TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Computer Science Institute for System Architecture, Operating Systems Group

LEGACY REUSE

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THIS LECTURE ...

- **So far ...**
  - Basic microkernel concepts
  - Drivers, resource management
- **Today:**
  - How to provide legacy OS personalities
  - How to reuse existing infrastructure
  - How to make applications happy

- **Virtualization:**
  - Reuse legacy OS + applications
  - Run applications in natural environment
- **Problem:** Applications trapped in VMs
  - Different resource pools, namespaces
  - Cooperation is cumbersome (network, ...)
  - Full legacy OS in VM adds overhead
  - Multiple desktops? Bad user experience

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MAKING THE CUT

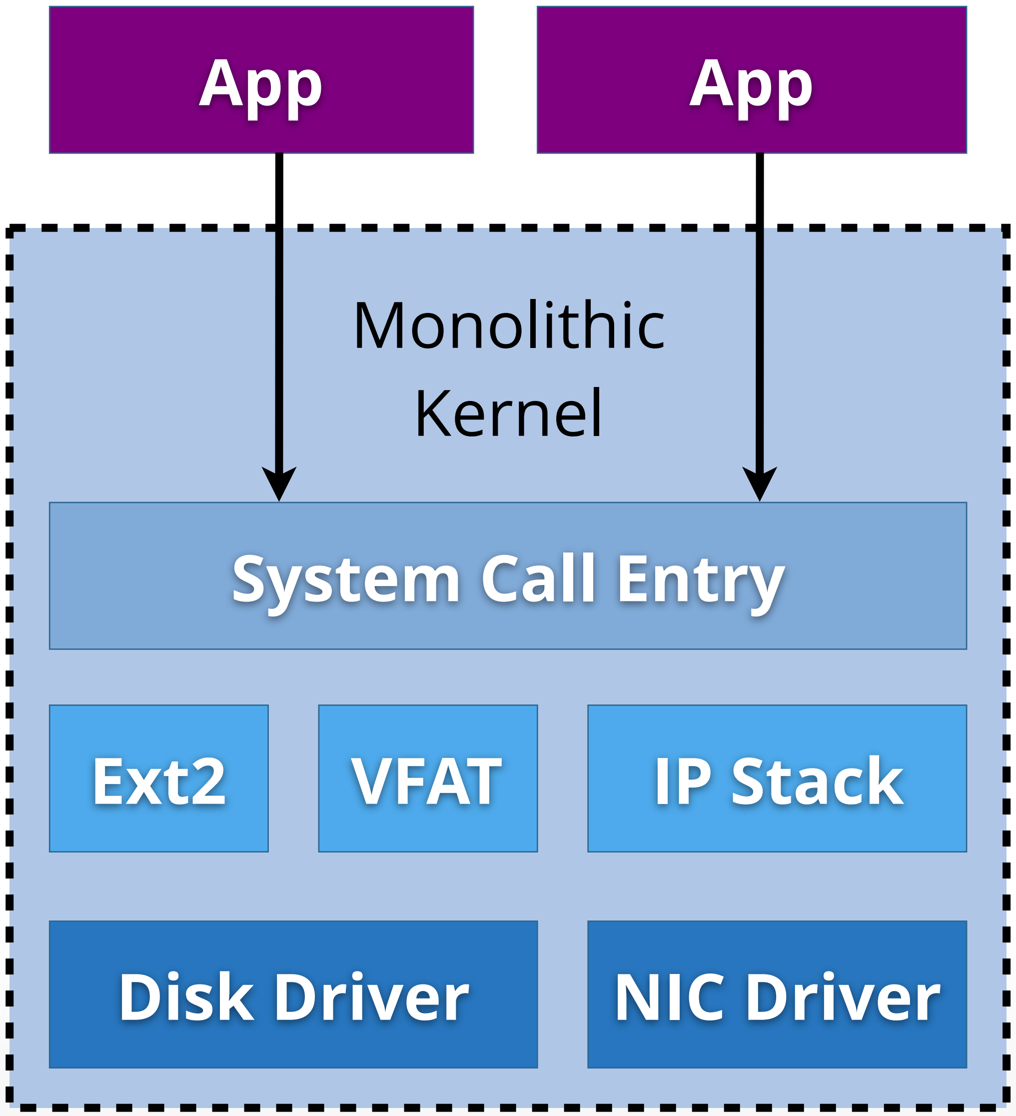
- **Hardware level:** **Next week**
  - Virtualize legacy OS on top of new OS
- **Operating System Personality:**
  - Legacy OS interfaces reimplemented on top of – or ported to – new OS
- **Hybrid operating systems:** **Today**
  - Run legacy OS virtualized …
  - … but tightly integrated with new OS

