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NOMMU Linux on RISC-V for platform bring-up and evaluation

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Call: Open source for cloud-based services, GA Nr: 101092993 (HaDEA)

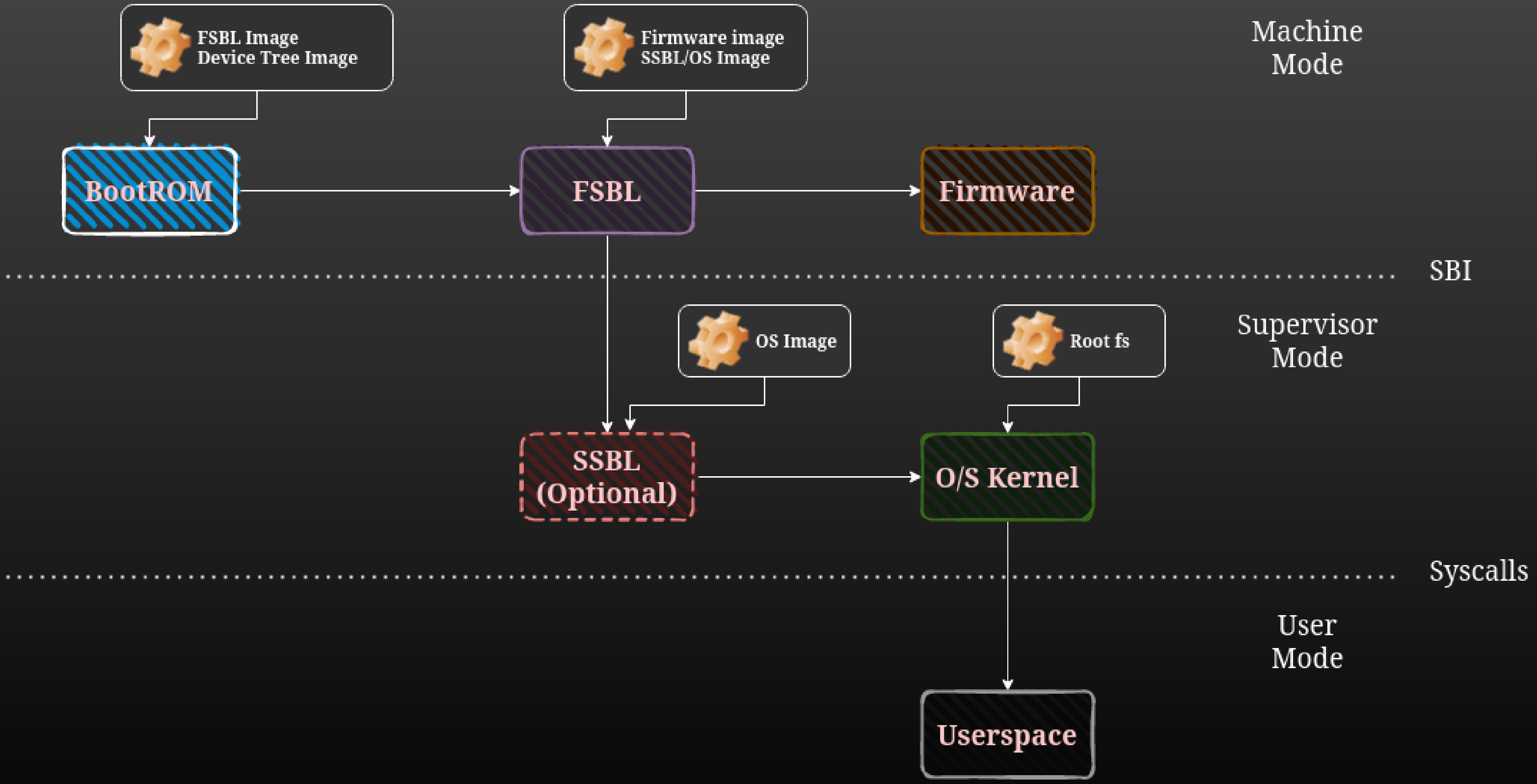
SoC: Design, Integration, Verification

- Design of individual CPU functional units
  - ALU, FPU, VPU, MMU, …
- Verification of individual functional units
  - e.g. directed/random tests, in a simulator
- Verification of the whole core
  - e.g. RISC-V ACT suite, checks against the SAIL model/reference simulator
- Post-synthesis co-simulation tests
- Integration with other IPs
  - Each IP with its own set of pre/post-synthesis tests

