RISC-V ARCHITECTURE TRAINING

@DEMO: Bare-metal assembly & SPIKE simulator

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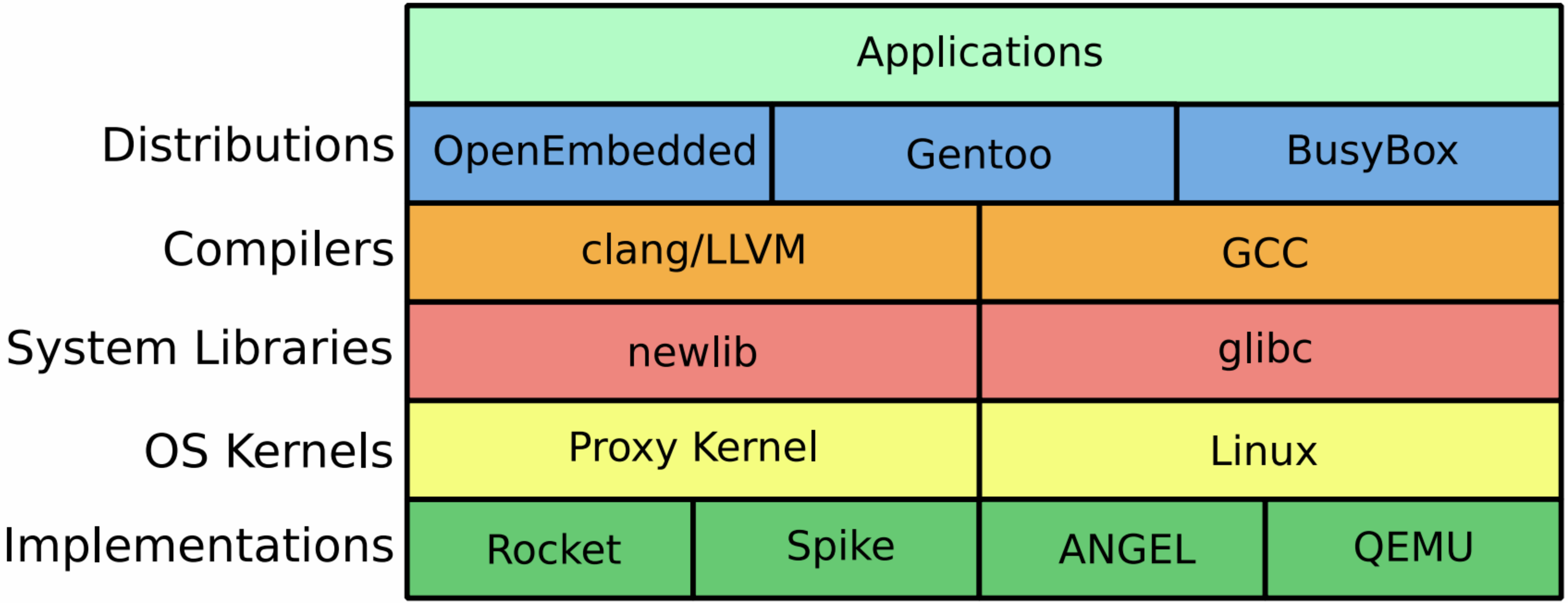
General software stack



Applications

Distributions: OpenEmbedded, Gentoo, BusyBox

Compilers: clang/LLVM, GCC

System Libraries: newlib, glibc

OS Kernels: Proxy Kernel, Linux

Implementations: Rocket, Spike, ANGEL, QEMU

Embedded system software stack

What is newlib?

https://en.wikipedia.org/wiki/Newlib

- C standard library implementation for **embedded system**
- GCC port for non-Linux embedded system
- When lacking of full-blown OS, how to **make a system call** and how to **use devices**

> Newlib code size will signaficant larger than Linux code size, because it includes the system calls that is already embedded inside Linux.

What is cross-compile?

