	CI	C.SLLI rd,imm
	Shift Right Immediate	CB	C.SRLI rd′,imm
	Shift Right Arith Imm	CB	C.SRAI rd′,imm
Branches	Branch=0	CB	C.BEQZ rs1′,imm
	Branch≠0	CB	C.BNEZ rs1′,imm
Jump	Jump	CJ	C.J imm
	Jump Register	CR	C.JR rd,rs1
Jump & Link	J&L	CJ	C.JAL imm
	Jump & Link Register	CR	C.JALR rs1
System	Env. BREAK	CI	C.EBREAK

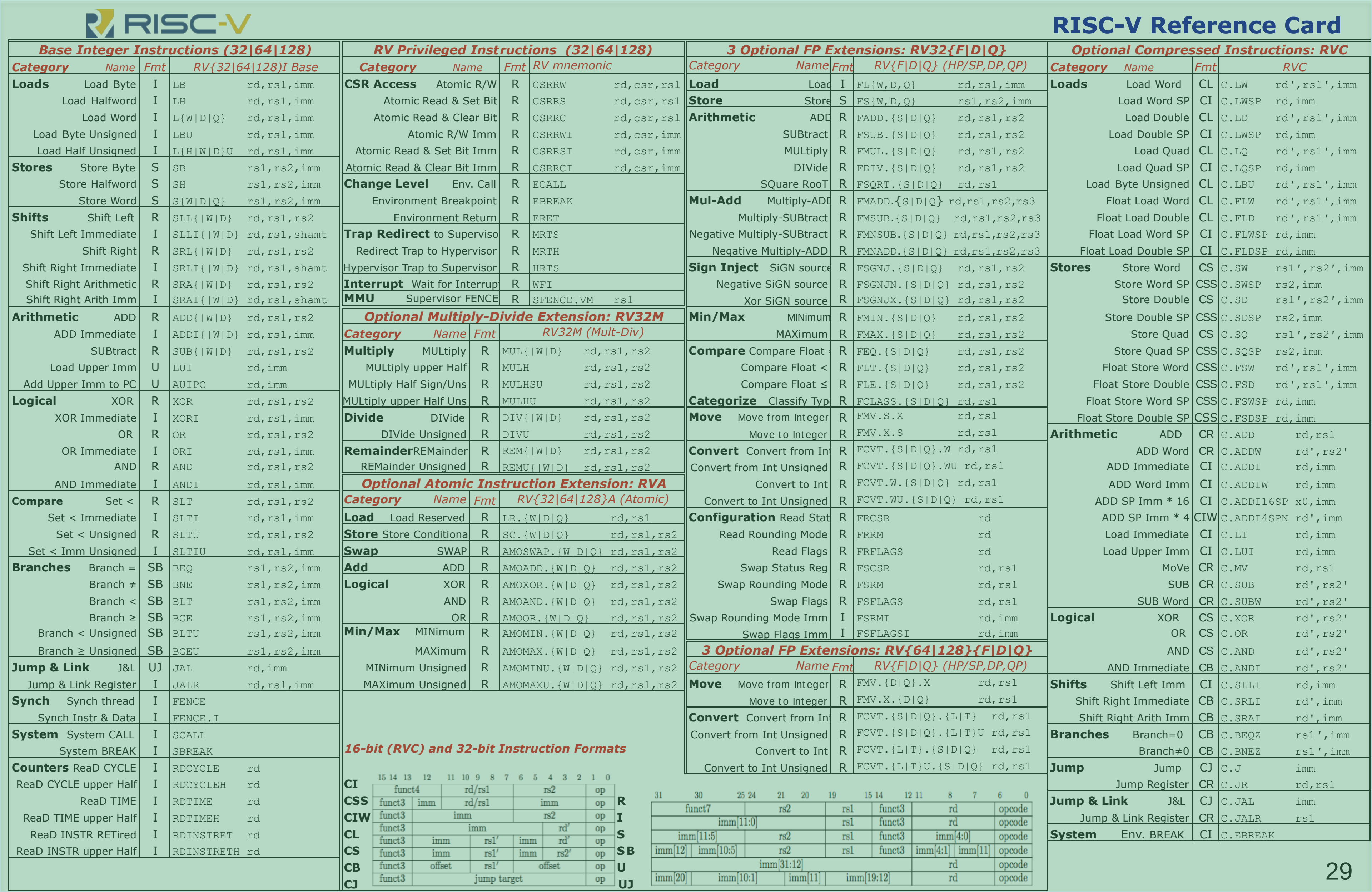
16-bit (RVC) and 32-bit Instruction Formats

	15 14 13	12	11 10	9 8 7	6 5	4 3 2	1 0
CI	funct4		rd/rs1		rs2		op
CSS	funct3	imm	rd/rs1		imm		op
CIW	funct3	imm			rs2		op
CL	funct3	imm				rd′	op
	funct3	imm		rs1′	imm	rd′	op
CS	funct3	imm		rs1′	imm	rs2′	op
CB	funct3	offset		rs1′	offset		op
CJ	funct3	jump target					op

	31	30 25	24 21	20	19 15	14 12	11 8	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]	imm[10:5]	rs2		rs1	funct3	imm[4:1]	imm[11]	opcode
U	imm[31:12]						rd		opcode
UJ	imm[20]	imm[10:1]		imm[11]	imm[19:12]		rd		opcode

+6 for 64{F|D|Q}/ 128{F|D|Q}

RV32I / RV64I / RV128I + M, A, F, D, Q, C
RISC-V “Green Card”



RISC-V Reference Card

Base Integer Instructions (32|64|128)

Category	Name	Fmt	RV{32|64|128}I Base
Loads	Load Byte	I	LB rd,rs1,imm
	Load Halfword	I	LH rd,rs1,imm
	Load Word	I	L{W|D|Q} rd,rs1,imm
	Load Byte Unsigned	I	LBU rd,rs1,imm
	Load Half Unsigned	I	L{H|W|D}U rd,rs1,imm
Stores	Store Byte	S	SB rs1,rs2,imm
	Store Halfword	S	SH rs1,rs2,imm
	Store Word	S	S{W|D|Q} rs1,rs2,imm
Shifts	Shift Left	R	SLL{|W|D} rd,rs1,rs2
	Shift Left Immediate	I	SLLI{|W|D} rd,rs1,shamt
	Shift Right	R	SRL{|W|D} rd,rs1,rs2
	Shift Right Immediate	I	SRLI{|W|D} rd,rs1,shamt
	Shift Right Arithmetic	R	SRA{|W|D} rd,rs1,rs2
	Shift Right Arith Imm	I	SRAI{|W|D} rd,rs1,shamt
Arithmetic	ADD	R	ADD{|W|D} rd,rs1,rs2
	ADD Immediate	I	ADDI{|W|D} rd,rs1,imm
	SUBtract	R	SUB{|W|D} rd,rs1,rs2
	Load Upper Imm	U	LUI rd,imm
	Add Upper Imm to PC	U	AUIPC rd,imm
Logical	XOR	R	XOR rd,rs1,rs2
	XOR Immediate	I	XORI rd,rs1,imm
	OR	R	OR rd,rs1,rs2
	OR Immediate	I	ORI rd,rs1,imm
	AND	R	AND rd,rs1,rs2
	AND Immediate	I	ANDI rd,rs1,imm
Compare	Set <	R	SLT rd,rs1,rs2
	Set < Immediate	I	SLTI rd,rs1,imm
	Set < Unsigned	R	SLTU rd,rs1,rs2
	Set < Imm Unsigned	I	SLTIU rd,rs1,imm
Branches	Branch =	SB	BEQ rs1,rs2,imm
	Branch ≠	SB	BNE rs1,rs2,imm
	Branch <	SB	BLT rs1,rs2,imm
	Branch ≥	SB	BGE rs1,rs2,imm
	Branch < Unsigned	SB	BLTU rs1,rs2,imm
	Branch ≥ Unsigned	SB	BGEU rs1,rs2,imm
Jump & Link	J&L	UJ	JAL rd,imm
	Jump & Link Register	I	JALR rd,rs1,imm
Synch	Synch thread	I	FENCE
	Synch Instr & Data	I	FENCE.I
System	System CALL	I	SCALL
	System BREAK	I	SBREAK
Counters	ReaD CYCLE	I	RDCYCLE rd
	ReaD CYCLE upper Half	I	RDCYCLEH rd
	ReaD TIME	I	RDTIME rd
	ReaD TIME upper Half	I	RDTIMEH rd
	ReaD INSTR RETired	I	RDINSTRET rd
	ReaD INSTR upper Half	I	RDINSTRETH rd