RISC-V SoC bring-up

- More advanced bare-metal tests for verification of the core
  - e.g. parts of the RISC-V spec not covered by ACT, custom extensions
- Progressively more complex bare-metal platform-level tests
  - e.g. interrupt delivery/delegation, communication between peripherals, peripheral operation
- Memory subsystem tests
  - e.g. litmus, cache-coherency with peripherals, IOMMU
- Security-related tests
  - e.g. constant-time requirements, TRNG operation, MTT, xPMP
- Stress testing/profiling/benchmarking

The way to full Linux boot

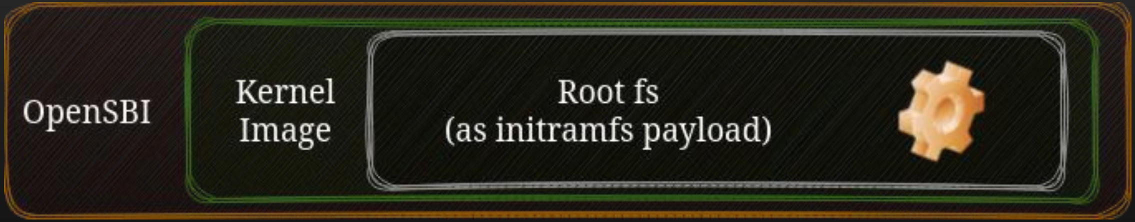


Step-by-step expansion of coverage

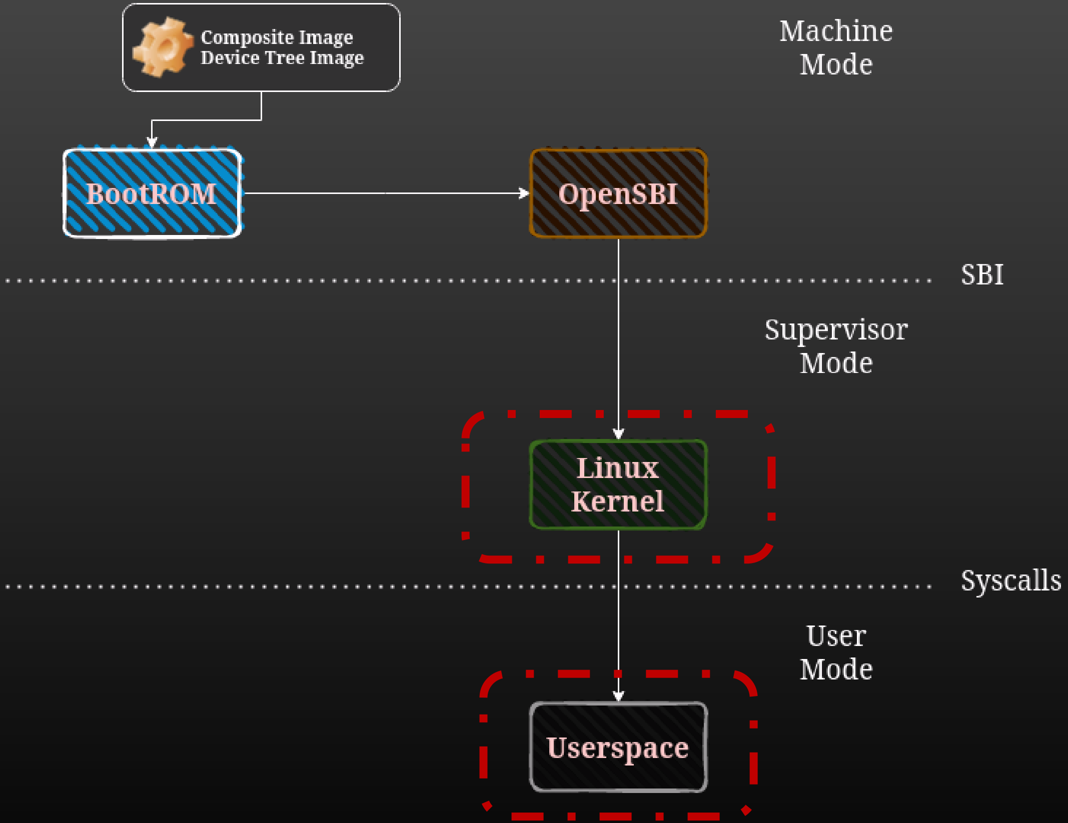
- Booting a full-blown Linux distro. greatly expands test coverage … and complexity
- Tracking down HW bugs in such a setup is a nightmare!
- We need a strategy to progressively expand test coverage

