UNIVERSITY OF CAMBRIDGE
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FreeBSD/RISC-V and Device Drivers

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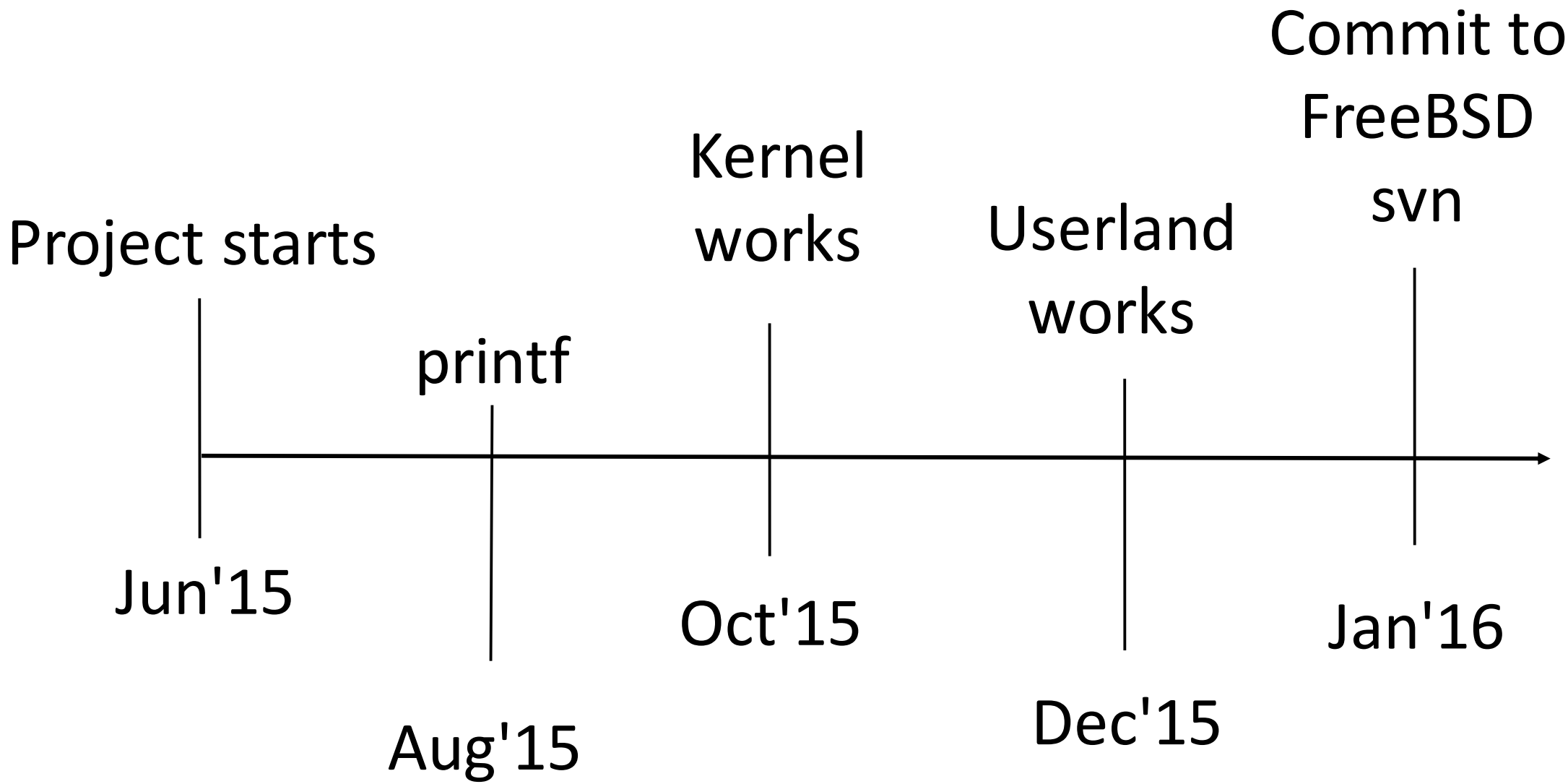
About the presenter

- FreeBSD architectural ports (ARM, MIPS, RISC-V, x86)
- Device Drivers (Sound, DMA, Ethernet, MMC, …)
- DTrace support (ARMv8, RISC-V)
- HWPMC (ARMv7, ARMv8)
- Intel® Software Guard Extensions (SGX)
- Intel® Processor Tracing Technology (under review)