OPERATING SYSTEM PERSONALITIES

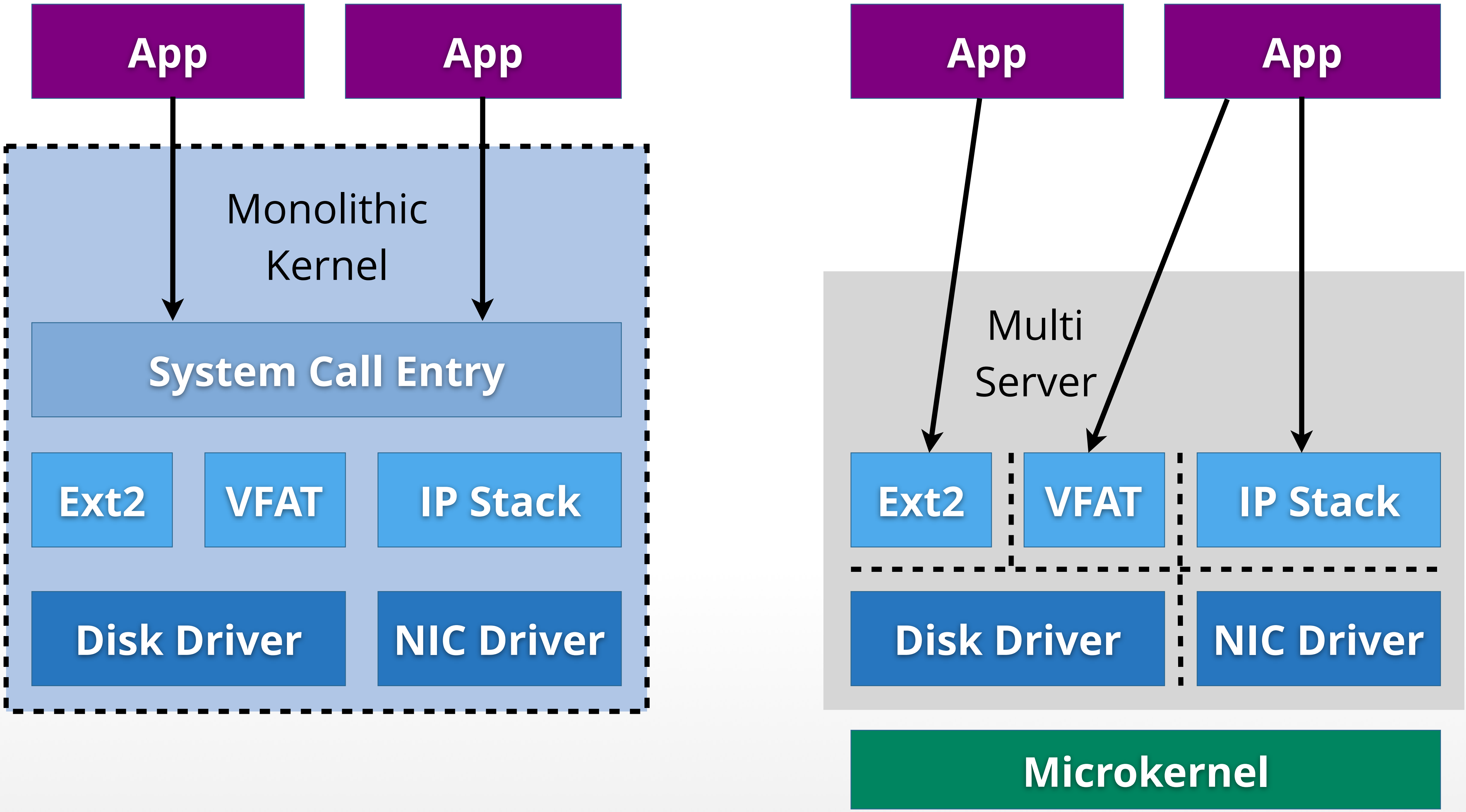
OS PERSONALITY

- **Idea:** Adapt OS / application boundary
  - (Re-)Implement legacy APIs, not whole OS
  - May need to recompile application
- **Benefits:**
  - Get desired application, established APIs
  - Good integration (namespaces, files, ...)
  - Smaller overhead than virtualization
  - Flexible, configurable, but more effort?