Simplifying the Linux boot process

- Use OpenSBI, a firmware implementation that also acts as FSBL
  - Get rid of SSBL and jump to Linux kernel directly
- Reduce number of external images
  - Kernel image as an OpenSBI payload
  - Root FS included as initramfs in the kernel image



Simplifying the Linux boot process



Simplifying the Linux kernel

- Start with a bare minimum kernel configuration
  - No networking, no storage, NOMMU
  - Limited functionality, single user
- Move on to more complex kernel configurations
  - With networking, storage, multiple users, …
- Finally, a full-blown kernel configuration
  - With systemd support and everything needed to boot a fully-featured Linux distro.

Simplifying userspace

- Start with a single process (busybox), statically linked
- Add more tools and networking support
  - e.g. iperf, ssh
- Use an off-the-shelf rootFS of a full-blown Linux distro.
  - e.g. Ubuntu

Why NOMMU Linux

- MMU is a common source of HW bugs in our experience
  - Microarchitectural bugs that are hard to reproduce in simple tests we previously did
  - Especially when we go multicore
- Why not go for a simple RTOS ? (e.g. FreeRTOS, Zephyr)
  - Using standard tools (e.g. busybox, iperf) would be harder (different syscall API)
  - Building the image would be more complicated (need to go through an SDK)
  - Usually support only M-mode/U-mode setups
  - Would be harder to compare behavior between MMU/NOMMU