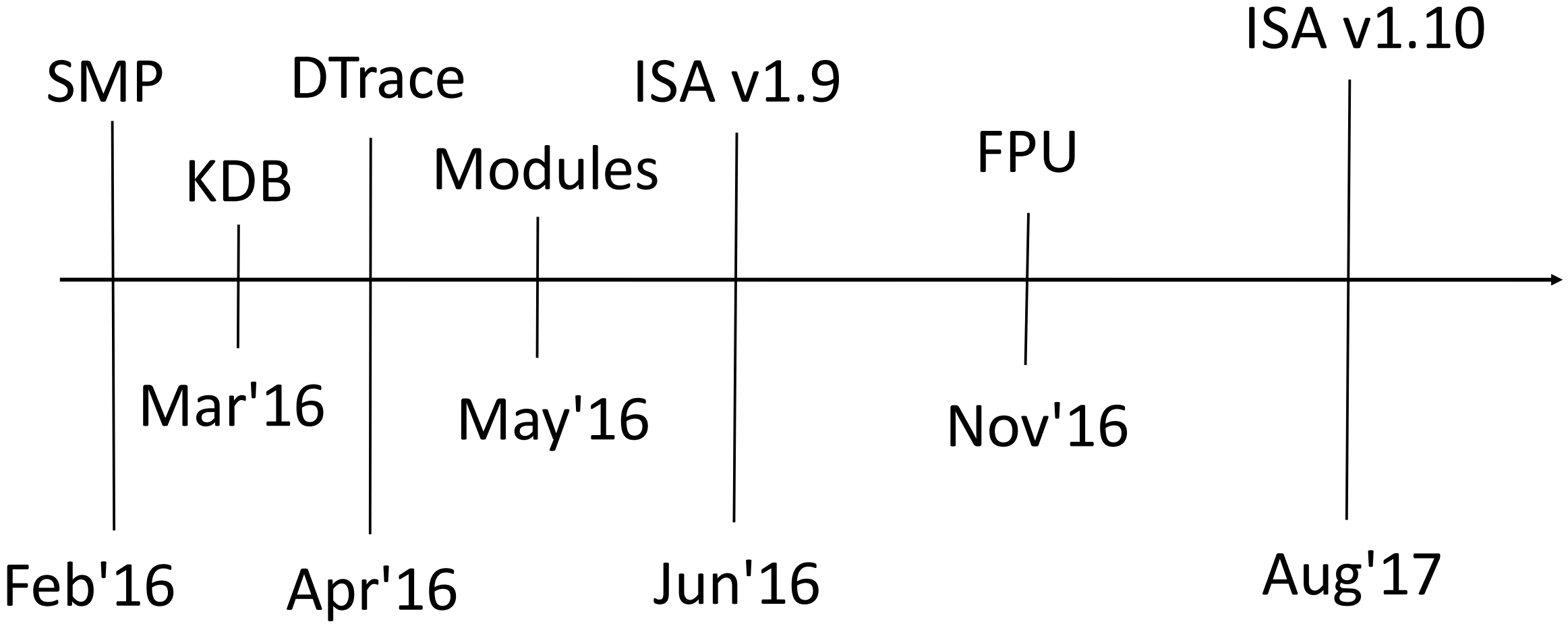
Overview

- History
- Porting process
- Challenges experienced
- Status updates on v1.10 privilege spec
- Drivers support

Timeline


Project starts
printf
Kernel works
Userland works
Commit to FreeBSD svn
Jun'15
Aug'15
Oct'15
Dec'15
Jan'16

Timeline (cont'd)



RISC-V privilege levels

- ❑ Machine (M-mode) – Berkeley BootLoader (BBL)
- ❑ Hypervisor (H-mode)
- ❑ Supervisor (S-mode) – FreeBSD OS kernel
- ❑ User (U-mode) – /sbin/init, libc and userspace

- Supported combination of modes:
  - M simple embedded
  - M, U simple embedded with protection
  - M, S, U UNIX like OS (FreeBSD, Linux)

Berkeley Boot Loader (BBL)

- Firmware/bootloader
- Operates in M-mode
- Provides access to console, timers, IPI
- All traps switch mode to M
  - However we can delegate some traps directly to S-mode using mtdeleg instruction

Start of work

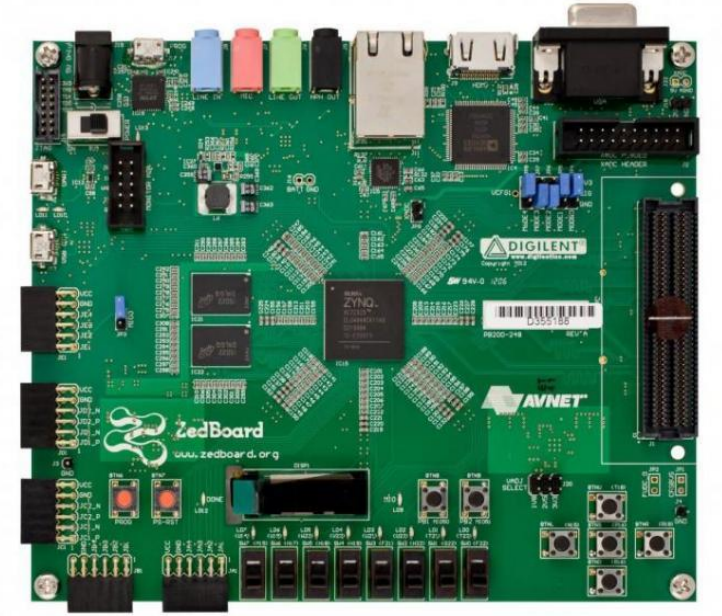
- Toolchain:
  - GNU toolchain (GCC, binutils, as, ...)
  - LLVM (no support yet)

Template

```
$ cp –R sys/arm64 sys/riscv
$ do {
$     vi sys/riscv/...
$     make TARGET_ARCH=riscv64
$ } while ($?)
```

Prepare hardware

- Emulators:
  - Spike
  - QEMU
- FPGA
- root disk



Porting: early assembly code

- _start in locore.S
- Put machine into known state
- Build initial page tables
- Enable MMU and branch to virtual addressing
- Setup stack pointer
- Jump to C-code

Porting: kernel (1)

- Console
- Atomics
  - atomic_add(), atomic_readandclear(), …
- Initialize physmap table
- PMAP implementation

PMAP

- 40 functions to implement:
  - pmap_enter()
  - pmap_extract()
  - pmap_remove()
  - pmap_invalidate()
  - pmap_protect()
  - pmap_activate()
  - pmap_unwire()
  - …

Porting: kernel (2)

- Exceptions
- cpu_switch()
- fork_trampoline()
- Kernel VA <-> user VA copy functions
  - copyin
  - copyout
  - …