MONOLITHIC KERNELS

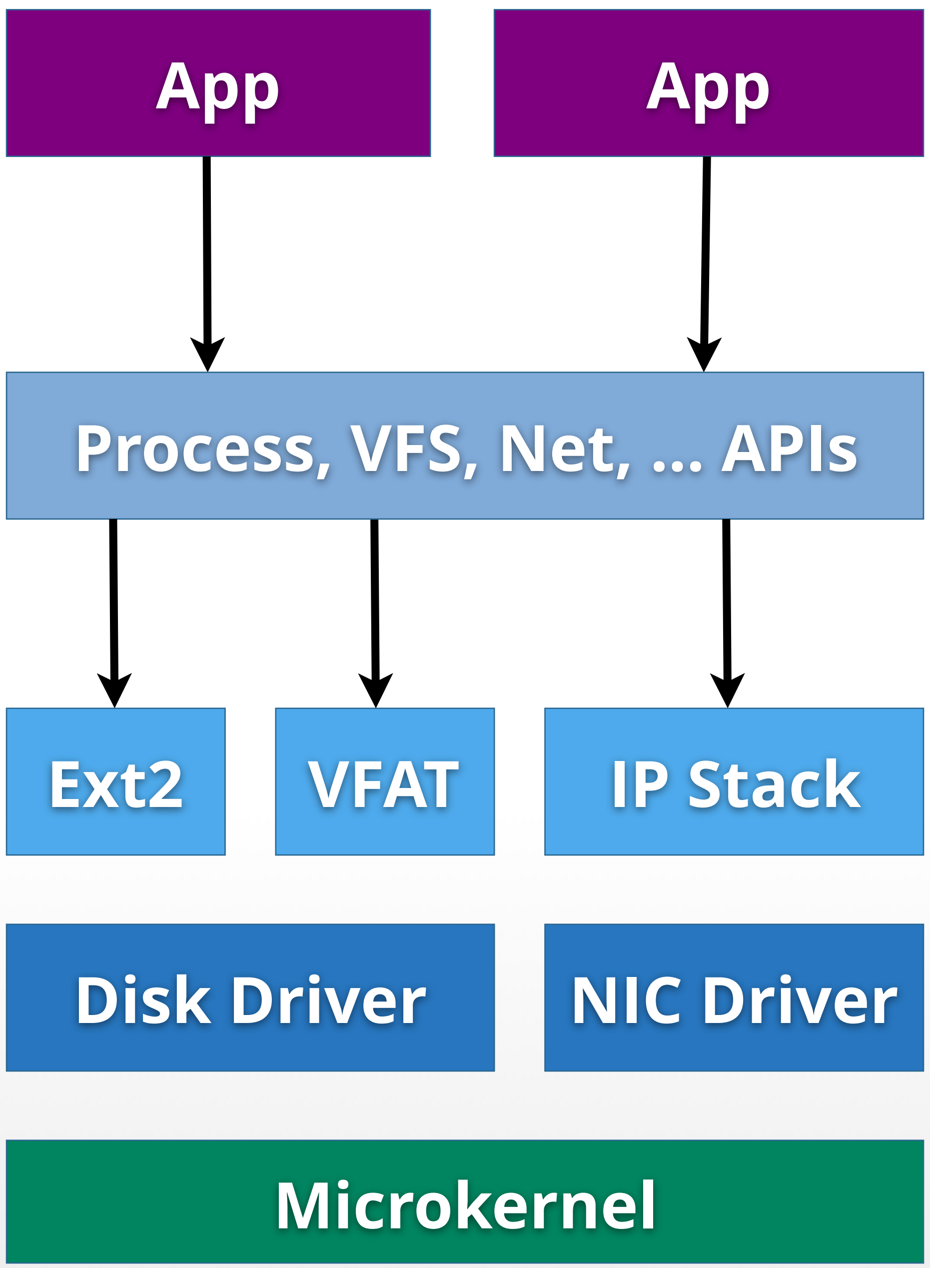


DECOMPOSITION



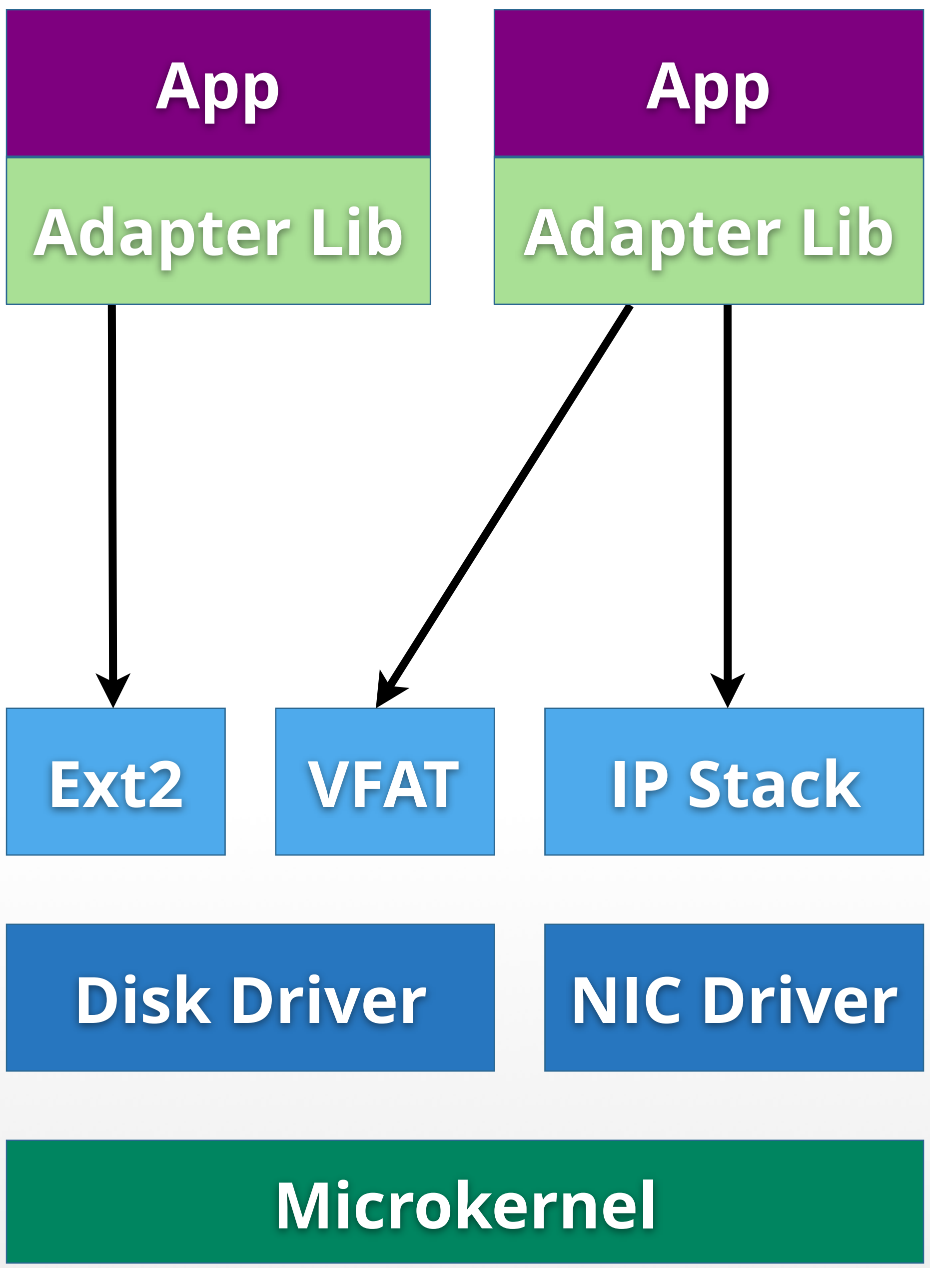
SINGLE ADAPTER

- **Central adapter** provides consistent view for:
  - **Servers:** client state (e.g., file tables)
  - **Applications:** system resources (e.g., files)
- Potential issues:
  - Single point of failure
  - No isolation



ADAPTER LIB

- **Adapter library:**
  - Linked into applications
  - Interacts with servers
  - Provides consistent view (per application)
- Each server keeps its own client state
- <u>No</u> single point of failure



WHAT APPLICATIONS DO (NOT)

- Applications don't talk to OS directly
- C library (libc) abstracts underlying OS
- Collection of common functionality (*)

(*) As defined by POSIX standard