RV Privileged Instructions (32|64|128)

Category	Name	Fmt	RV mnemonic
CSR Access	Atomic R/W	R	CSRRW rd,csr,rs1
	Atomic Read & Set Bit	R	CSRRS rd,csr,rs1
	Atomic Read & Clear Bit	R	CSRRC rd,csr,rs1
	Atomic R/W Imm	R	CSRRWI rd,csr,imm
	Atomic Read & Set Bit Imm	R	CSRRSI rd,csr,imm
	Atomic Read & Clear Bit Imm	R	CSRRCI rd,csr,imm
Change Level	Env. Call	R	ECALL
	Environment Breakpoint	R	EBREAK
	Environment Return	R	ERET
Trap Redirect	to Superviso	R	MRTS
	Redirect Trap to Hypervisor	R	MRTH
	Hypervisor Trap to Supervisor	R	HRTS
Interrupt	Wait for Interrup	R	WFI
MMU	Supervisor FENCE	R	SFENCE.VM rs1

Optional Multiply-Divide Extension: RV32M

Category	Name	Fmt	RV32M (Mult-Div)
Multiply	MULtiply	R	MUL{|W|D} rd,rs1,rs2
	MULtiply upper Half	R	MULH rd,rs1,rs2
	MULtiply Half Sign/Uns	R	MULHSU rd,rs1,rs2
	MULtiply upper Half Uns	R	MULHU rd,rs1,rs2
Divide	DIVide	R	DIV{|W|D} rd,rs1,rs2
	DIVide Unsigned	R	DIVU rd,rs1,rs2
Remainder	REMainder	R	REM{|W|D} rd,rs1,rs2
	REMainder Unsigned	R	REMU{|W|D} rd,rs1,rs2

Optional Atomic Instruction Extension: RVA

Category	Name	Fmt	RV{32|64|128}A (Atomic)
Load	Load Reserved	R	LR.{W|D|Q} rd,rs1
Store	Store Conditiona	R	SC.{W|D|Q} rd,rs1,rs2
Swap	SWAP	R	AMOSWAP.{W|D|Q} rd,rs1,rs2
Add	ADD	R	AMOADD.{W|D|Q} rd,rs1,rs2
Logical	XOR	R	AMOXOR.{W|D|Q} rd,rs1,rs2
	AND	R	AMOAND.{W|D|Q} rd,rs1,rs2
	OR	R	AMOOR.{W|D|Q} rd,rs1,rs2
Min/Max	MINimum	R	AMOMIN.{W|D|Q} rd,rs1,rs2
	MAXimum	R	AMOMAX.{W|D|Q} rd,rs1,rs2
	MINimum Unsigned	R	AMOMINU.{W|D|Q} rd,rs1,rs2
	MAXimum Unsigned	R	AMOMAXU.{W|D|Q} rd,rs1,rs2

3 Optional FP Extensions: RV32{F|D|Q}

Category	Name	Fmt	RV{F|D|Q} (HP/SP,DP,QP)
Load	Load	I	FL{W,D,Q} rd,rs1,imm
Store	Store	S	FS{W,D,Q} rs1,rs2,imm
Arithmetic	ADD	R	FADD.{S|D|Q} rd,rs1,rs2
	SUBtract	R	FSUB.{S|D|Q} rd,rs1,rs2
	MULtiply	R	FMUL.{S|D|Q} rd,rs1,rs2
	DIVide	R	FDIV.{S|D|Q} rd,rs1,rs2
	SQuare RooT	R	FSQRT.{S|D|Q} rd,rs1
Mul-Add	Multiply-ADD	R	FMADD.{S|D|Q} rd,rs1,rs2,rs3
	Multiply-SUBtract	R	FMSUB.{S|D|Q} rd,rs1,rs2,rs3
	Negative Multiply-SUBtract	R	FMNSUB.{S|D|Q} rd,rs1,rs2,rs3
	Negative Multiply-ADD	R	FMNADD.{S|D|Q} rd,rs1,rs2,rs3
Sign Inject	SiGN source	R	FSGNJ.{S|D|Q} rd,rs1,rs2
	Negative SiGN source	R	FSGNJN.{S|D|Q} rd,rs1,rs2
	Xor SiGN source	R	FSGNJX.{S|D|Q} rd,rs1,rs2
Min/Max	MINimum	R	FMIN.{S|D|Q} rd,rs1,rs2
	MAXimum	R	FMAX.{S|D|Q} rd,rs1,rs2
Compare	Compare Float =	R	FEQ.{S|D|Q} rd,rs1,rs2
	Compare Float <	R	FLT.{S|D|Q} rd,rs1,rs2
	Compare Float ≤	R	FLE.{S|D|Q} rd,rs1,rs2
Categorize	Classify Typ	R	FCLASS.{S|D|Q} rd,rs1
Move	Move from Integer	R	FMV.S.X rd,rs1
	Move to Integer	R	FMV.X.S rd,rs1
Convert	Convert from Int	R	FCVT.{S|D|Q}.W rd,rs1
	Convert from Int Unsigned	R	FCVT.{S|D|Q}.WU rd,rs1
	Convert to Int	R	FCVT.W.{S|D|Q} rd,rs1
	Convert to Int Unsigned	R	FCVT.WU.{S|D|Q} rd,rs1
Configuration	Read Stat	R	FRCSR rd
	Read Rounding Mode	R	FRRM rd
	Read Flags	R	FRFLAGS rd
	Swap Status Reg	R	FSCSR rd,rs1
	Swap Rounding Mode	R	FSRM rd,rs1
	Swap Flags	R	FSFLAGS rd,rs1
	Swap Rounding Mode Imm	I	FSRMI rd,imm
	Swap Flags Imm	I	FSFLAGSI rd,imm

3 Optional FP Extensions: RV{64|128}{F|D|Q}

Category	Name	Fmt	RV{F|D|Q} (HP/SP,DP,QP)
Move	Move from Integer	R	FMV.{D|Q}.X rd,rs1
	Move to Integer	R	FMV.X.{D|Q} rd,rs1
Convert	Convert from Int	R	FCVT.{S|D|Q}.{L|T} rd,rs1
	Convert from Int Unsigned	R	FCVT.{S|D|Q}.{L|T}U rd,rs1
	Convert to Int	R	FCVT.{L|T}.{S|D|Q} rd,rs1
	Convert to Int Unsigned	R	FCVT.{L|T}U.{S|D|Q} rd,rs1