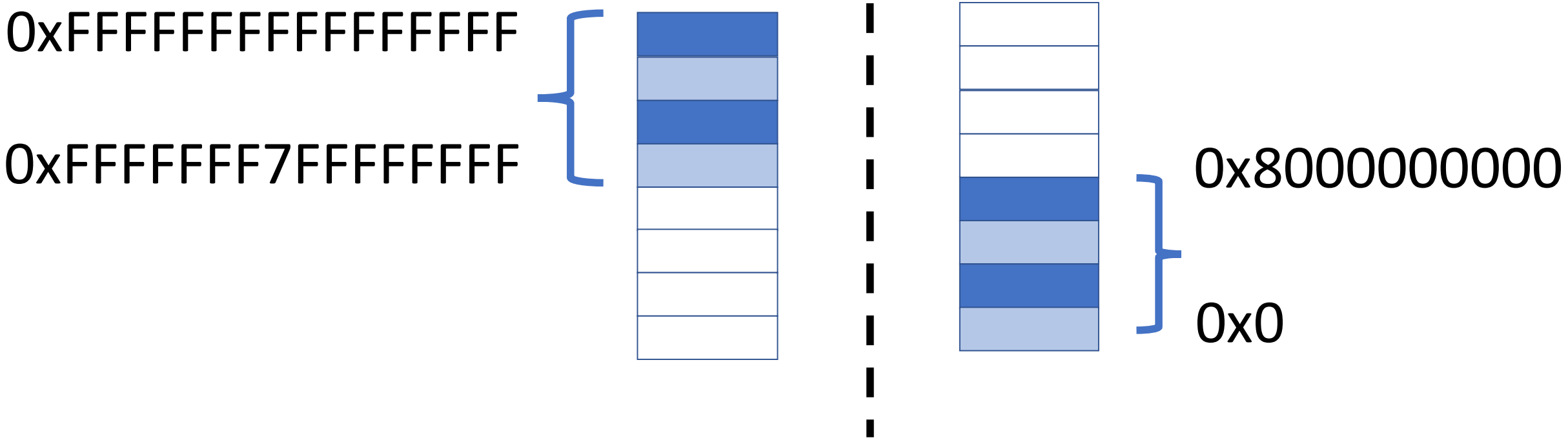
Porting: kernel (3)

- Timer driver
- Interrupt controller driver
- Disk driver
- Done

Challenge #1: page table base

Kernel page directory

User page directory

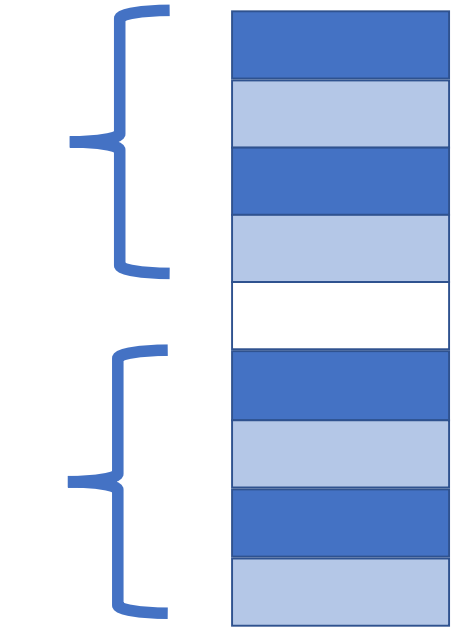


Challenge #1: page table base (cont'd)

User page directory

Kernel PT entries

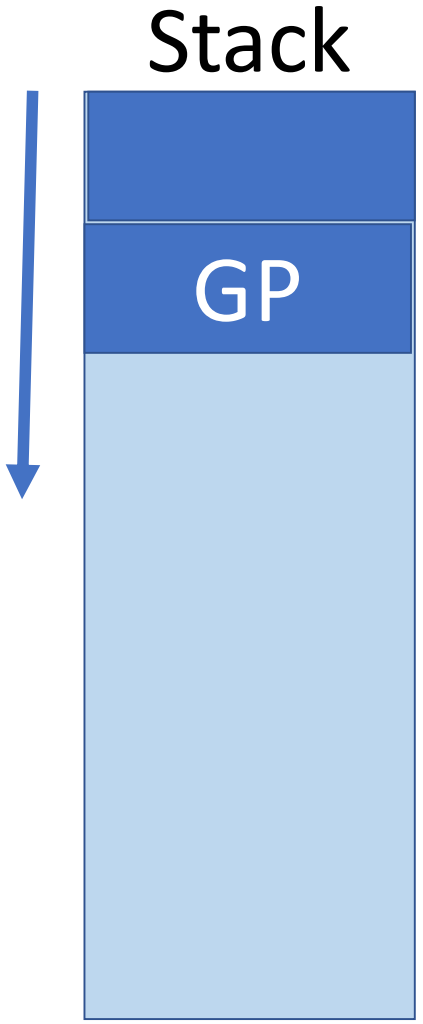
User PT entries



Challenge #2: single TP register

- PCPU pointer

- Solution:
  - Store GP to supervisor stack
  - Reload GP on return from user thread



Porting: userspace (1)

- jemalloc
- csu
  - crt1.S, crtN.S, crti.S
- libc
  - syscalls
  - setjmp, longjmp, _set_tp
- msun

Porting: userspace (2)

- Compile world
- Try to run /bin/sh
- rtld (run-time linker)