POSIX STANDARD

- „Portable Operating System Interface“ is a family of standards (POSIX 1003.*)
- Ensures source-code compatibility for UNIX variants (also: Windows NT)
- Defines interfaces and properties:
  - I/O: files, sockets, terminal, ...
  - Threads, synchronization: pthreads
  - System tools (not discussed here)

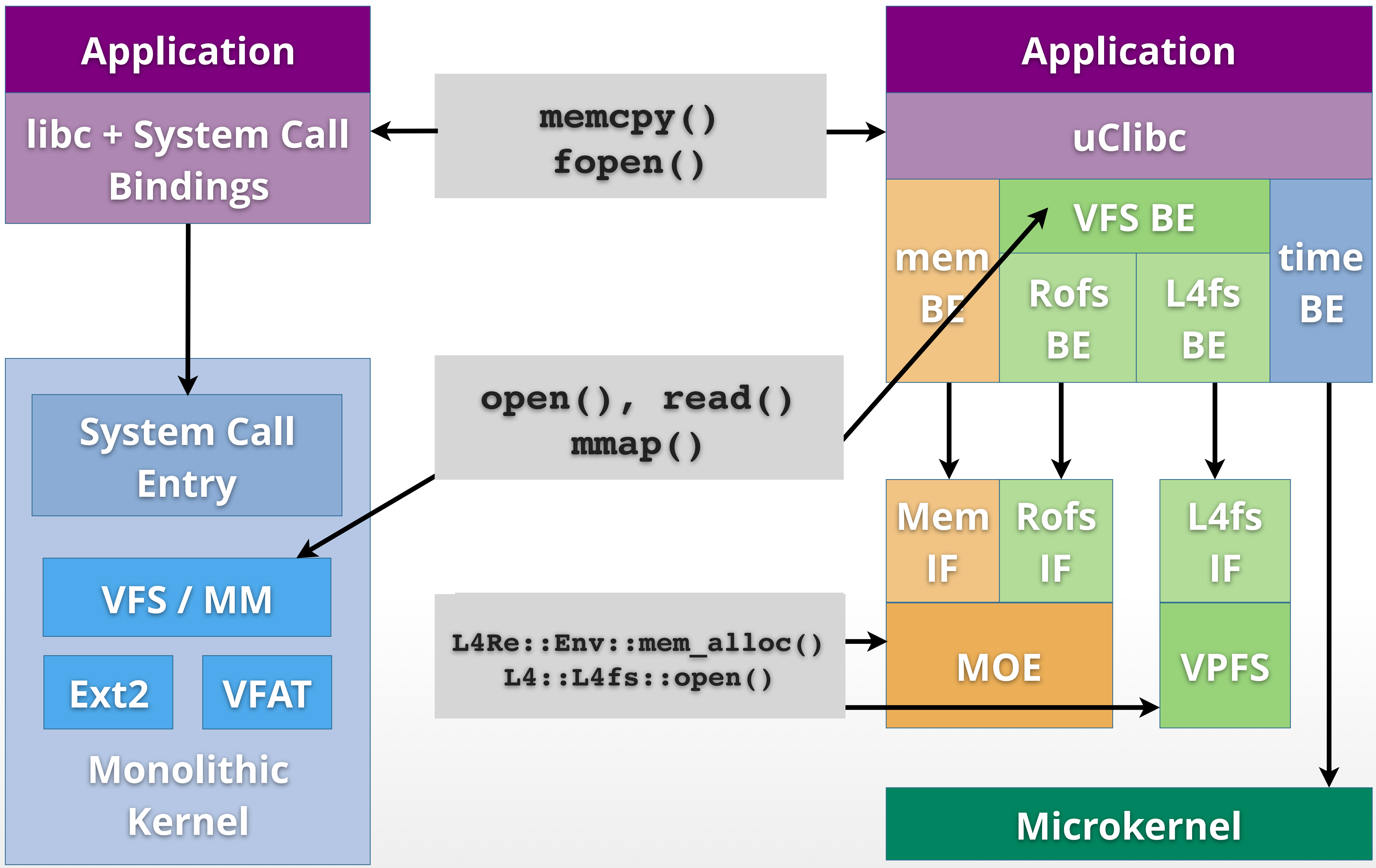
LIBC: POSIX FUNCTIONALITY

- Abstraction level varies:
  - low level: **`memcpy()`**, **`strlen()`**
  - medium level: **`fopen()`**, **`fread()`**
  - high level: **`getpwent()`**
- … and so do dependencies:
  - none (freestanding): **`memcpy()`**, **`strlen()`**
  - small: **`malloc()`** depends on **`mmap()`**
  - strong: **`getpwent()`** needs file access, name service, …