Optional Compressed Instructions: RVC

Category	Name	Fmt	RVC
Loads	Load Word	CL	C.LW rd′,rs1′,imm
	Load Word SP	CI	C.LWSP rd,imm
	Load Double	CL	C.LD rd′,rs1′,imm
	Load Double SP	CI	C.LWSP rd,imm
	Load Quad	CL	C.LQ rd′,rs1′,imm
	Load Quad SP	CI	C.LQSP rd,imm
	Load Byte Unsigned	CL	C.LBU rd′,rs1′,imm
	Float Load Word	CL	C.FLW rd′,rs1′,imm
	Float Load Double	CL	C.FLD rd′,rs1′,imm
	Float Load Word SP	CI	C.FLWSP rd,imm
	Float Load Double SP	CI	C.FLDSP rd,imm
Stores	Store Word	CS	C.SW rs1′,rs2′,imm
	Store Word SP	CSS	C.SWSP rs2,imm
	Store Double	CS	C.SD rs1′,rs2′,imm
	Store Double SP	CSS	C.SDSP rs2,imm
	Store Quad	CS	C.SQ rs1′,rs2′,imm
	Store Quad SP	CSS	C.SQSP rs2,imm
	Float Store Word	CSS	C.FSW rd′,rs1′,imm
	Float Store Double	CSS	C.FSD rd′,rs1′,imm
	Float Store Word SP	CSS	C.FSWSP rd,imm
	Float Store Double SP	CSS	C.FSDSP rd,imm
Arithmetic	ADD	CR	C.ADD rd,rs1
	ADD Word	CR	C.ADDW rd′,rs2′
	ADD Immediate	CI	C.ADDI rd,imm
	ADD Word Imm	CI	C.ADDIW rd,imm
	ADD SP Imm * 16	CI	C.ADDI16SP x0,imm
	ADD SP Imm * 4	CIW	C.ADDI4SPN rd′,imm
	Load Immediate	CI	C.LI rd,imm
	Load Upper Imm	CI	C.LUI rd,imm
	MoVe	CR	C.MV rd,rs1
	SUB	CR	C.SUB rd′,rs2′
	SUB Word	CR	C.SUBW rd′,rs2′
Logical	XOR	CS	C.XOR rd′,rs2′
	OR	CS	C.OR rd′,rs2′
	AND	CS	C.AND rd′,rs2′
	AND Immediate	CB	C.ANDI rd′,rs2′
Shifts	Shift Left Imm	CI	C.SLLI rd,imm
	Shift Right Immediate	CB	C.SRLI rd′,imm
	Shift Right Arith Imm	CB	C.SRAI rd′,imm
Branches	Branch=0	CB	C.BEQZ rs1′,imm
	Branch≠0	CB	C.BNEZ rs1′,imm
Jump	Jump	CJ	C.J imm
	Jump Register	CR	C.JR rd,rs1
Jump & Link	J&L	CJ	C.JAL imm
	Jump & Link Register	CR	C.JALR rs1
System	Env. BREAK	CI	C.EBREAK

16-bit (RVC) and 32-bit Instruction Formats

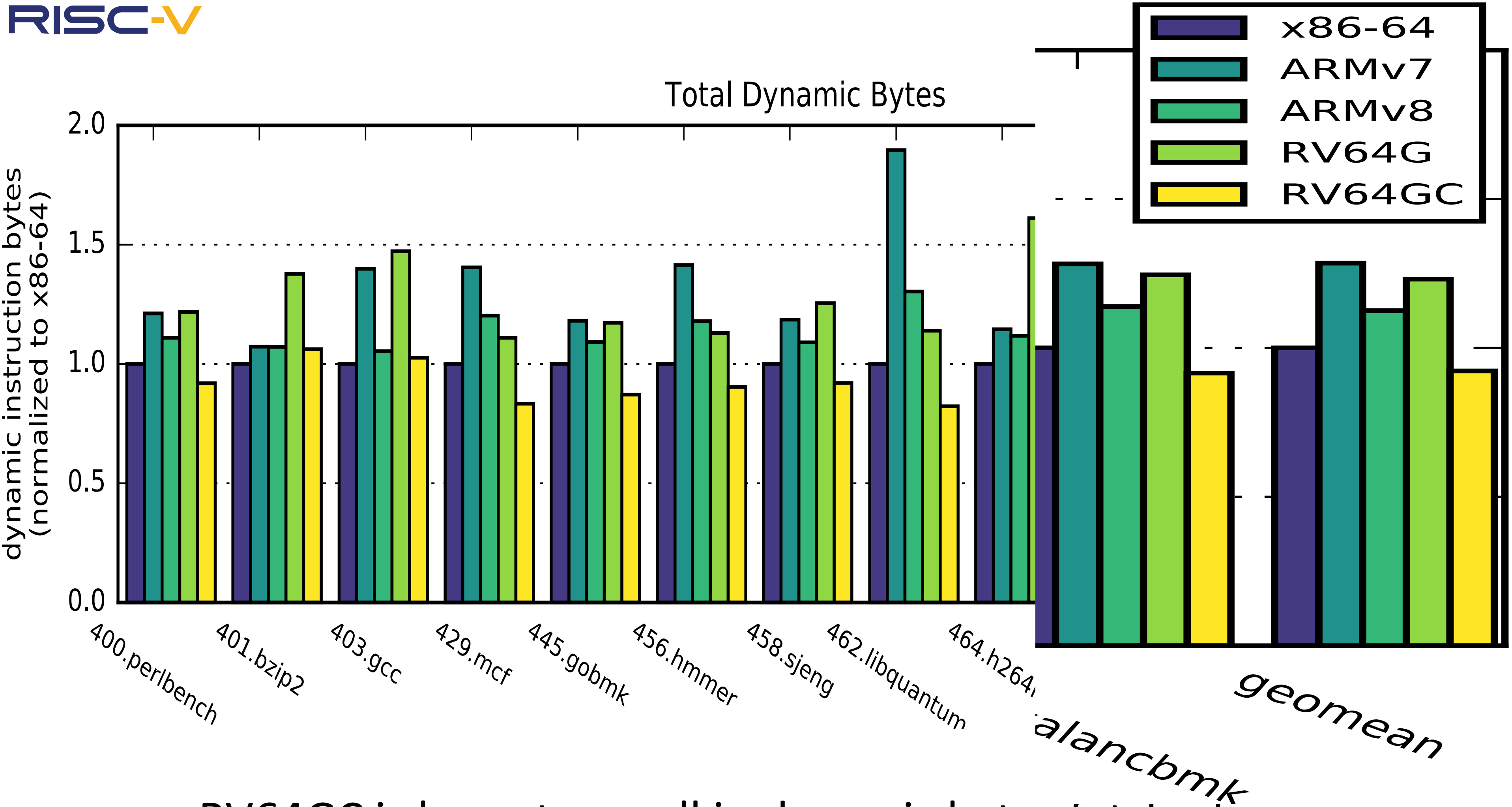
	15 14 13	12	11 10	9 8 7	6 5	4 3 2	1 0
CI	funct4		rd/rs1		rs2		op
CSS	funct3	imm	rd/rs1		imm		op
CIW	funct3	imm			rs2		op
CL	funct3	imm				rd′	op
	funct3	imm		rs1′	imm	rd′	op
CS	funct3	imm		rs1′	imm	rs2′	op
CB	funct3	offset		rs1′	offset		op
CJ	funct3	jump target					op

	31	30 25	24 21	20	19 15	14 12	11 8	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]	imm[10:5]	rs2		rs1	funct3	imm[4:1]	imm[11]	opcode
U	imm[31:12]						rd		opcode
UJ	imm[20]	imm[10:1]		imm[11]	imm[19:12]		rd		opcode

Simplicity breeds Contempt

- How can simple ISA compete with industry monsters?
- How do measure ISA quality?
  - Static code bytes for program
  - Dynamic code bytes fetched for execution
  - Microarchitectural work generated for execution