NOMMU Linux basics

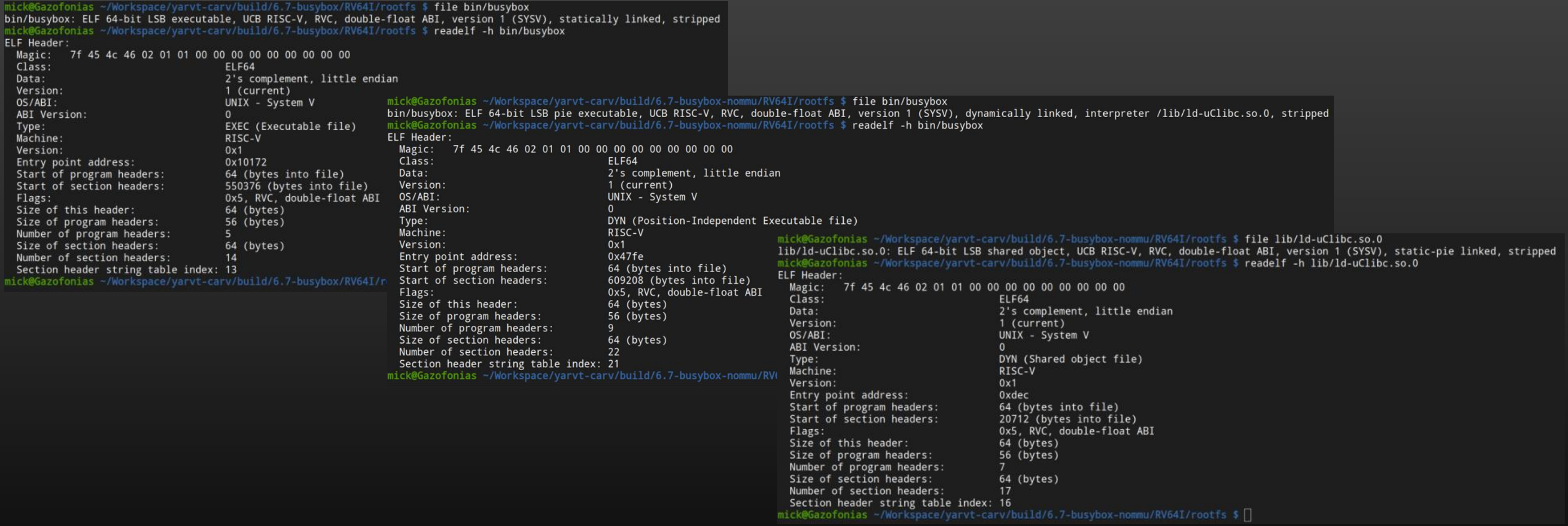
Part of mainline Linux kernel

- Different memory allocators: mm/nommu.c
- Limitations on mmap: Documentation/nommu-mmap.txt
  - No memory protection
  - No fork() support
    - fork() relies on COW, but vfork() is supported
  - No overcommit / lazy binding
  - No swap
  - No dynamic heap/stack
    - avoid using alloca(), brk(), sbrk(), use malloc()/free() instead
  - No MAP_SHARED on files
    - in general MAP_SHARED functionality is limited
  - No MAP_FIXED
  - Limitations on MAP_PRIVATE
    - no COW/paging
  - Excessive fragmentation, avoid large mappings

NOMMU Linux basics

- When MMU is available, the BINFMT_ELF loader is used to load executables / shared libraries.
- Without MMU, alternative loaders/binary formats are used
  - BINMFT_FLAT
    - Stripped down ELF (through elf2flt)
    - No dynamic loading (libld)
    - No shared libraries
    - Limitations on executable’s size
  - BINFMT_ELF_FDPIC
    - Position Independent (PIC/PIE) ELF, no ET_EXEC support
    - Support for shared libraries through function descriptors (FD)
    - Support for dynamic loading (libld)
    - May also be used when MMU is enabled
- Alternative toolchains also required
  - based on µClibc or musl

NOMMU Linux basics



```
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox/RV64I/rootfs $ file bin/busybox
bin/busybox: ELF 64-bit LSB executable, UCB RISC-V, RVC, double-float ABI, version 1 (SYSV), statically linked, stripped
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox/RV64I/rootfs $ readelf -h bin/busybox
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           RISC-V
  Version:                           0x1
  Entry point address:               0x10172
  Start of program headers:          64 (bytes into file)
  Start of section headers:          550376 (bytes into file)
  Flags:                             0x5, RVC, double-float ABI
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         5
  Size of section headers:           64 (bytes)
  Number of section headers:         14
  Section header string table index: 13
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox/RV64I/r
```

```
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV64I/rootfs $ file bin/busybox
bin/busybox: ELF 64-bit LSB pie executable, UCB RISC-V, RVC, double-float ABI, version 1 (SYSV), dynamically linked, interpreter /lib/ld-uClibc.so.0, stripped
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV64I/rootfs $ readelf -h bin/busybox
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              DYN (Position-Independent Executable file)
  Machine:                           RISC-V
  Version:                           0x1
  Entry point address:               0x47fe
  Start of program headers:          64 (bytes into file)
  Start of section headers:          609208 (bytes into file)
  Flags:                             0x5, RVC, double-float ABI
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         9
  Size of section headers:           64 (bytes)
  Number of section headers:         22
  Section header string table index: 21
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV
```

```
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV64I/rootfs $ file lib/ld-uClibc.so.0
lib/ld-uClibc.so.0: ELF 64-bit LSB shared object, UCB RISC-V, RVC, double-float ABI, version 1 (SYSV), static-pie linked, stripped
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV64I/rootfs $ readelf -h lib/ld-uClibc.so.0
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              DYN (Shared object file)
  Machine:                           RISC-V
  Version:                           0x1
  Entry point address:               0xdec
  Start of program headers:          64 (bytes into file)
  Start of section headers:          20712 (bytes into file)
  Flags:                             0x5, RVC, double-float ABI
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         7
  Size of section headers:           64 (bytes)
  Number of section headers:         17
  Section header string table index: 16
mick@Gazofonias ~/Workspace/yarvt-carv/build/6.7-busybox-nommu/RV64I/rootfs $
```

Currently, RISC-V does not support static PIE.