CASE STUDY: LIBC ON L4RE

- libc support on L4Re: **uClibc**
  - Compatible to GNU C library **glibc**
  - Works well with **libstdc++**
  - Small and portable
  - Designed for embedded Linux
- **But:** Fiasco.OC + L4Re != Linux
- How does an **"adapter library"** look like?

MULTI-SERVER LIBC



LIBC BACKENDS

- Four examples:
  - Time
  - Memory
  - Signals
  - I/O

Example 1: POSIX time API

```
uint64_t __libc_l4_rt_clock_offset;

int libc_be_rt_clock_gettime(struct timespec *tp)
{
  uint64_t clock;

  clock = l4re_kip()->clock;
  clock += __libc_l4_rt_clock_offset;

  tp->tv_sec  = clock / 1000000;
  tp->tv_nsec = (clock % 1000000) * 1000;

  return 0;
}
```

L4Re-specific backend function (called by `time()` and other POSIX functions)

Replacment of POSIX **function** `time()`

```
time_t time(time_t *t)
{
  struct timespec a;

  libc_be_rt_clock_gettime(&a);

  if (t)
    *t = a.tv_sec;
  return a.tv_sec;
}
```

LIBC BE: MEMORY

Example 2: memory management

- uClibc implements heap allocator
- Requests memory pages via **`mmap()`**
- Can be reused, if we provide **`mmap()`**
  - **Minimalist:** use static pages from BSS
  - **l4re_file:**
    - Supports **`mmap()`**, **`munmap()`** for anon memory
    - Based on dataspaces + L4Re region manager
    - Usually gets its memory from MOE

ANONYMOUS MEMORY

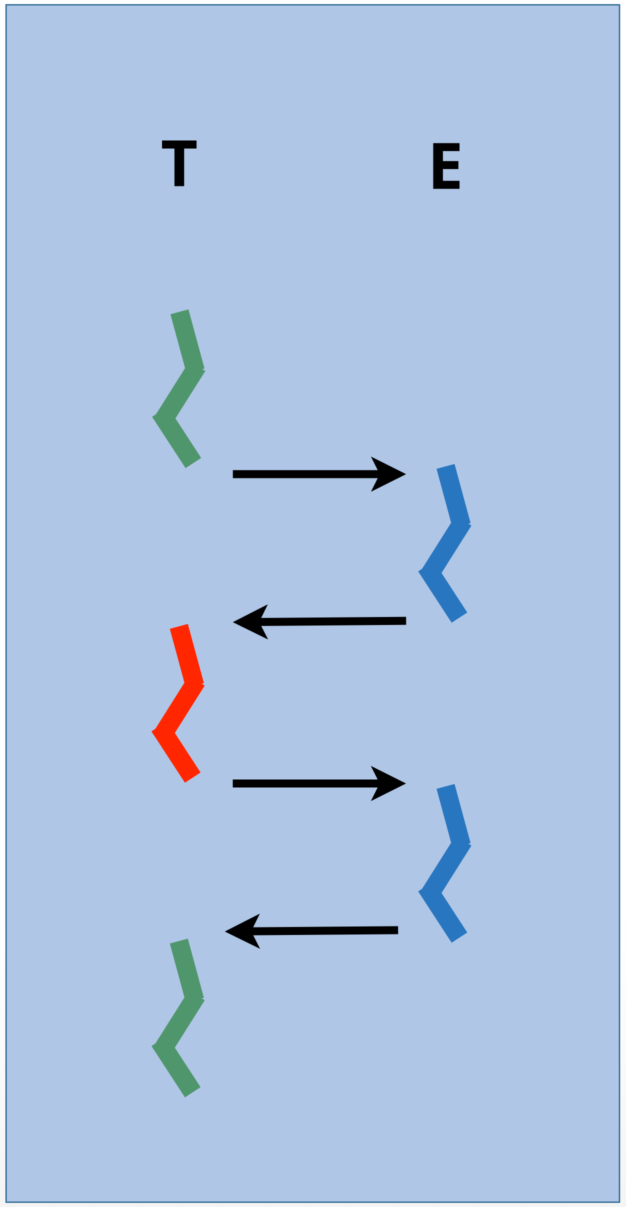
- **`malloc()`** calls **`mmap()`** with flags **`MAP_PRIVATE|MAP_ANONYMOUS`**
  - Pages taken from large dataspace
  - Attached via L4Re region manager **`Rm`**
  - Reference counter tracks mapped regions
- **`munmap()`** detaches dataspace regions
  - `if (region_split) refs++; else refs--;`
  - **`Dataspace`** released on zero references

Example 3: POSIX signals

- Asynchronous event notification:
  - Timers: **`setitimer()`**
  - Exceptions: **`SIGFPE`**, **`SIGSEGV`**, **`SIGCHLD`**, …
  - Issued by applications: **`SIGUSR1`**, …
- Common implementation (i.e., Linux)
  - Built-in kernel mechanism
  - Delivered upon return from kernel
- **How to implement signals in L4Re?**