Dynamic Bytes Fetched



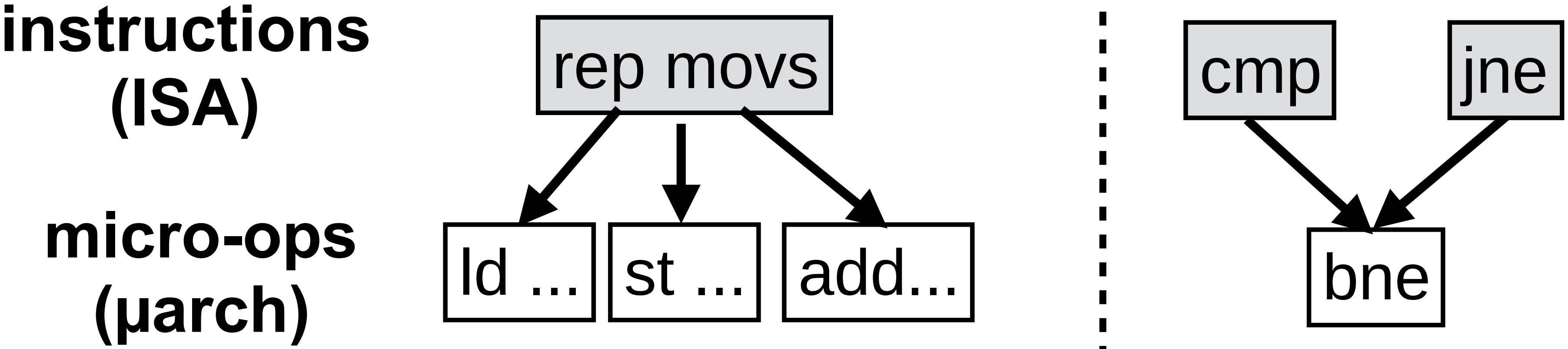
- RV64GC is lowest overall in dynamic bytes fetched
  - Despite current lack of support for vector operations

Converting Instructions to Microops

Microops are measure of microarchitectural work performed

Micro:ops% general on

Macro:op% Fusion



Multiple microinstructions from one macroinstruction

Or one microinstruction from multiple macroinstructions

RISC-V Macro-Op Fusion Examples

- “Load effective address LEA” &(array[offset])

```
slli rd, rs1, {1,2,3}
add rd, rd, rs2
```

- “indexed load” M[rs1+rs2]

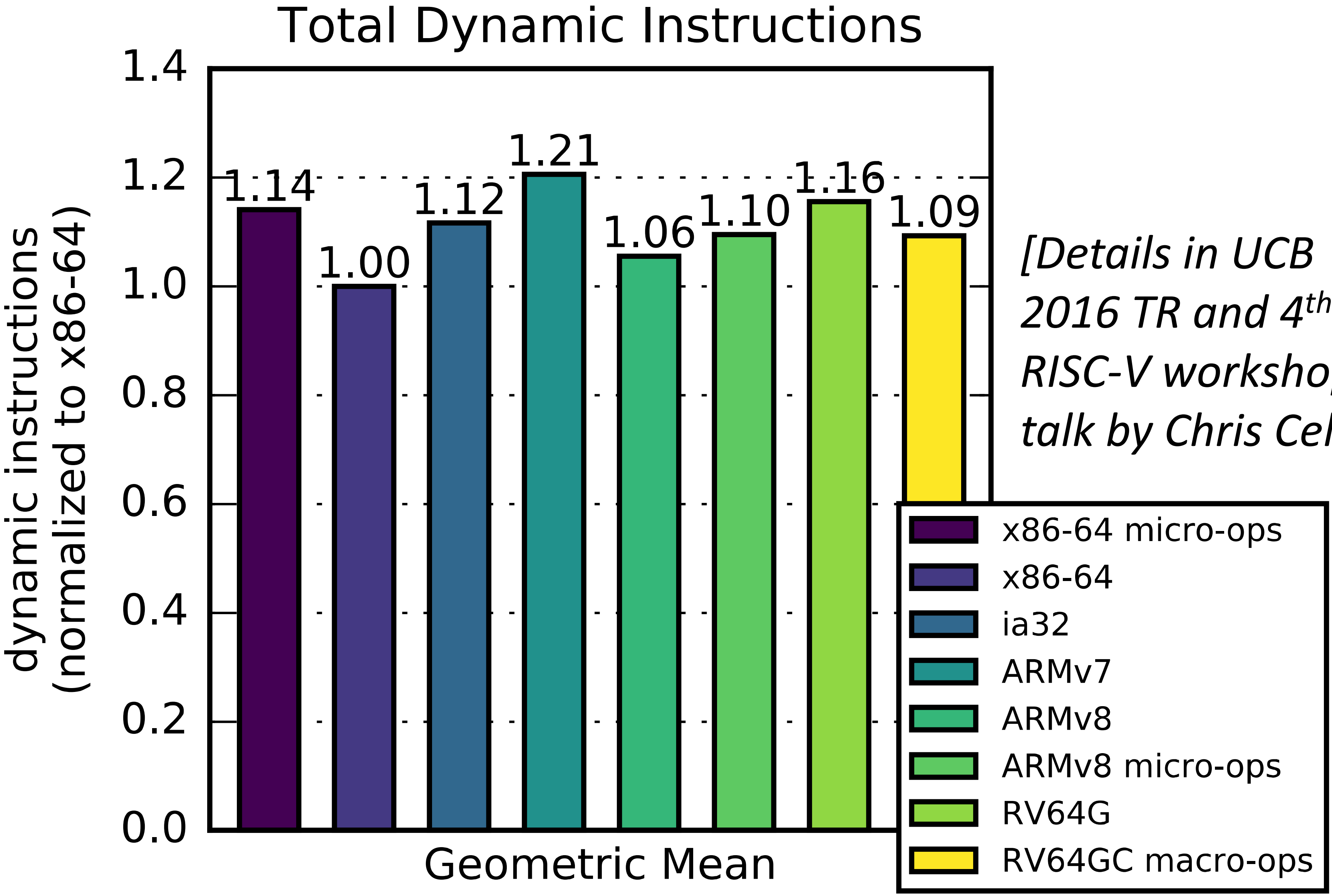
```
add rd, rs1, rs2
ld rd, 0(rd)
```

- “clear upper word” // rd = rs1 & 0xffff_ffff

```
slli rd, rs1, 32
srli rd, rd, 32
```

- Can all be fused simply in decode stage
  - Many are expressible with 2-byte compressed instructions, so effectively just adds new 4-byte instructions
- RISC-V approach: prefer macroop fusion to larger ISA