Porting: finalize

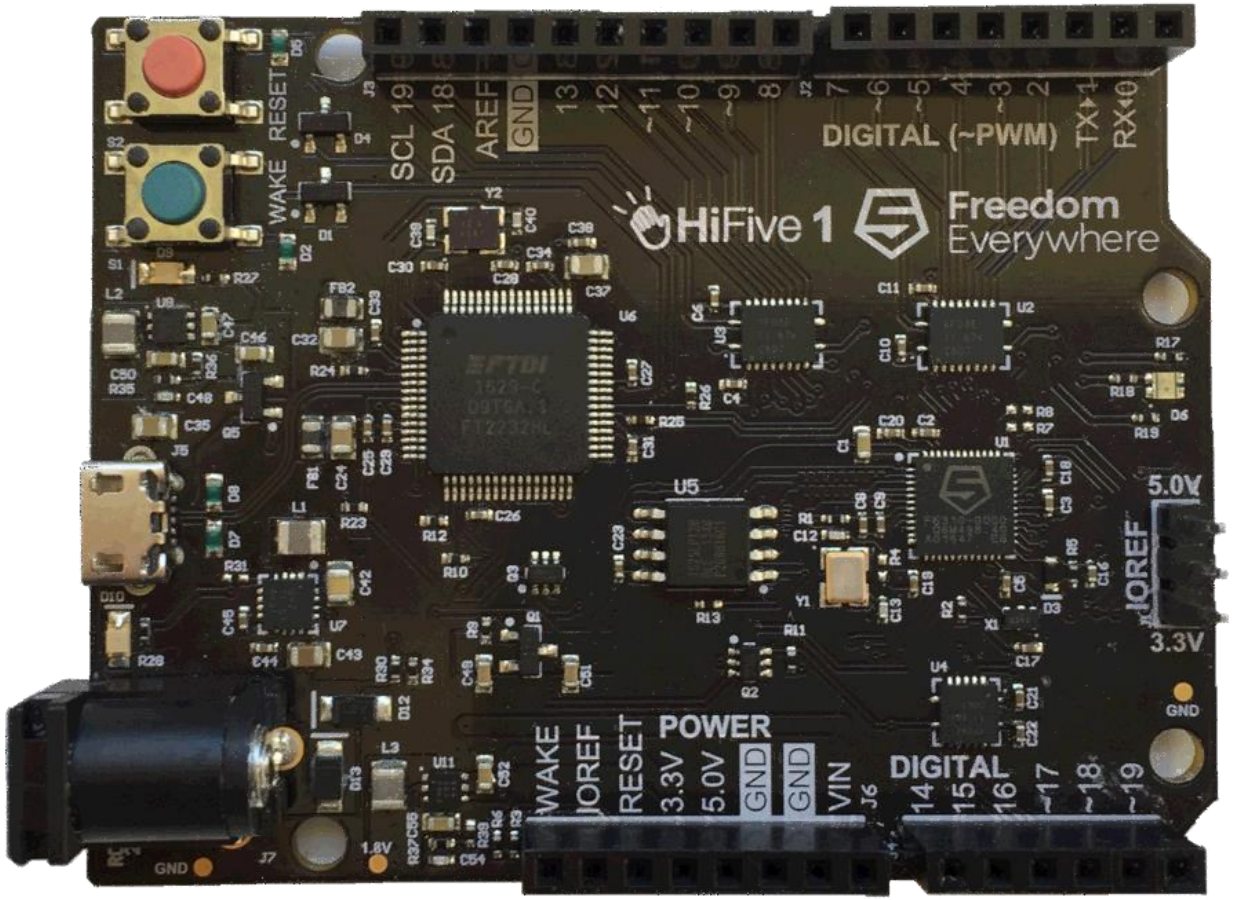
- Most challenging parts:
  - pmap in kernel
  - Run-time linker in userspace
- 6 months from scratch
- 25k lines diff (200 new files)
- Thanks to people involved: Arun Thomas, Andrew Turner, Robert Watson, Ed Maste, David Chisnall, Yukishige Shibata (Sony Japan), Li-Wen Hsu

Status update

- v1.10 of Privilege Specification
- HiFive1 board release
- FreeBSD board is planned on Quarter 1 2018
- GCC 7 target upstream
- NVIDIA is to ship all of their GPUs with RISC-V processor
- Next RISC-V workshop November 2017 in San Jose

SiFive HiFive1

- TSMC 180nm
- 320+ MHZ
- 16kb SRAM
- 16kb I-cache
- Chisel, open source
- Board available $59