LIBC BE: SIGNALS

- **Idea:** implement signals based on exception mechanism
- **E** is exception handler of thread **T**
- Exceptions in **T** are reflected to **E**
- If app configured signal handler:
  - **E** sets up signal handler context
  - **E** resets **T**'s program counter to start of signal handler
  - **T** executes signal handler, returns
- If possible, **E** restarts **T** where it had been interrupted



LIBC BE: SIGNALS (PRIMITIVES)

- **Basic mechanism:** exception IPC
  - Start exception handler thread **E**, which waits in a loop for incoming exceptions
  - For all threads **T**: set **E** as exception handler
  - Let kernel forward exceptions as IPC messages
- **Timers:** implement as IPC timeouts
  - **`sigaction()`** / **`setitimer()`** called by **T**
  - **T** communicates time **`t`** to wait to **E**
  - **E** waits in IPC with timeout **`t`**
  - **E** raises exception in **T** to deliver **`SIGALRM`**

LIBC BE: SIGNALS (CONTEXT)

- **E**: handles exceptions:
  - Set up signal handler context:
    - Save **T**'s context
    - Push pointer to **`siginfo_t`**, signal number
    - Push address of return trap
  - **`l4_utcb_exc_pc_set(ctx, handler)`**
- **T**: execute signal handler, „returns“ to trap
- **E**: resume thread after signal:
  - Exception generated, reflected to **E**
  - Detects return by looking at **T**'s exception PC
  - Restore **T's** context saved on stack, resume

Stack Frames (pre-exception)
ucontext_t ctx
siginfo_t *siginfo
int signum
Return address

```
void libc_be_sig_return_trap()
{
  /* trap, cause exception */
}
```

LIBC BE: FILE I/O

Example 4: Simple I/O support:

- **`fprintf()`** support: easy, just replace **`write()`**
- Minimalist backend can output text

```
#include <unistd.h>
#include <errno.h>
#include <l4/sys/kdebug.h>

int write(int fd, const void *buf, size_t count) __THROW
{
  /* just accept write to stdout and stderr */
  if ((fd == STDOUT_FILENO) || (fd == STDERR_FILENO))
    {
      l4kdb_outnstring((const char*)buf, count);
      return count;
    }
  /* writes to other fds shall fail fast */
  errno = EBADF;
  return -1;
}
```

LIBC BE: FILE I/O (ROM FS)

(1) Application calls **`open(„rom/hello“)`**

(2) VFS traverses mount tree, finds **`Ro_fs`** mounted at path **`/rom`**

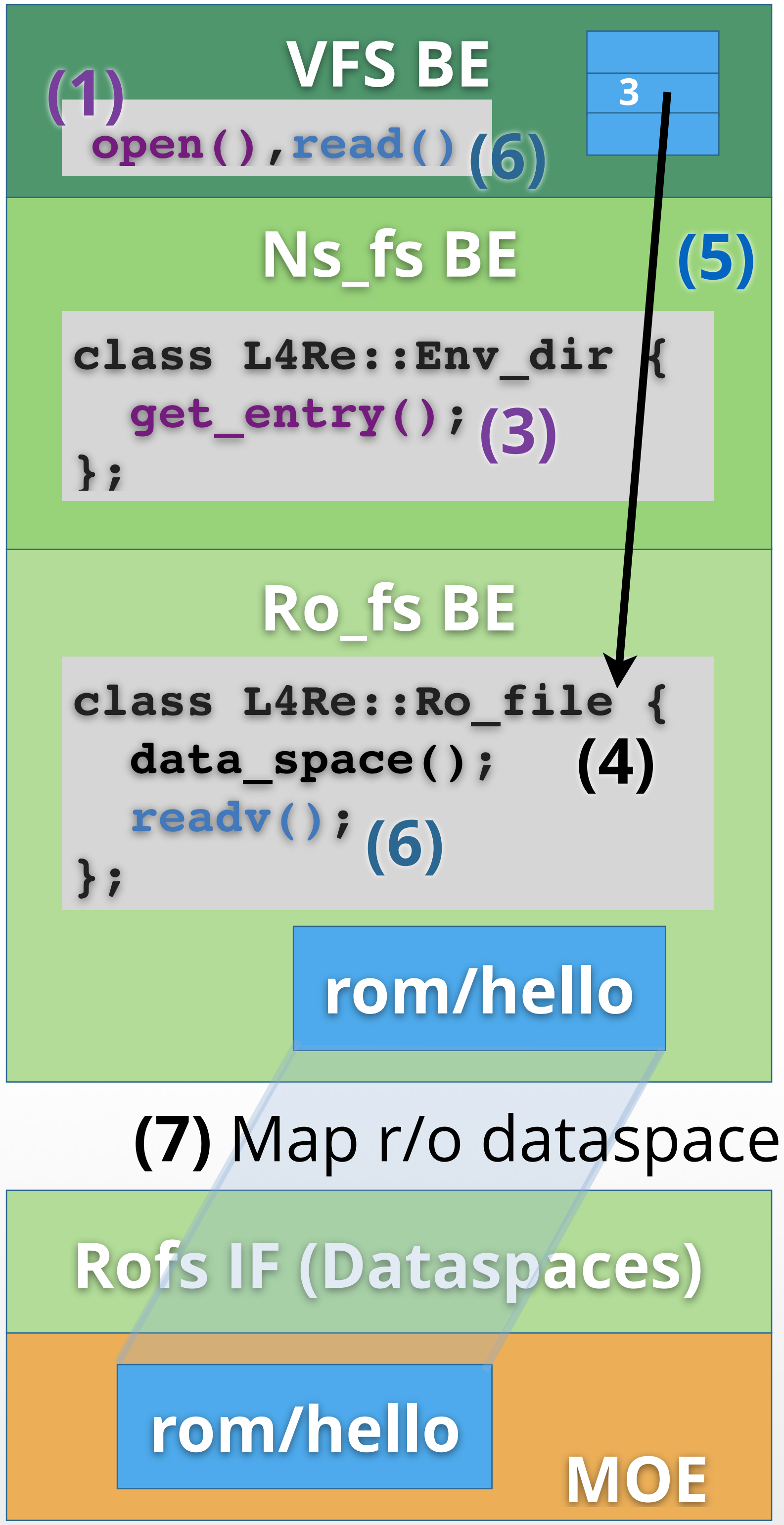
(3) VFS asks **`Ro_fs`** to provide a file for name **`"hello"`**, calls **`Ro_fs::get_entry()`** method