RISC-V Competitive µarch Effort after Fusion

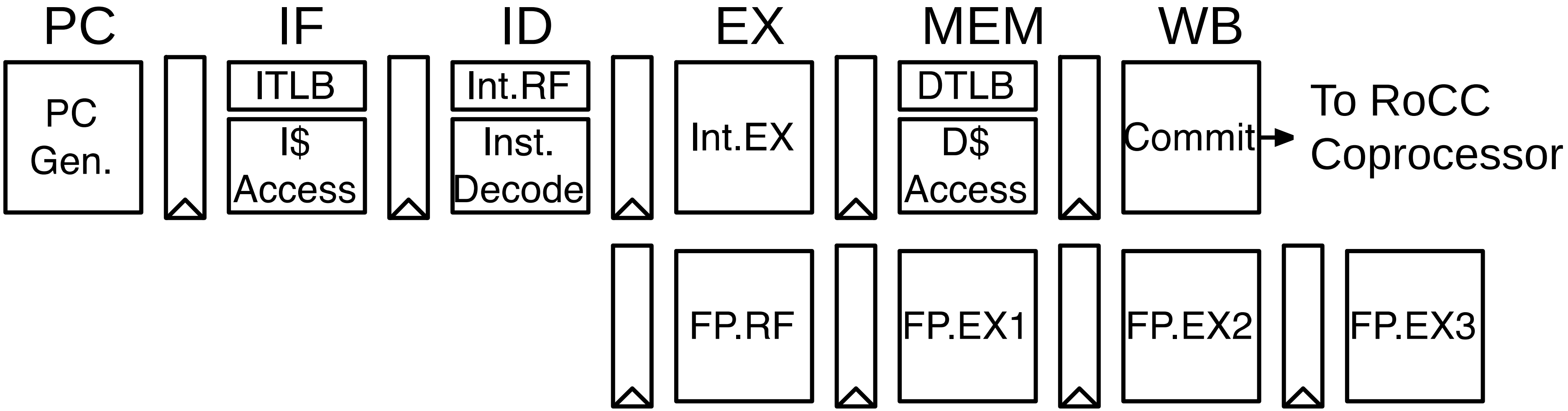


[Details in UCB 2016 TR and 4th RISC-V workshop talk by Chris Celio]

UC Berkeley RISC-V Core Generators

- **Rocket:** Family of In-order Cores
  - Supports 32-bit and 64-bit single-issue only
  - Dual-issue soon
  - Similar in spirit to ARM Cortex M-series and A5/A7/A53
- **BOOM:** Family of Out-of-Order Cores
  - Supports 64-bit single-, dual-, quad-issue
  - Similar in spirit to ARM Cortex A9/A15/A57

RISC-V Rocket In-Order Core



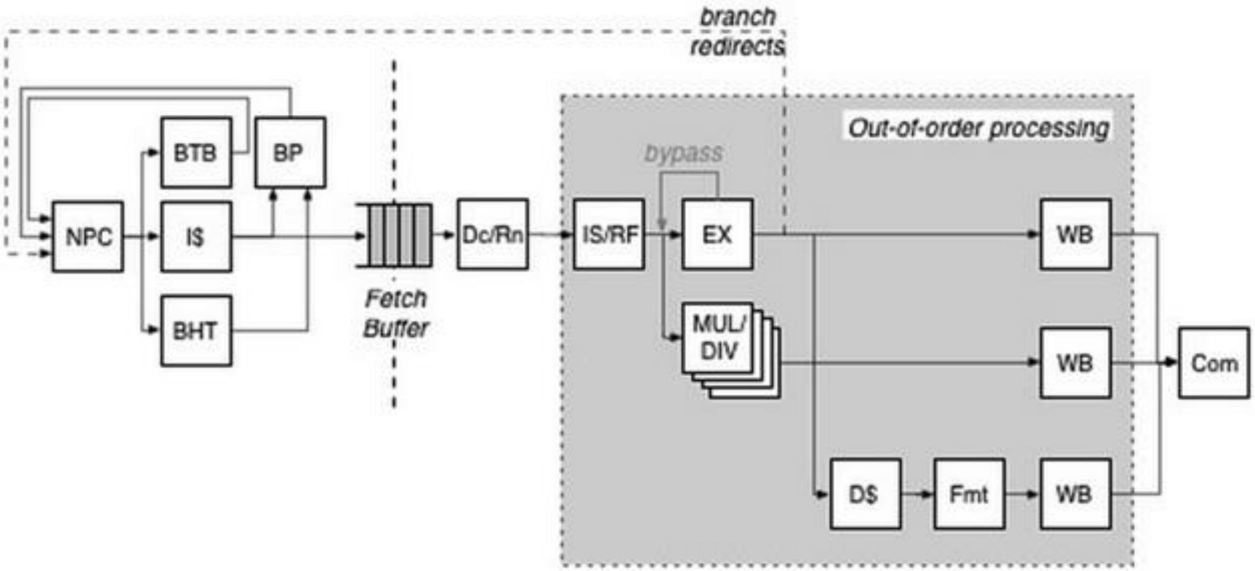
- 64-bit 5-stage single-issue in-order pipeline
- Design minimizes impact of long clock-to-output delays of compiler-generated RAMs
- 64-entry BTB, 256-entry BHT, 2-entry RAS
- MMU supports page-based virtual memory
- IEEE 754-2008-compliant FPU
  - Supports SP, DP fused multiply-adds with hardware support for subnormals
- Currently working on dual-issue in-order Rocket

ARM Cortex-A5 vs. RISC-V Rocket

Category	ARM Cortex-A5	RISC-V Rocket
ISA	32-bit ARM v7	64-bit RISC-V v2
Architecture	Single-Issue In-Order	Single-Issue In-Order 5-stage
Performance	1.57 DMIPS/MHz	1.72 DMIPS/MHz
Process	TSMC 40GPLUS	TSMC 40GPLUS
Area w/o Caches	0.27 mm^2	0.14 mm^2
Area with 16K Caches	0.53 mm^2	0.39 mm^2
Area Efficiency	2.96 DMIPS/MHz/mm^2	4.41 DMIPS/MHz/mm^2
Frequency	>1GHz	>1GHz
Dynamic Power	<0.08 mW/MHz	0.034 mW/MHz

- PPA reporting conditions
  - 85% utilization, use Dhrystone for benchmark, frequency/power at TT 0.9V 25C, all regular VT transistors
- 10% higher in DMIPS/MHz, 49% more area-efficient

RISC-V BOOM Out-of-Order Core



- Baseline Design
  - Superscalar (parameterizable widths)
  - Full branch speculation (BTB/BHT/RAS)
  - Load/store queue with store ordering
    - Loads execute fully OoO wrt stores, other loads
    - Store-data forwards to loads
- Estimated 2GHz+ in 45nm (<30 FO4)