Cross-compiler

- A compiler capable of creating executable code for a platform other than the one on which the compiler is running
- In our case: RISC-V compiler running on top of x86

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Setup GNU toolchain for RISC-V

2 options

1. Build from scratch
2. Download pre-built version from SiFive (or other vendors)

> Here we choose option 1, because it's more useful in the future. You probably need to choose your own instruction subsets.

Setup GNU toolchain for RISC-V (cont'd)

1. Download source

- Community version GNU toolchain on Github: https://github.com/riscv/riscv-gnu-toolchain
    - riscv-gcc
    - riscv-gdb
    - riscv-glibc
    - riscv-binutil
    - riscv-newlib
    - riscv-dejagnu

```
git clone https://github.com/riscv/riscv-gnu-toolchain --recursive
```

2. Install prerequisites

Ubuntu 16.04

```
sudo apt-get install -y autoconf automake autotools-dev curl libmpc-dev libmpfr-dev libgmp-dev gawk build-e
sudo apt-get install -y build-essential zlib1g-dev pkg-config libglib2.0-dev binutils-dev libboost-all-dev 
sudo apt-get install -y autoconf automake autotools-dev curl libmpc-dev libmpfr-dev libgmp-dev libusb-1.0-0
```

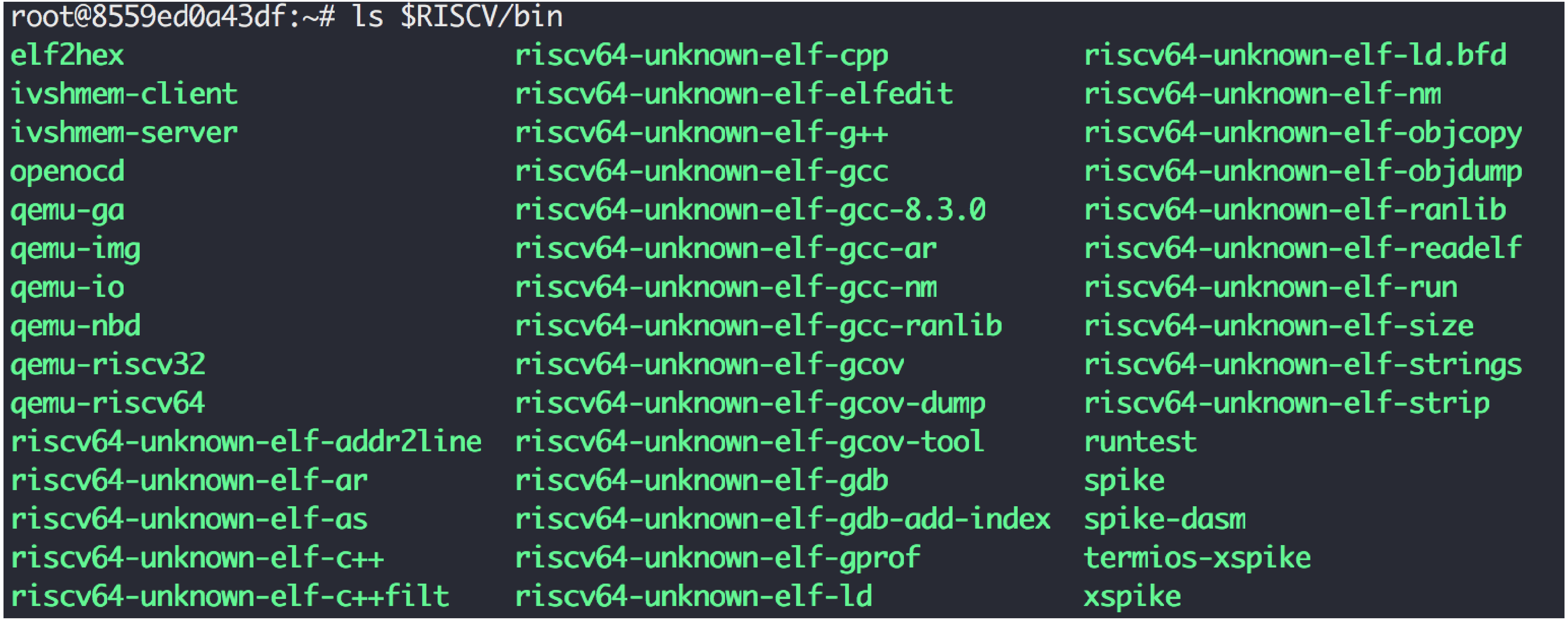
Setup GNU toolchain for RISC-V (cont'd)