VC707

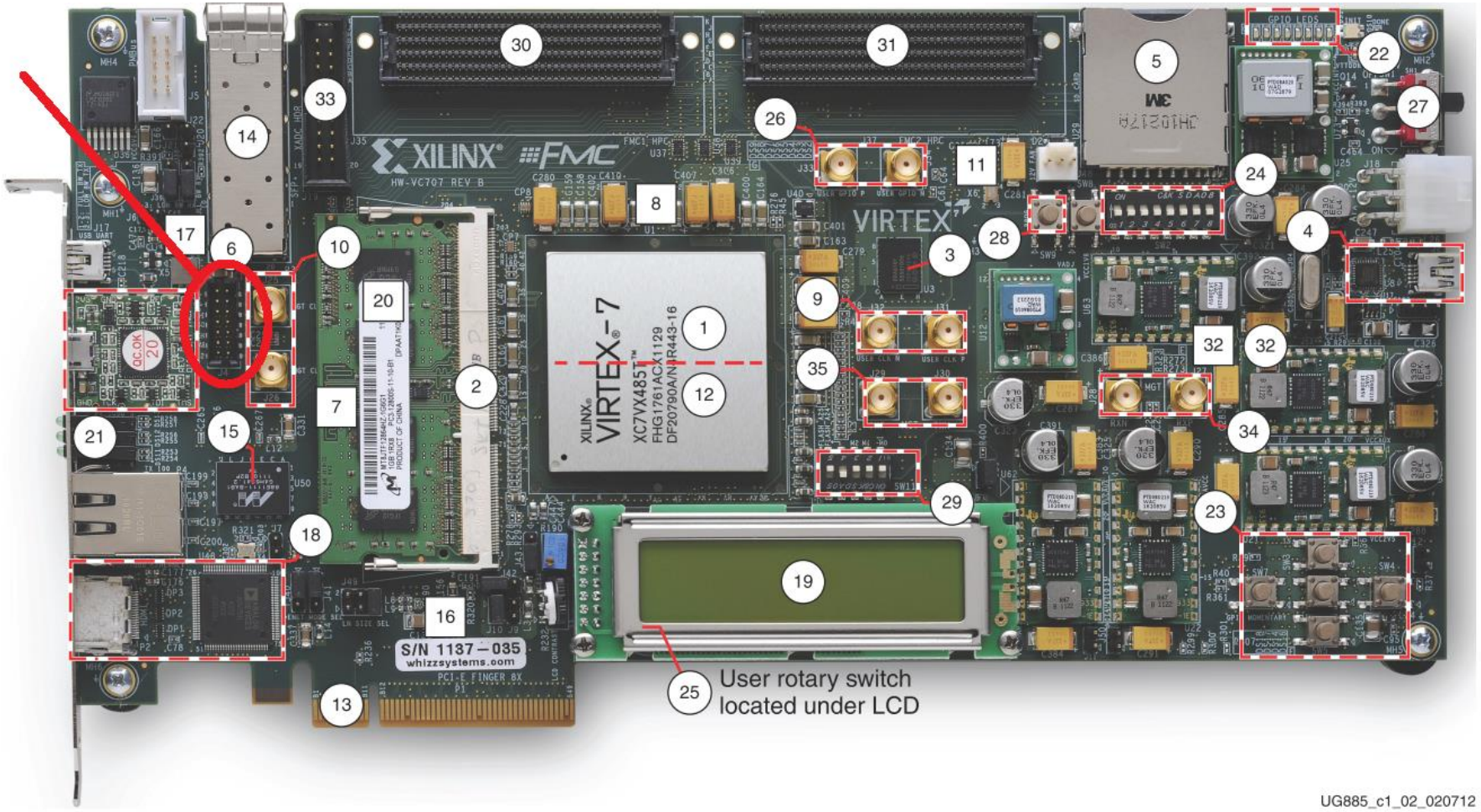


Figure 1-2: **VC707 Board Component Locations**

Privileged Architecture v1.10: changes

- Not compatible on S-mode with v1.9
  - Next versions “should” be compatible with v1.10 on S-mode
- Changes:
  - Built-in macros and compiler arguments changed
  - SBI interface, VM changes, BBL changes
  - Physical Memory Protection (PMP) Unit introduced
  - Support for FDT

Compiler arguments changed

-mno-float, -msoft-float removed

-march=rv64imafdc -mabi=lp64

“a” – atomic
“m” – multiplication
“fd” – double precision floating point unit
“c” – compressed

Compiler built-in defines

- __riscv__, __riscv64 removed!

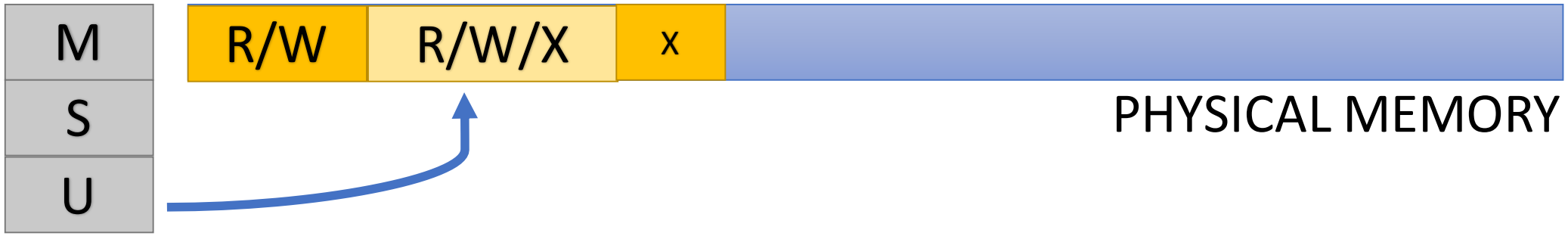
__riscv
__riscv_compressed
__riscv_atomic
__riscv_mul
__riscv_div
__riscv_muldiv
__riscv_fdiv
__riscv_fsqrt

__riscv_float_abi_soft
__riscv_float_abi_single
__riscv_float_abi_double
__riscv_cmodel_medlow
__riscv_cmodel_medany
__riscv_cmodel_pic
__riscv_xlen == 64

SBI interface changed

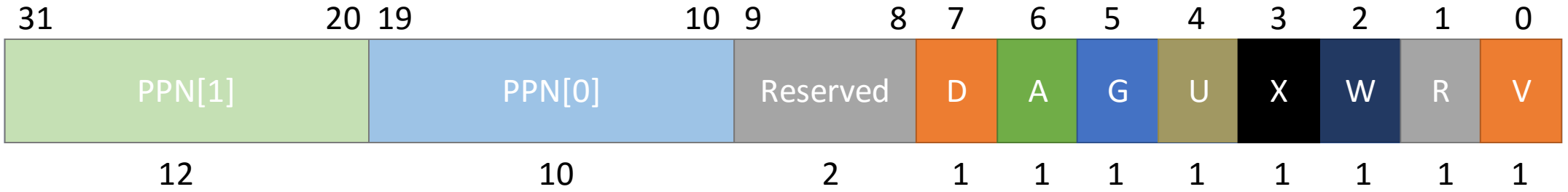
- Old way: pre-defined function address in physical memory
- New way: ecall to upper (machine) privileged level
- Required for:
  - Timer
  - Console
  - IPI
  - Shutdown
  - Hart ID