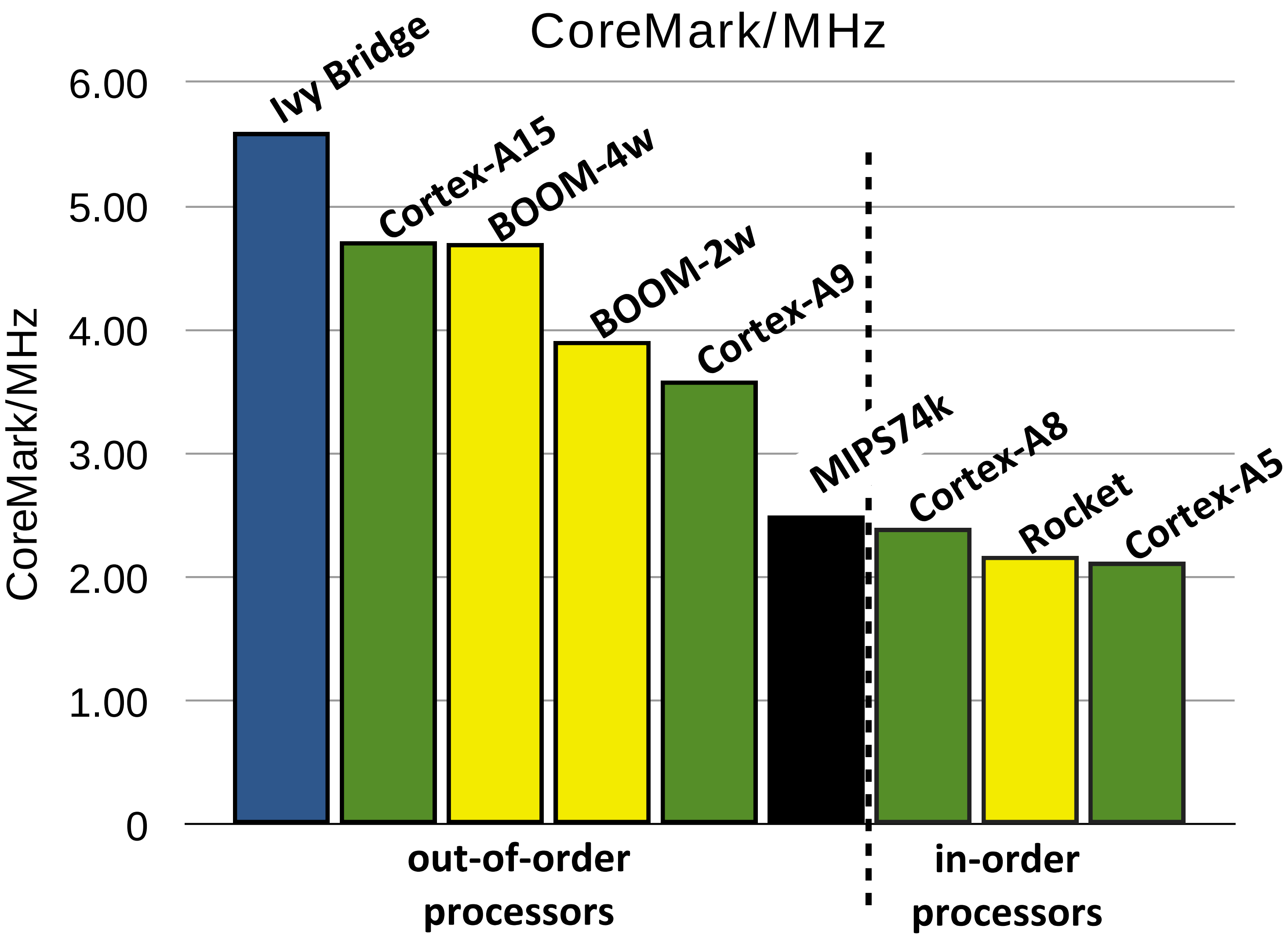
ARM Cortex-A9 vs. RISC-V BOOM

Category	ARM Cortex-A9	RISC-V BOOM-2w
ISA	32-bit ARM v7	64-bit RISC-V v2 (RV64G)
Architecture	2 wide, 3+1 issue Out-of-Order 8-stage	2 wide, 3 issue Out-of-Order 6-stage
Performance	3.59 CoreMarks/MHz	3.91 CoreMarks/MHz
Process	TSMC 40GPLUS	TSMC 40GPLUS
Area with 32K caches	2.5 mm^2	1.00 mm^2
Area efficiency	1.4 CoreMarks/MHz/mm^2	3.9 CoreMarks/MHz/mm^2
Frequency	1.4 GHz	1.5 GHz

Caveats: A9 includes NEON

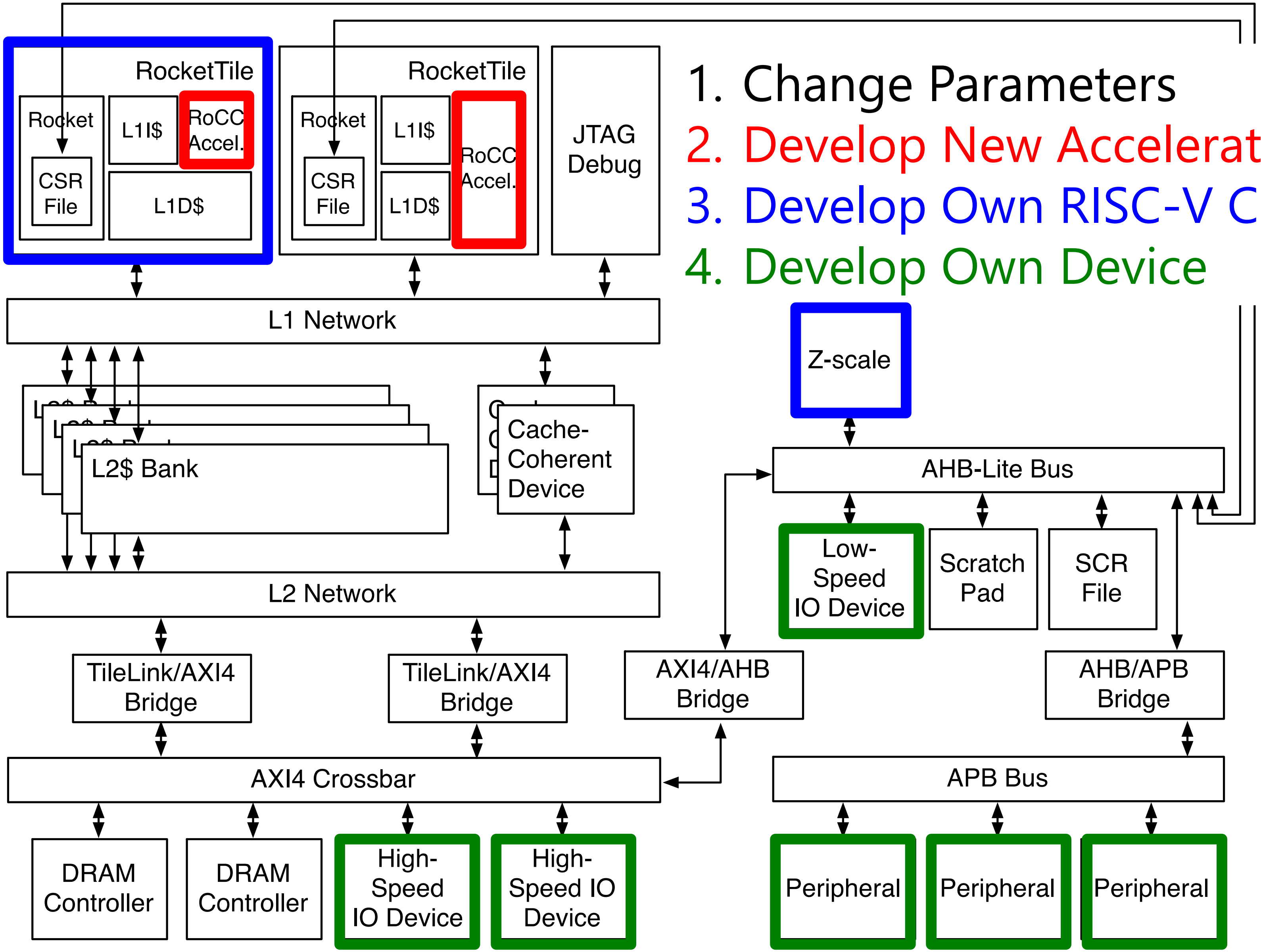
BOOM is 64-bit, has IEEE-2008 fused mul-add

CoreMark Scores



See Chris Celio's "BOOM: Berkeley Out-of-Order Machine" talk from 2nd RISC-V Workshop for more details