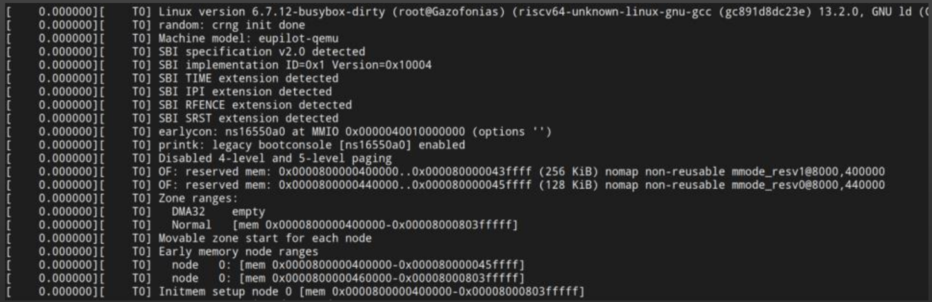
NOMMU Linux on RISC-V (kernel)

- Initial support added on Linux 5.5
  - Only M-mode/U-mode scenario
  - Mainly to support the Kendryte K210 that had a non-compliant MMU
- Almost declared deprecated on Feb. 2024
  - But after community feedback, it remains supported
    - New patches came up, and support keeps getting better
  - Support for running NOMMU Linux on S-mode has been added
    - Still needs further work though

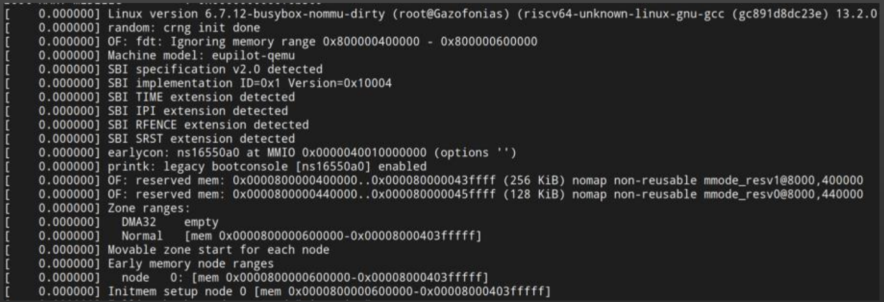
NOMMU Linux on RISC-V (userspace)

- FLAT binaries supported, but won’t work for us
  - Due to custom memory layout in our prototypes
- ELF psABI for FDPIC support is still WiP
  - But we can at least run busybox (64-bit)
- µClibc added support for RISC-V
  - Still no upstream toolchain, or support on crosstool-ng
  - We are working on it:
    - https://github.com/riscv-collab/riscv-gnu-toolchain/pull/1475
    - https://github.com/CARV-ICS-FORTH/riscv-gnu-toolchain/tree/uclibc
  - To replicate our setup with yarvt (Yet Another RISC-V Tool):
  - https://github.com/CARV-ICS-FORTH/yarvt/tree/riser