PMP unit



- R/W/X on 4-byte granularity, 16 regions
- Composable with MMU
- Can be locked on M-mode
- When enabled, modes below M have no memory permissions

Virtual Memory changes

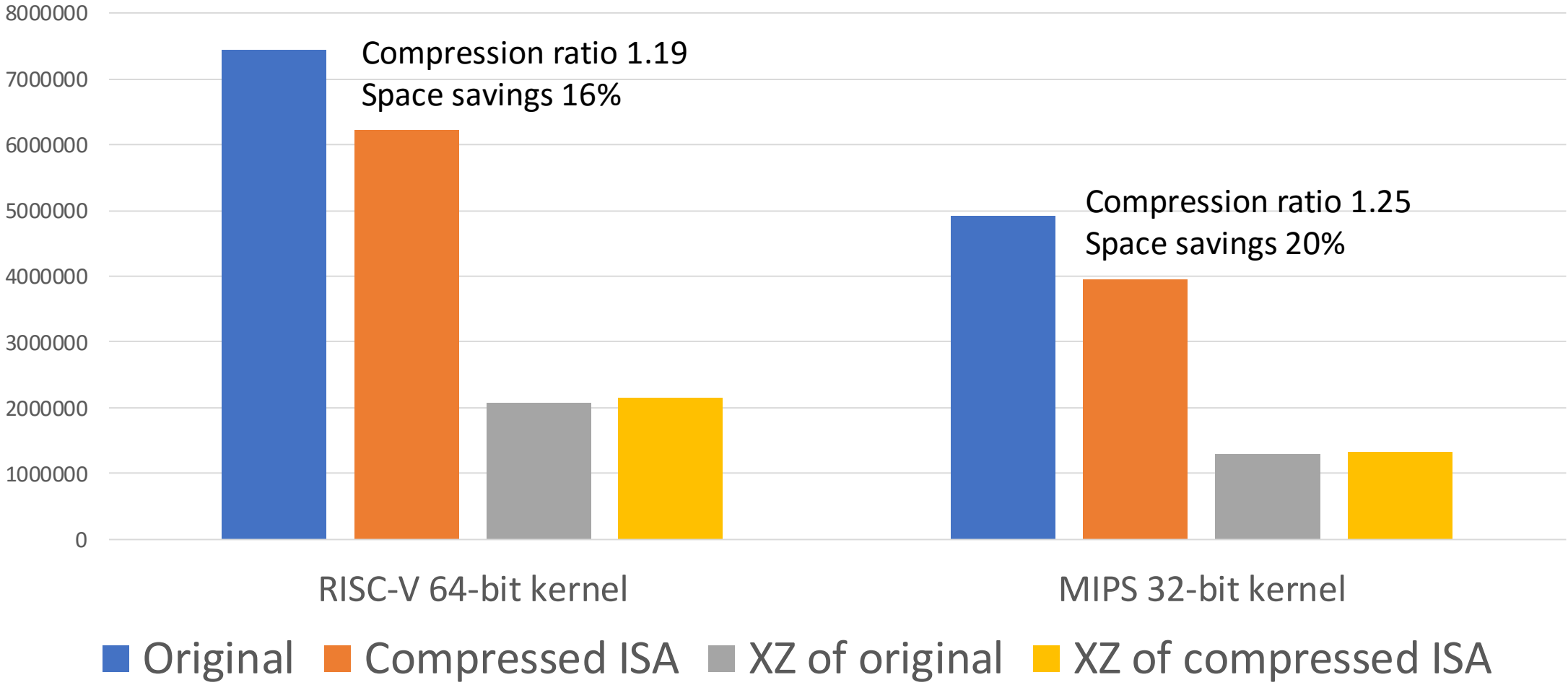


- VM turn on/off using satp register
- Supervisor can't access user pages by default
  - Syscalls: set SUM bit in sstatus register
- R, W, X controlled separately
  - Support for X-only pages
  - Combination W & ~R reserved

“C”- Compressed Extension

- Saves space for low-end deeply embedded
- Saves cache footprint for high-end workload
- Compresses some instructions to 2 bytes
- Declared 25-30% smaller code with extension turned on

“C”- Compressed Extension (continued)