Rocket Chip Generator

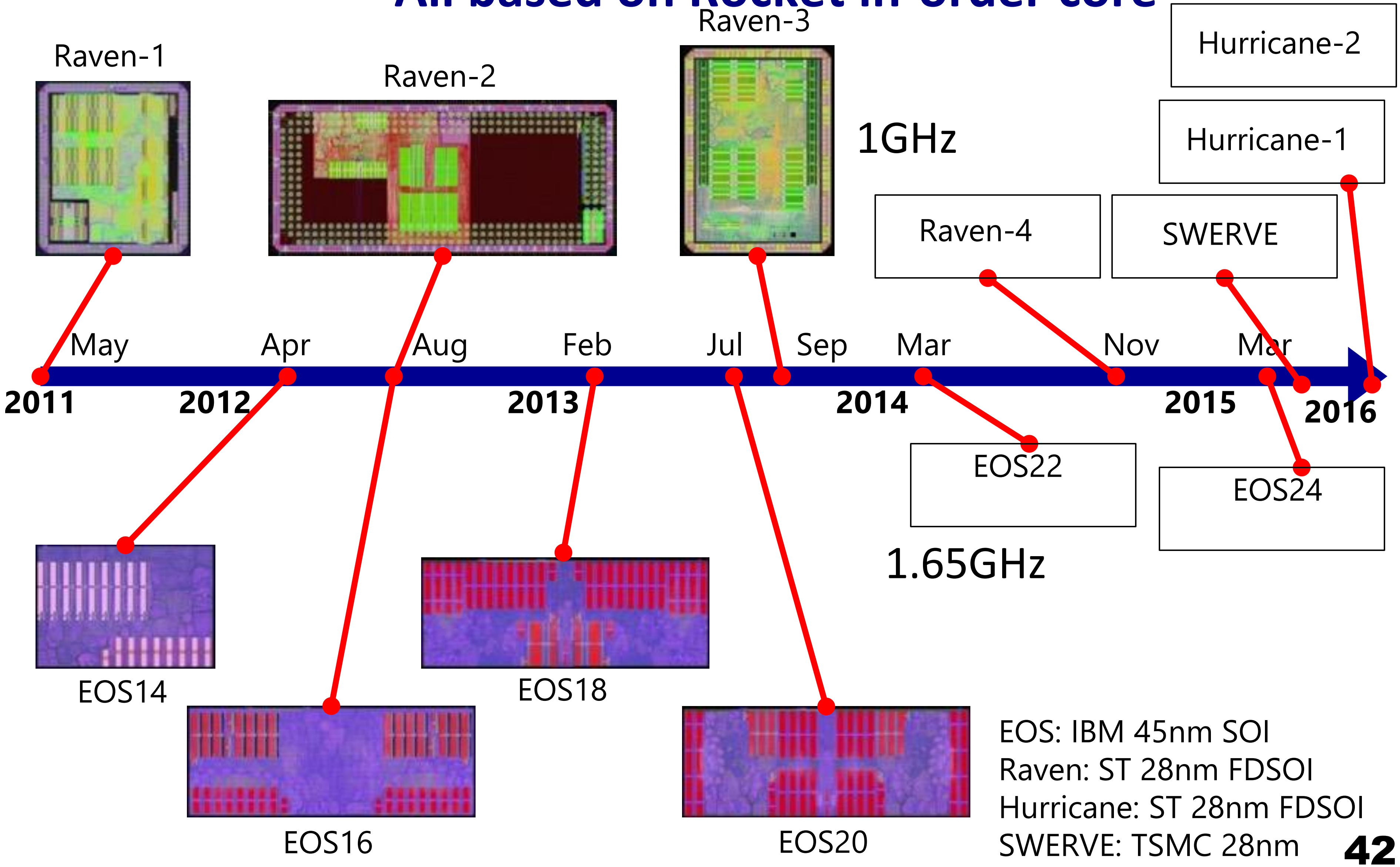


1. Change Parameters
2. Develop New Accelerators
3. Develop Own RISC-V Core
4. Develop Own Device

UC Berkeley RISC-V Cores:

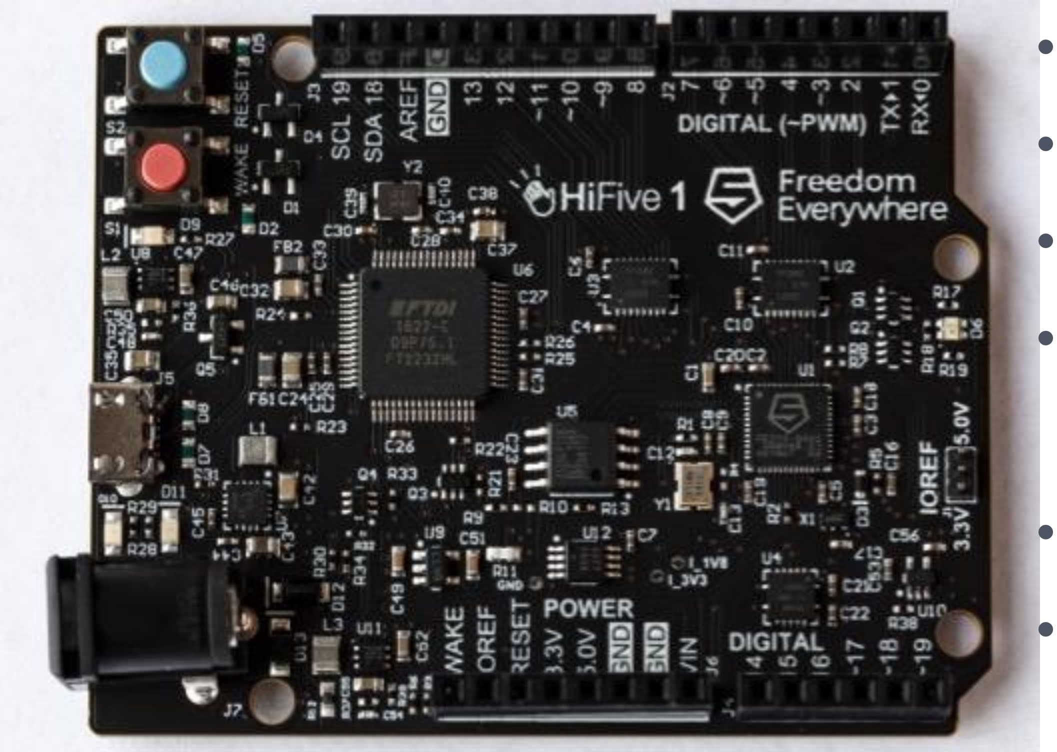
Seven 28nm & Six 45nm RISC-V Chips Tapeouts

All based on Rocket in-order core



EOS: IBM 45nm SOI
Raven: ST 28nm FDSOI
Hurricane: ST 28nm FDSOI
SWERVE: TSMC 28nm

SiFive HiFive 1



- Open-Source RTL
- Arduino-Compatible
- Freedom E SDK
- Arduino IDE Environment

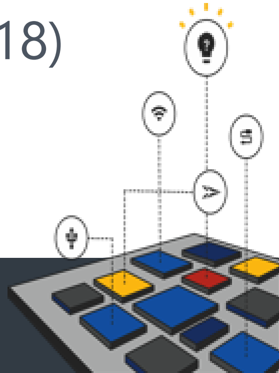
- Available for sale now!
- $59

https://www.crowdsupply.com/sifive/hifive1

RISC-V is GREAT at Perf and Power

Microcontroller	CPU Core	CPU ISA	CPU Speed	DMIPs/MHz	Total Dhrystones	DMIPs/mW
Intel Curie Module	Intel Quark SE	x86	32 MHz	1.3	41.6	0.35
ATmega328P	AVR	AVR (8-bit)	16 MHz	0.30	5	0.10
ATSAMD21G18	ARM Cortex M0+	ARMv6-M	48 MHz	0.93	44.64	
Nordic NRF51	ARM Cortex M0	ARMv6-M	16 MHz	0.93	14.88	1.88
Freedom E310	SiFive E31	RISC-V RV32IMAC	200 MHz 320 MHz (max)	1.61	320.39	3.16

- 10x Faster Clock than Intel's Arduino 101 uController
- 11x More Dhrystones than ARM's Arduino Zero (ATSAMD21G18)
- 9x More Power Efficient than Intel Quark
- 2x More Power Efficient than ARM Cortex M0+