3. Compile & install

```
git clone --recursive https://github.com/riscv/riscv-gnu-toolchain
    # this will take a long time to download

cd riscv-gnu-toolchain; mkdir build; cd build

../configure --prefix=/opt/riscv --with-arch=rv64gc --with-abi=ilp64d
    # --with-arch=rv64gc defines target architecture is rv64gc (64-bit IMACFD extentions support)
    # option example: rv64imac (64-bit IMAC extenstions support)
    # --with-abi=ilp64d defines target ABI (applicaiton binary interface)
    # "d" means hard-float
    # option example: ilp64 (64-bit soft float)

make newlib -j4 # compile & install
make report-newlib # run DejaGnu test suite (super slow)
```

Setup GNU toolchain for RISC-V (cont'd)

Toolchain directory content



```
root@8559ed0a43df:~# ls $RISCV/bin
elf2hex                        riscv64-unknown-elf-cpp            riscv64-unknown-elf-ld.bfd
ivshmem-client                 riscv64-unknown-elf-elfedit        riscv64-unknown-elf-nm
ivshmem-server                 riscv64-unknown-elf-g++            riscv64-unknown-elf-objcopy
openocd                        riscv64-unknown-elf-gcc            riscv64-unknown-elf-objdump
qemu-ga                        riscv64-unknown-elf-gcc-8.3.0      riscv64-unknown-elf-ranlib
qemu-img                       riscv64-unknown-elf-gcc-ar         riscv64-unknown-elf-readelf
qemu-io                        riscv64-unknown-elf-gcc-nm         riscv64-unknown-elf-run
qemu-nbd                       riscv64-unknown-elf-gcc-ranlib     riscv64-unknown-elf-size
qemu-riscv32                   riscv64-unknown-elf-gcov           riscv64-unknown-elf-strings
qemu-riscv64                   riscv64-unknown-elf-gcov-dump      riscv64-unknown-elf-strip
riscv64-unknown-elf-addr2line  riscv64-unknown-elf-gcov-tool      runtest
riscv64-unknown-elf-ar         riscv64-unknown-elf-gdb            spike
riscv64-unknown-elf-as         riscv64-unknown-elf-gdb-add-index  spike-dasm
riscv64-unknown-elf-c++        riscv64-unknown-elf-gprof          termios-xspike
riscv64-unknown-elf-c++filt    riscv64-unknown-elf-ld             xspike
```

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Assembly / programmer's handbook

Please refer to handouts: ***RISC-V Reference Card***

Register	ABI Name	Saver	Description
x0	zero		Hard-wired zero
x1	ra	Caller	Return address
x2	sp	**Callee**	Stack pointer
x3	gp		Global pointer
x4	tp		Thread pointer
x5-7 & x28-31	t0-6	Caller	Temporaries
x8-9 & x18-27	s0-11	**Callee**	Saved registers
x10-17	a0-7	Caller	Function arguments / return value

Separation of saved registers and temporary registers makes it possible to reduce 32 registers to 16 registers in E extension

Assembly / what is ABI?