(4) **`Ro_fs::get_entry()`** creates new **`Ro_file`** object from read-only dataspace (provided by MOE, see Exercise 1 slides)

(5) VFS registers file handle for **`Ro_file`** object

(6) Application calls **`read()`**: ends in **`Ro_file::readv()`**

(7) **`Ro_file::readv()`** attaches dataspace, copies requested data into read buffer



POSIX: SUMMARY

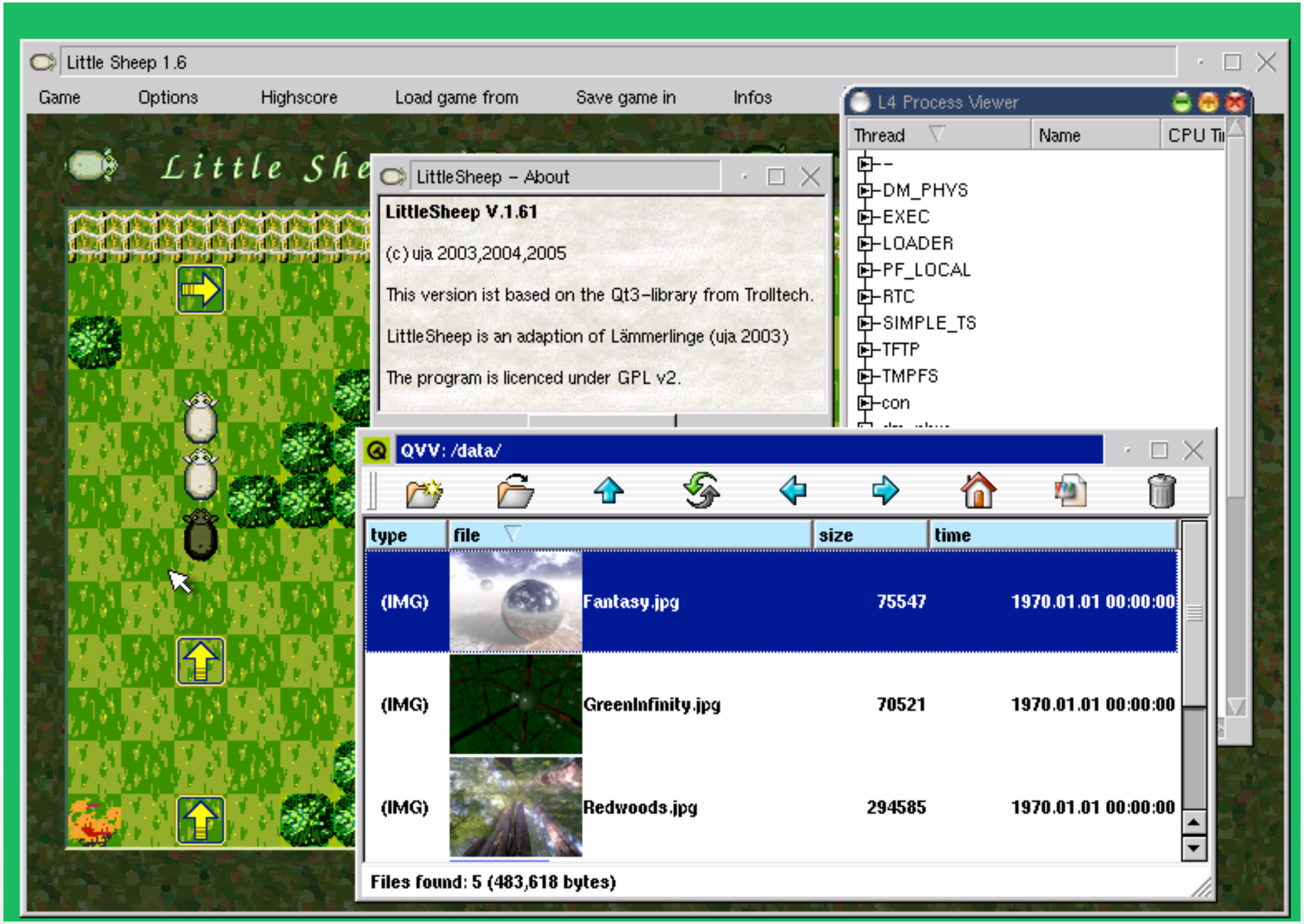
- L4Re offers most important POSIX APIs
  - C library: **`strcpy()`**, …
  - Dynamic memory allocation:
    - **`malloc()`**, **`free()`**, **`mmap()`**, …
    - Based on L4Re **`Dataspaces`**
  - Threads, synchronization: **`pthreads`**
  - Signal handling: exception handler + IPC
  - I/O support: files, terminal, time, (sockets)
- POSIX is enabler: sqlite, Cairo, SDL, MPI, …