SiFive

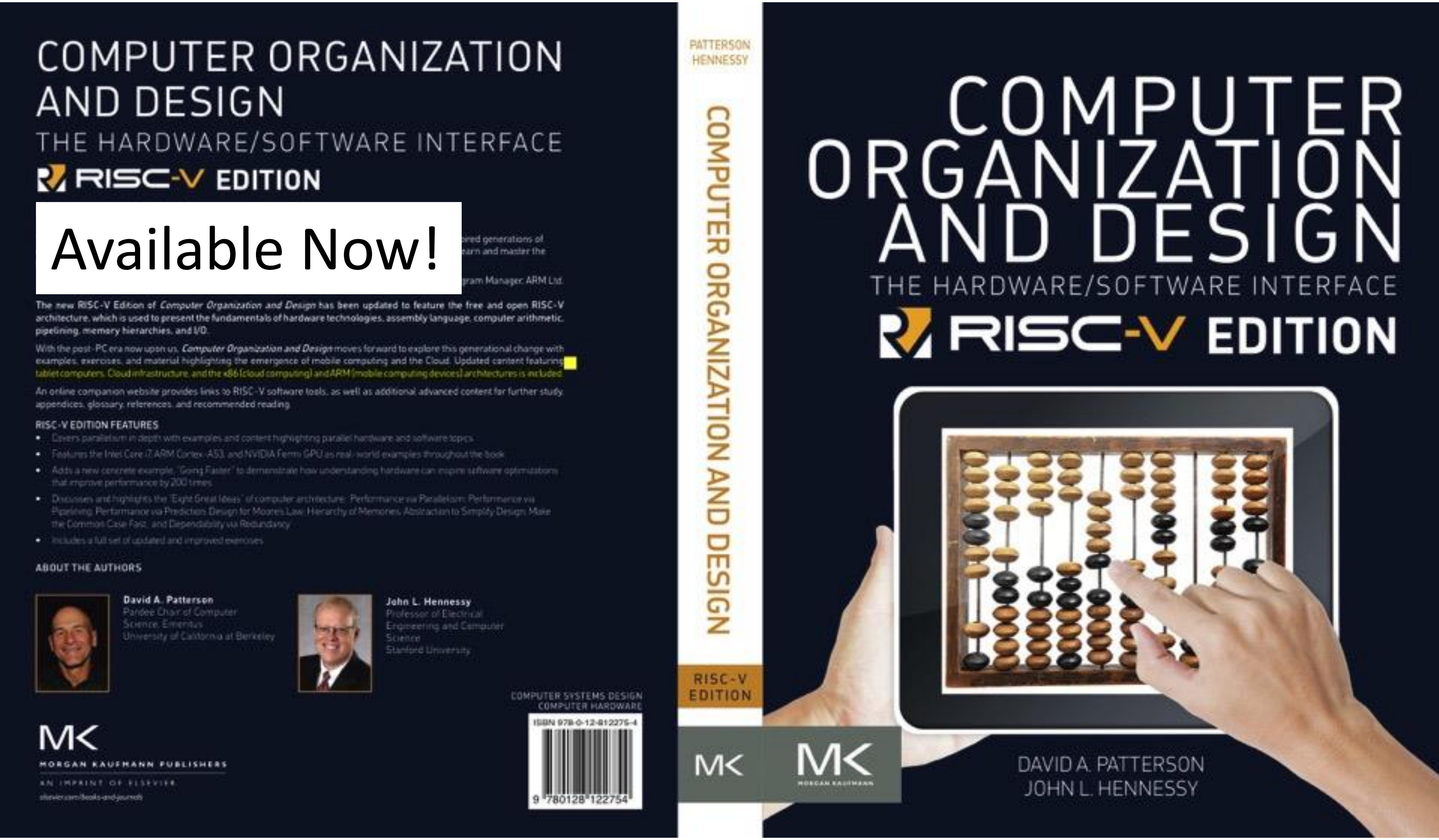
RISC-V Outside Berkeley

- Adopted as “standard ISA” for **India**
  - IIT-Madras $90M funding to build 6 different open-source RISC-V cores, from microcontrollers to servers
  - C-DAC $45M funding to build 2GHz quad-core
- **NVIDIA** selected RISC-V for on-chip microcontrollers
- **LowRISC** project based in Cambridge, UK producing open-source RISC-V Rocket-based SoCs
  - Led by Raspberry Pi co-founder, privately funded
- Many companies developing RISC-V cores for use in tightly integrated hardware/software IP blocks
- First commercial RISC-V cores have already shipped!
  - Rumble Development Corp, for dental camera/imaging
- Multiple commercial silicon implementations should be for sale later this year

RISC-V Foundation

- Mission statement
  - “to standardize, protect, and promote the free and open RISC-V instruction set architecture and its hardware and software ecosystem for use in all computing devices.”
- Established as a 501(c)(6) non-profit corporation on August 3, 2015
- Rick O’Connor recruited as Executive Director
- First year, 41+ “founding” members. Additional members welcome

RISC-V in Education, Patterson/Hennessy books



COMPUTER ORGANIZATION AND DESIGN

THE HARDWARE/SOFTWARE INTERFACE

RISC-V EDITION

Available Now!

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gram Manager, ARM Ltd

The new RISC-V Edition of *Computer Organization and Design* has been updated to feature the free and open RISC-V architecture, which is used to present the fundamentals of hardware technologies, assembly language, computer arithmetic, pipelining, memory hierarchies, and I/O.

With the post-PC era now upon us, *Computer Organization and Design* moves forward to explore this generational change with examples, exercises, and material highlighting the emergence of mobile computing and the Cloud. Updated content featuring tablet computers, Cloud infrastructure, and the x86 (cloud computing) and ARM (mobile computing devices) architectures is included.

An online companion website provides links to RISC-V software tools, as well as additional advanced content for further study, appendices, glossary, references, and recommended reading.

RISC-V EDITION FEATURES

- Covers parallelism in depth with examples and content highlighting parallel hardware and software topics
- Features the Intel Core i7, ARM Cortex-A53, and NVIDIA Fermi GPU as real-world examples throughout the book
- Adds a new concrete example, "Going Faster," to demonstrate how understanding hardware can inspire software optimizations that improve performance by 200 times
- Discusses and highlights the "Eight Great Ideas" of computer architecture: Performance via Parallelism; Performance via Pipelining; Performance via Prediction; Design for Moore's Law; Hierarchy of Memories; Abstraction to Simplify Design; Make the Common Case Fast; and Dependability via Redundancy
- Includes a full set of updated and improved exercises

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Graduate book 6th edition will also use RISC-V

Why use a free and open ISA like RISC-V?

Would you like to:	Or are you happy with:
Pick ISA then pick vendor	Pick vendor, use their ISA
Get competitive bid for 2nd gen. core	Vendor lock in
Enable open software stack	Binary blobs / software NDAs
Build your own core configuration	Buying a vendor configuration
Sharing your core designs	No community for core designs
Share spec and verification	Trusting vendors' verification
Teach class with real core design	Using crippled cores in teaching
Resell IP with controller core inside	Ask customers to license controller
Be assured support for 50+ years	Trusting vendor business decisions

Modest RISC-V Project Goal

Become the industry-standard ISA for all computing devices

RISC-V Research Project Sponsors

- DoE Isis Project
- DARPA PERFECT program
- DARPA POEM program (Si photonics)
- STARnet Center for Future Architectures (C-FAR)
- Lawrence Berkeley National Laboratory
- Industrial sponsors (ParLab + ASPIRE)
  - Intel, Google, HPE, ***Huawei***, LG, NEC, Microsoft, Nokia, NVIDIA, Oracle, Samsung

Questions?