ABI (application binary interface) includes:

- Instruction set
- Calling convention
  - Function's argument passing and return value retrieving
    - Stack vs. registers
    - If stack, which parameter is pushed first?
    - If register, which registers are used for what?
- How to make system calls to operating system
  - More details in our next DEMO

Assembly / `ra` return address

- `ecall`: `ra <= PC + 4`
- `ret`: jump back to `ra` (`PC <= ra`)

Assembly / `sp` stack pointer

When goes into function call, save registers to stack

```
00000000000114da <_realloc_r>:
    114da:      715d                 addi    sp,sp,-80     # reserve 80-byte space on stack
    114dc:      f84a                 sd      s2,48(sp)     # push s2
    114de:      e486                 sd      ra,72(sp)     # push ra
    114e0:      e0a2                 sd      s0,64(sp)     # push s0
    114e2:      fc26                 sd      s1,56(sp)     # push s1
    114e4:      f44e                 sd      s3,40(sp)     # push s3
...                                                        # push s4 ~ s7
    114ee:      e062                 sd      s8,0(sp)      # push s8
...                                                        # function
    115e0:      60a6                 ld      ra,72(sp)     # pop ra
    115e2:      6406                 ld      s0,64(sp)     # pop s0
    115e4:      854a                 mv      a0,s2
    115e6:      74e2                 ld      s1,56(sp)     # pop s1
...                                                        # pop s2 ~ s7
    115f4:      6c02                 ld      s8,0(sp)      # pop s8
    115f6:      6161                 addi    sp,sp,80      # release 80-byte space on stack
    115f8:      8082                 ret                   # return
```

Assembly / gp global pointer

`gp` = global pointer = pointer to global variables

- GP is pointing at the center of `.data` section that allows program to index to any global variables easily without the need to `auipc` every time

Example: C program uses global variables

```c
/* Global Variables: */
Boolean         Bool_Glob;
char            Ch_1_Glob,
                Ch_2_Glob;
Proc_4 () /* without parameters */ {
  Boolean Bool_Loc;
  Bool_Loc = Ch_1_Glob == 'A';
  Bool_Glob = Bool_Loc | Bool_Glob;
  Ch_2_Glob = 'B';
} /* Proc_4 */
```

Assembly / gp global pointer (cont'd)

ASM disabled GP

```
0000000040400826 <Proc_4>:
    40400826:   3fc00797                auipc   a5,0x3fc00
    4040082a:   f777c783                lbu     a5,-137(a5) # 8000079d <Ch_1_Glob>
    4040082e:   3fc00717                auipc   a4,0x3fc00
    40400832:   f7272703                lw      a4,-142(a4) # 800007a0 <Bool_Glob>
    40400836:   fbf78793                addi    a5,a5,-65
    4040083a:   0017b793                seqz    a5,a5
    4040083e:   8fd9                    or      a5,a5,a4
    40400840:   3fc00717                auipc   a4,0x3fc00
    40400844:   f6f72023                sw      a5,-160(a4) # 800007a0 <Bool_Glob>
    40400848:   3fc00797                auipc   a5,0x3fc00
    4040084c:   04200713                li      a4,66
    40400850:   f4e78a23                sb      a4,-172(a5) # 8000079c <Ch_2_Glob>
    40400854:   8082                    ret
```

Assembly / gp global pointer (cont'd)

ASM enabled GP (cont'd)

```
00000000400003f0 <Proc_4>:
    400003f0:   8651c783                lbu     a5,-1947(gp) # 80001fbd <Ch_1_Glob>
    400003f4:   8681a703                lw      a4,-1944(gp) # 80001fc0 <Bool_Glob>
    400003f8:   fbf78793                addi    a5,a5,-65
    400003fc:   0017b793                seqz    a5,a5
    40000400:   00e7e7b3                or      a5,a5,a4
    40000404:   86f1a423                sw      a5,-1944(gp) # 80001fc0 <Bool_Glob>
    40000408:   04200713                li      a4,66
    4000040c:   86e18223                sb      a4,-1948(gp) # 80001fbc <Ch_2_Glob>
    40000410:   00008067                ret
```

Assembly / `tp` thread pointer

`tp` (thread pointer) is a pointer to thread-level global variables (aka thread-local storage)

Assembly / code example

@DEMO

- Directory `~/riscv-training/lab/21-lab.compile`
    - Source code `example-asm.s` and `example-c.s`

Function of `example-asm.s`

- 4x4 Matrix multiplication, and result checking against Excel
- Use 2-level function calls to do the job
    - Demostrate calling convention by passing argument and return value via registers `a*`
    - Save registers `s*` to stack before using them

Compare with `example-c.c` with the same functionality

- Assembly code is much harder to write and debug for normal functionality
- Assembly code's binary size is smaller (6624 bytes vs. 6000 bytes)

Assembly / what is linker script?