Compressed extension assembly

```
/home/br/obj/riscv.riscv64/usr/home/br/dev/freebsd-riscv/sys/GENERIC/kernel:     file format e


Disassembly of section .text:

ffffffc000200000 <_start>:
ffffffc000200000:       000402b7                lui     t0,0x40
ffffffc000200004:       1002a073                csrs    sstatus,t0
ffffffc000200008:       8d2a                    mv      s10,a0
ffffffc00020000a:       8dae                    mv      s11,a1
ffffffc00020000c:       000d0463                beqz    s10,ffffffc000200014 <_start+0x14>
ffffffc000200010:       1b00406f                j       ffffffc0002041c0 <mpentry>
ffffffc000200014:       00461497                auipc   s1,0x461
ffffffc000200018:       fec48493                addi    s1,s1,-20 # ffffffc000661000 <pagetab
ffffffc00020001c:       00462917                auipc   s2,0x462
ffffffc000200020:       fe490913                addi    s2,s2,-28 # ffffffc000662000 <pagetab
ffffffc000200024:       00c95913                srli    s2,s2,0xc
ffffffc000200028:       fff0079b                addiw   a5,zero,-1
ffffffc00020002c:       02679793                slli    a5,a5,0x26
ffffffc000200030:       83f9                    srli    a5,a5,0x1e
ffffffc000200032:       1ff7f793                andi    a5,a5,511
ffffffc000200036:       4e85                    li      t4,1
ffffffc000200038:       00a91f13                slli    t5,s2,0xa
ffffffc00020003c:       01eeefb3                or      t6,t4,t5
ffffffc000200040:       4821                    li      a6,8
ffffffc000200042:       030787bb                mulw    a5,a5,a6
ffffffc000200046:       00f482b3                add     t0,s1,a5
ffffffc00020004a:       01f2b023                sd      t6,0(t0) # 40000 <kernbase-0xffffffbf
ffffffc00020004e:       00462497                auipc   s1,0x462
ffffffc000200052:       fb248493                addi    s1,s1,-78 # ffffffc000662000 <pagetab
:
```

FDT support

- GENERIC kernel
- timer/console moved from OFW bus to nexus bus

./spike -dump-dts

./spike -m2048 -p8 /path/to/bbl

Hardware support for v1.10 privilege spec

Implementation	Status
Spike	Fully supported
RocketChip	Unknown
lowRISC	Unknown
QEMU	Unknown
Gem5	Unknown
Real hardware	N/A

Future plans

- ASIC chips and boards
- LLVM support
- Ports and packages
  - QEMU user (syscall emulation) mode
- bhyve support ?

Device driver

- How to attach
- Resources
  - How to access
  - Where to request

Device driver frameworks

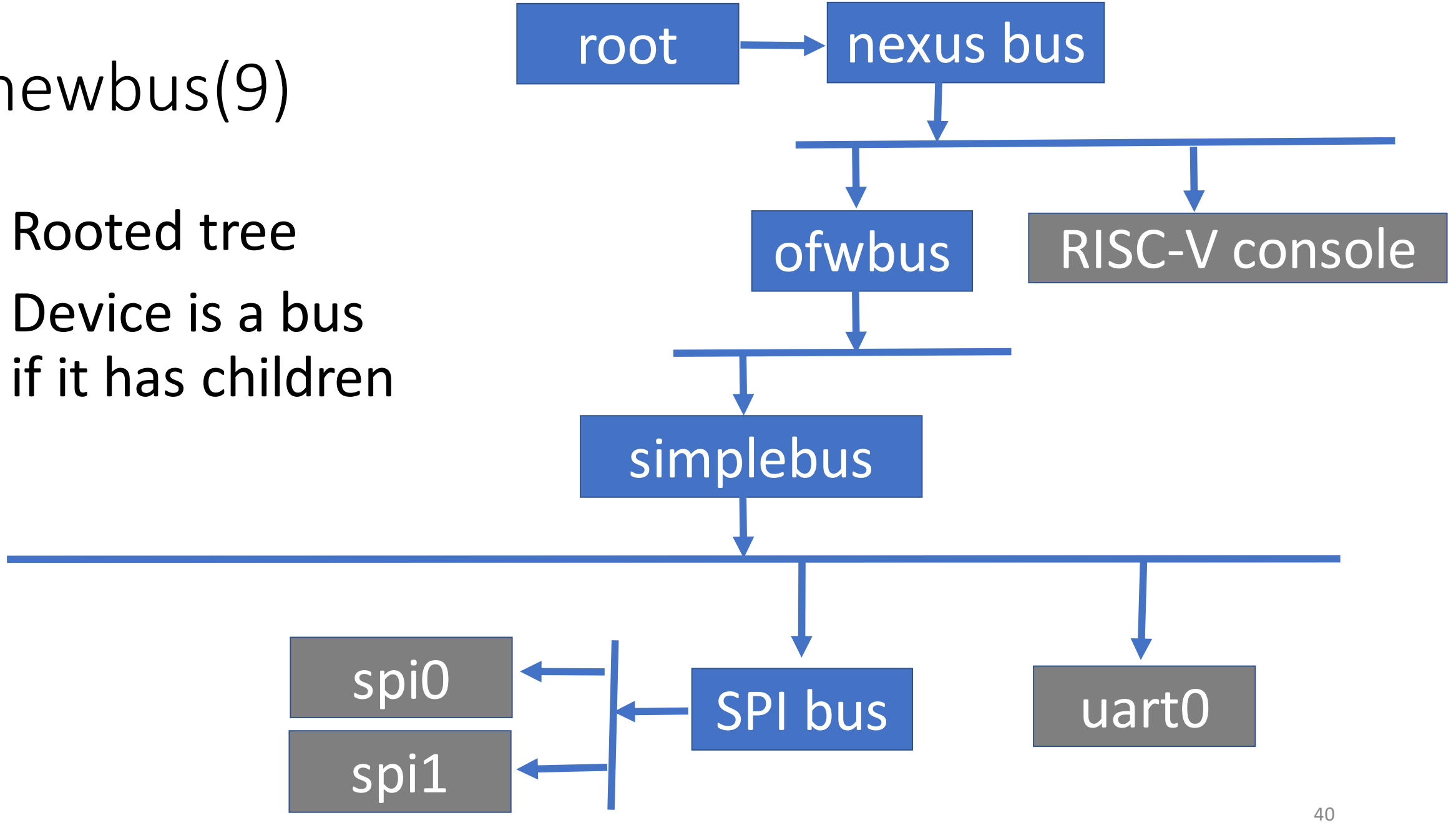
- kld
- newbus(9)
- rman(9)
- cdevsw
- ofw and FDT
- bus_space
- bus_dma
- sysctl
- SYSINIT