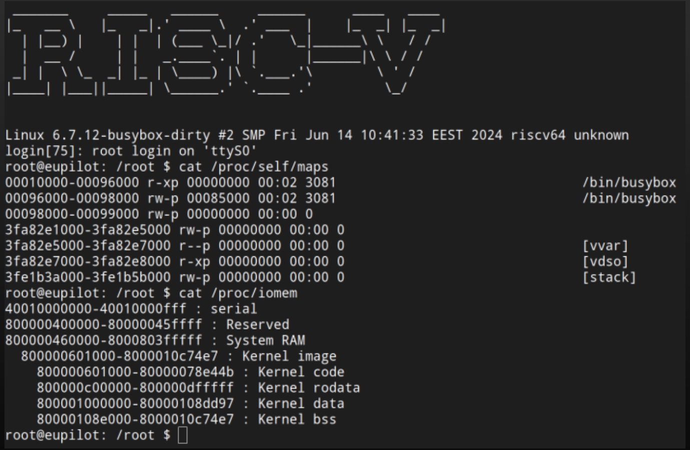
Testing MMU vs NOMMU



```
[    0.000000][    T0] Linux version 6.7.12-busybox-dirty (root@Gazofonias) (riscv64-unknown-linux-gnu-gcc (gc891d8dc23e) 13.2.0, GNU ld ((
[    0.000000][    T0] random: crng init done
[    0.000000][    T0] Machine model: eupilot-qemu
[    0.000000][    T0] SBI specification v2.0 detected
[    0.000000][    T0] SBI implementation ID=0x1 Version=0x10004
[    0.000000][    T0] SBI TIME extension detected
[    0.000000][    T0] SBI IPI extension detected
[    0.000000][    T0] SBI RFENCE extension detected
[    0.000000][    T0] SBI SRST extension detected
[    0.000000][    T0] earlycon: ns16550a0 at MMIO 0x0000040010000000 (options '')
[    0.000000][    T0] printk: legacy bootconsole [ns16550a0] enabled
[    0.000000][    T0] Disabled 4-level and 5-level paging
[    0.000000][    T0] OF: reserved mem: 0x0000800000400000..0x000080000043ffff (256 KiB) nomap non-reusable mmode_resv1@8000,400000
[    0.000000][    T0] OF: reserved mem: 0x0000800000440000..0x000080000045ffff (128 KiB) nomap non-reusable mmode_resv0@8000,440000
[    0.000000][    T0] Zone ranges:
[    0.000000][    T0]   DMA32    empty
[    0.000000][    T0]   Normal   [mem 0x0000800000400000-0x00008000803fffff]
[    0.000000][    T0] Movable zone start for each node
[    0.000000][    T0] Early memory node ranges
[    0.000000][    T0]   node   0: [mem 0x0000800000400000-0x000080000045ffff]
[    0.000000][    T0]   node   0: [mem 0x0000800000460000-0x00008000803fffff]
[    0.000000][    T0] Initmem setup node 0 [mem 0x0000800000400000-0x00008000803fffff]
```



```
[    0.000000] Linux version 6.7.12-busybox-nommu-dirty (root@Gazofonias) (riscv64-unknown-linux-gnu-gcc (gc891d8dc23e) 13.2.0
[    0.000000] random: crng init done
[    0.000000] OF: fdt: Ignoring memory range 0x800000400000 - 0x800000600000
[    0.000000] Machine model: eupilot-qemu
[    0.000000] SBI specification v2.0 detected
[    0.000000] SBI implementation ID=0x1 Version=0x10004
[    0.000000] SBI TIME extension detected
[    0.000000] SBI IPI extension detected
[    0.000000] SBI RFENCE extension detected
[    0.000000] SBI SRST extension detected
[    0.000000] earlycon: ns16550a0 at MMIO 0x0000040010000000 (options '')
[    0.000000] printk: legacy bootconsole [ns16550a0] enabled
[    0.000000] OF: reserved mem: 0x0000800000400000..0x000080000043ffff (256 KiB) nomap non-reusable mmode_resv1@8000,400000
[    0.000000] OF: reserved mem: 0x0000800000440000..0x000080000045ffff (128 KiB) nomap non-reusable mmode_resv0@8000,440000
[    0.000000] Zone ranges:
[    0.000000]   DMA32    empty
[    0.000000]   Normal   [mem 0x0000800000600000-0x00008000403fffff]
[    0.000000] Movable zone start for each node
[    0.000000] Early memory node ranges
[    0.000000]   node   0: [mem 0x0000800000600000-0x00008000403fffff]
[    0.000000] Initmem setup node 0 [mem 0x0000800000600000-0x00008000403fffff]
```



```
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  | |__) |    | |  | (___ \_|/ .'   \_|______ \ \   / /
  |  __ /     | |   _.____`. | |      |______| \ \ / /
 _| |  \ \_  _| |_ | \____) |\ `.___.'\         \ ' /
|____| |___||_____| \______.' `.____ .'          \_/


Linux 6.7.12-busybox-dirty #2 SMP Fri Jun 14 10:41:33 EEST 2024 riscv64 unknown
login[75]: root login on 'ttyS0'
root@eupilot: /root $ cat /proc/self/maps
00010000-00096000 r-xp 00000000 00:02 3081                               /bin/busybox
00096000-00098000 rw-p 00085000 00:02 3081                               /bin/busybox
00098000-00099000 rw-p 00000000 00:00 0
3fa82e1000-3fa82e5000 rw-p 00000000 00:00 0
3fa82e5000-3fa82e7000 r--p 00000000 00:00 0                              [vvar]
3fa82e7000-3fa82e8000 r-xp 00000000 00:00 0                              [vdso]
3fe1b3a000-3fe1b5b000 rw-p 00000000 00:00 0                              [stack]
root@eupilot: /root $ cat /proc/iomem
40010000000-40010000fff : serial
800000400000-80000045ffff : Reserved
800000460000-8000803fffff : System RAM
  800000601000-8000010c74e7 : Kernel image
    800000601000-80000078e44b : Kernel code
    800000c00000-800000dfffff : Kernel rodata
    800001000000-80000108dd97 : Kernel data
    80000108e000-8000010c74e7 : Kernel bss
root@eupilot: /root $ ▯
```