- Describe how the sections in the input files should be mapped into the outpufile
- Control the memory layout of the output file

Entry point

- The first instruction to execute in the problem

Common section

- `.text`: actual machine instructions
- `.data`: static data in your code
- `.bss`: uninitialized global or static variables, will be initialized to zero during startup
    - `.noinit`: part of bss but will not be initialized to zero

Assembly / compile assembly

Compile -> link -> objdump

```
# assemble
${RISCV}/bin/riscv64-unknown-elf-as example-asm.s -o example-asm.o
# link
${RISCV}/bin/riscv64-unknown-elf-ld -T linker-asm.ld example-asm.o -o example-asm.elf
# object dump
${RISCV}/bin/riscv64-unknown-elf-objdump -D example-asm.elf > example-asm.elf.dump
```

Linker script

```
SECTIONS
{
    . = 0x10000;
    .text : { *(.text) }
    .data : { *(.data) }
}

ENTRY (_start)
```

- Both code and data start from `0x0001_0000`
- `_start` is the entry point label

Assembly / compile C code

Compile bare-metal C program

```
# compile
${RISCV}/bin/riscv64-unknown-elf-gcc example-c.c -o example-c.elf
# object dump
${RISCV}/bin/riscv64-unknown-elf-objdump -D example-c.elf > example-c.elf.dump
```

Assembly / ASM vs. C

Development effort

Myself

- 2 hours in ASM
- 2 mins in C

Size of the code

With `printf`

```
riscv@riscv:~/riscv-training/lab/21-lab.compile$ ll *.elf
-rwxr-xr-x 1 1380539737 1876110778   6000 Dec  7 17:07 example-asm.elf*
-rwxr-xr-x 1 1380539737 1876110778 138792 Dec  7 17:18 example-c.elf*
```

Without `printf` and turn on `-Os`: 107.2%

```
-rwxr-xr-x 1 1380539737 1876110778 6000 Dec  7 17:30 example-asm.elf*
-rwxr-xr-x 1 1380539737 1876110778 6432 Dec  7 17:30 example-c.elf*
```

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# SPIKE

- SPIKE: official ISS (instruction set simulator) of RISC-V
  - GDB-like TUI (text-based user interface)
  - Support single step execution / breakpoint / watchpoint
  - XSPIKE: open a separate terminal (in GUI mode) to capture the `printf` output

How to invoke SPIKE

```
# run SPIKE in direct mode
> ${RISCV}/bin/spike target.elf

# run SPIKE in interactive debug mode: -d
> ${RISCV}/bin/spike -d target.elf

# run SPIKE with log dumping: -l
> ${RISCV}/bin/spike -l target.elf 2>&1 | less
```

SPIKE (cont'd)

SPIKE interactive debug mode

- `: pc 0`: show current PC in core 0
- `: reg 0 a0`: show content of register `a0` in core 0
- `: mem 2020`: show content of memory at `0x2020`
- `: until pc 0 80000000`: stop when PC hits `0x8000_0000`

More commands type `help` under interactive debug mode

> Note: don't forget the "0" for core 0

SPIKE (cont'd)

@DEMO

- Run SPIKE in direct mode
- Run SPIKE in interactive debug mode
  - Show register/memory content
  - Set breakpoint
- Run SPIKE with log dumping

Next session: LAB

@LAB: factorial in assembly

Use assembly to implement factorial function

```
n! = n * (n-1) * (n-2) * ... * 2 * 1
```