SYSINIT

```
static int
test_handler(module_t mod, int what, void *arg)
{
	switch (what) {
	case MOD_LOAD:
	case MOD_UNLOAD:
	}
}
DECLARE_MODULE(test, SI_SUB_VM, ...)
```

newbus(9)

- Rooted tree
- Device is a bus
  if it has children



newbus(9) methods

```
static device_method_t test_methods[] = {
        DEVMETHOD(device_probe,         test_probe),
        DEVMETHOD(device_attach,        test_attach),
}

DRIVER_MODULE(test, simplebus, test_methods, ...)
```

Resources

- Device tree source (DTS)

- bus_alloc_resources(dev, …)
- bus_setup_intr(dev, intr_func, …)

cdevsw

- open(2)
- read(2)
- ioctl(2)
- mmap(2)
- poll(2)

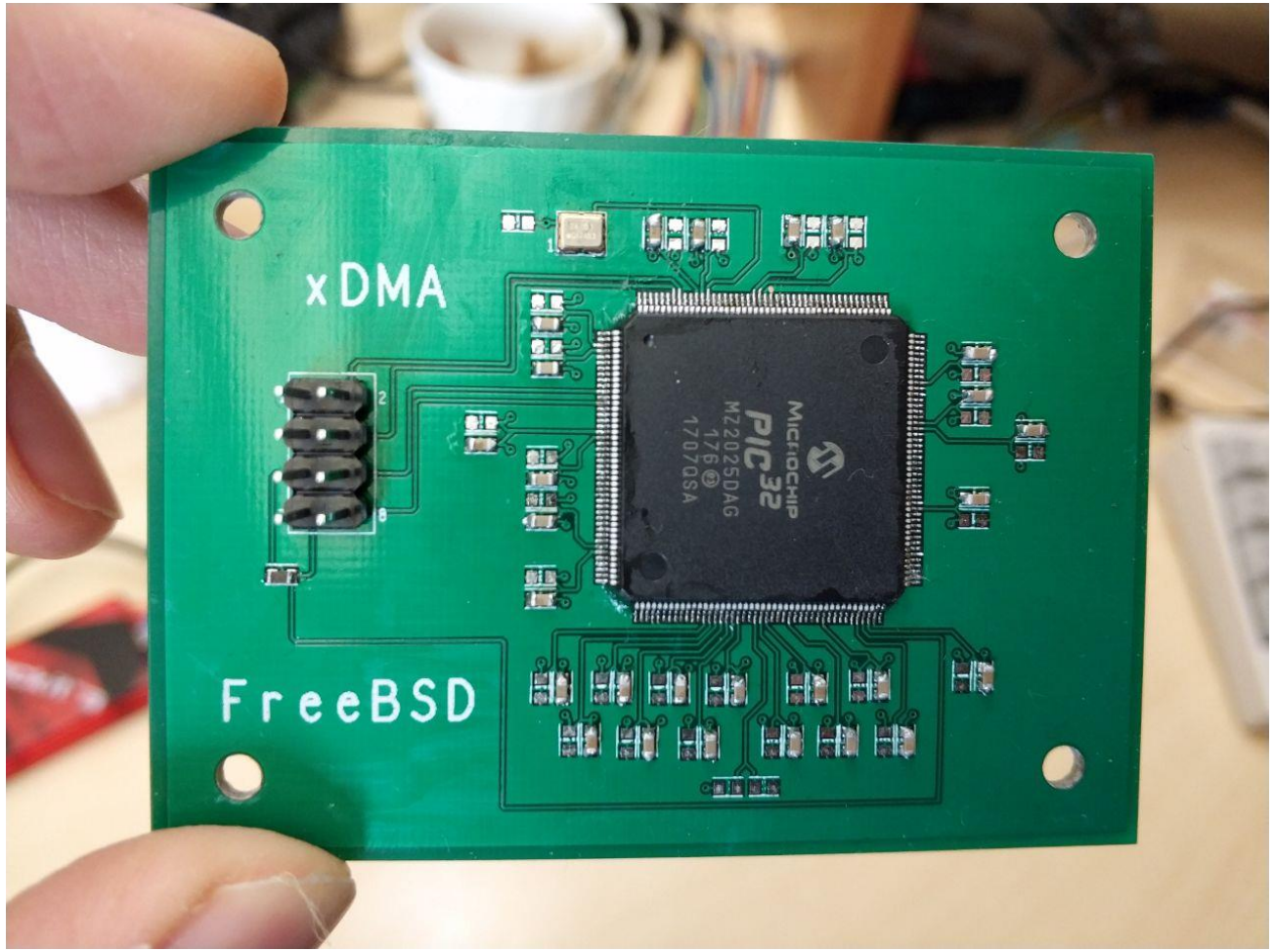
```
fd = open("/dev/test", ...)
vaddr = mmap(fd, ...)
```

Frameworks / subsystems

- SPI bus
- I2C bus
- xdma(9)
- Ifnet(9)
- callout(9)
- pci
- sound(9)
- Wi-Fi stack
- vt(4)
- taskqueue(9)

FreeBSD/MIPS board

- 27 capacitors
- 1 resistor
- 1 pin header
- 1 crystal oscillator
- 1 MIPS CPU



Questions ?

Project home:

http://wiki.freebsd.org/riscv