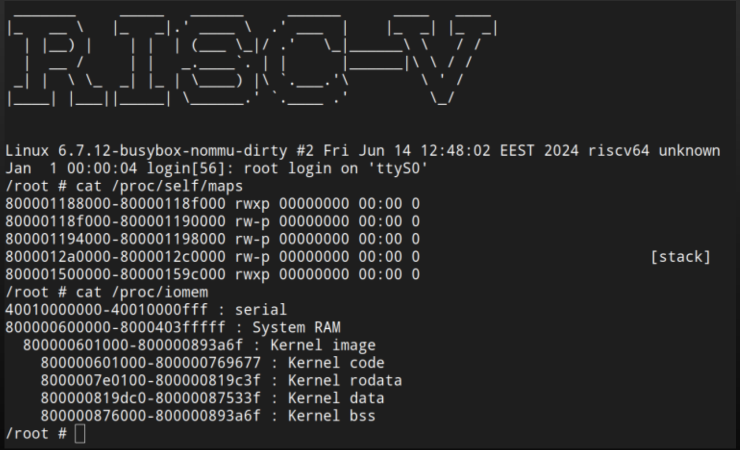

```
 _______     _____   ______     ______       ____   ____
|_   __ \   |_   _|.' ____ \  .' ___  |     |_  _| |_  _|
  | |__) |    | |  | (___ \_|/ .'   \_|______ \ \   / /
  |  __ /     | |   _.____`. | |      |______| \ \ / /
 _| |  \ \_  _| |_ | \____) |\ `.___.'\         \ ' /
|____| |___||_____| \______.' `.____ .'          \_/


Linux 6.7.12-busybox-nommu-dirty #2 Fri Jun 14 12:48:02 EEST 2024 riscv64 unknown
Jan  1 00:00:04 login[56]: root login on 'ttyS0'
/root # cat /proc/self/maps
800001188000-80000118f000 rwxp 00000000 00:00 0
80000118f000-800001190000 rw-p 00000000 00:00 0
800001194000-800001198000 rw-p 00000000 00:00 0
8000012a0000-8000012c0000 rw-p 00000000 00:00 0                              [stack]
800001500000-80000159c000 rwxp 00000000 00:00 0
/root # cat /proc/iomem
40010000000-40010000fff : serial
800000600000-8000403fffff : System RAM
  800000601000-800000893a6f : Kernel image
    800000601000-800000769677 : Kernel code
    8000007e0100-800000819c3f : Kernel rodata
    800000819dc0-80000087533f : Kernel data
    800000876000-800000893a6f : Kernel bss
/root # ▯
```

RISER: RISC-V for cloud services

https://riser-project.eu

Thank you for your attention. Questions and comments ?

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