RICH FRAMEWORKS

- POSIX is limited to basic OS abstractions
  - No graphics, GUI support
  - No audio support
- Examples for more powerful APIs:
  - SDL (Simple Direct Media Layer):
    - Multimedia applications and games
  - Qt toolkit:
    - Rich GUIs with tool support
    - Fairly complete OS abstractions

SOFTWARE ON L4

SOFTWARE ON L4



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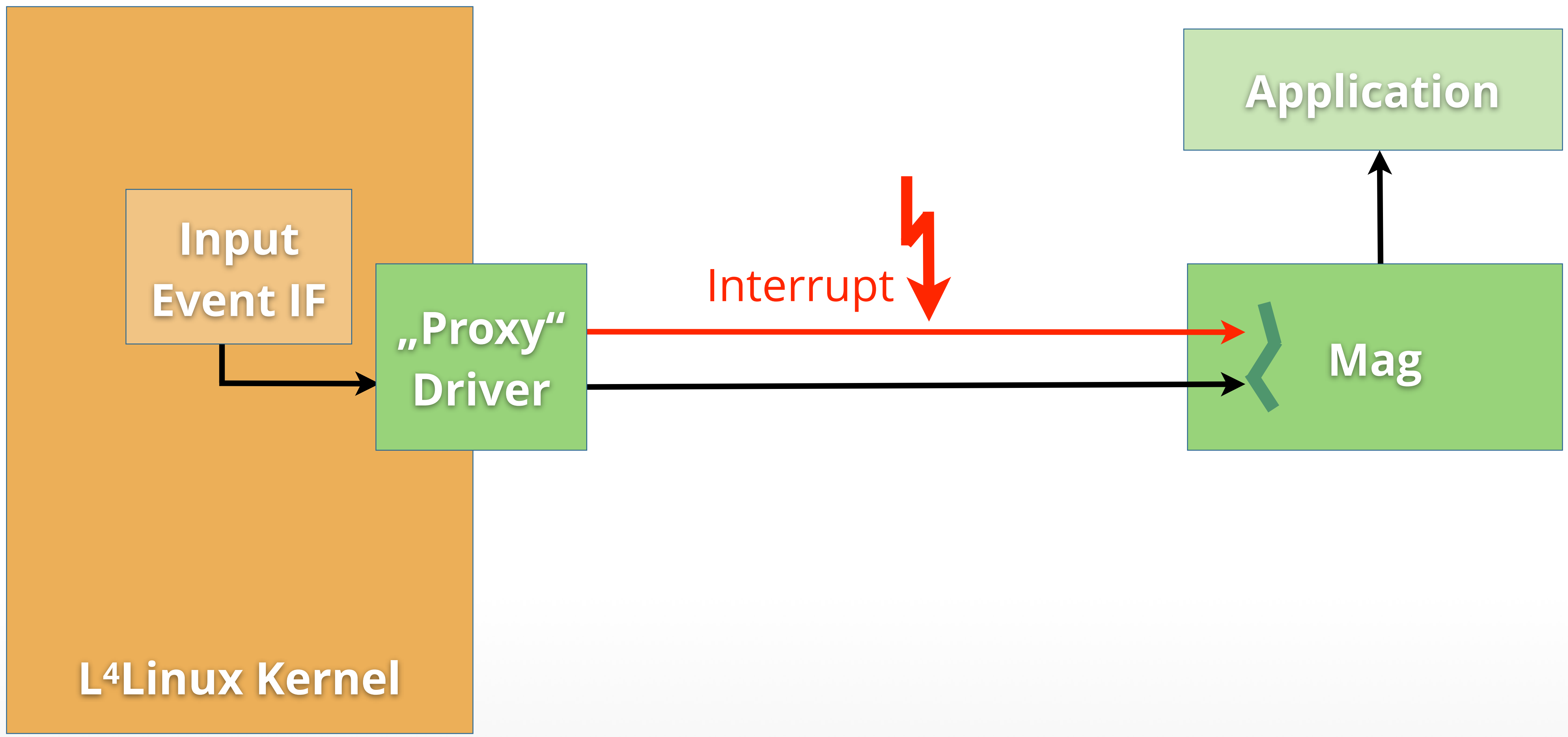
LEGACY OPERATING SYSTEM AS A TOOLBOX

LINUX TOOLBOX

- Legacy OSes have lots of:
  - Device drivers
  - Protocol stacks
  - File systems
- Reuse drivers in natural environment
  - Also see paper [3]: *„Unmodified Device Driver Reuse and Improved System Dependability via Virtual Machines“* , by LeVasseur, Uhlig, Stoess, Götz)
- L4Linux:
  - **Hybrid applications:** access legacy OS + L4Re
  - **In-kernel support:** export Linux services to L4Re

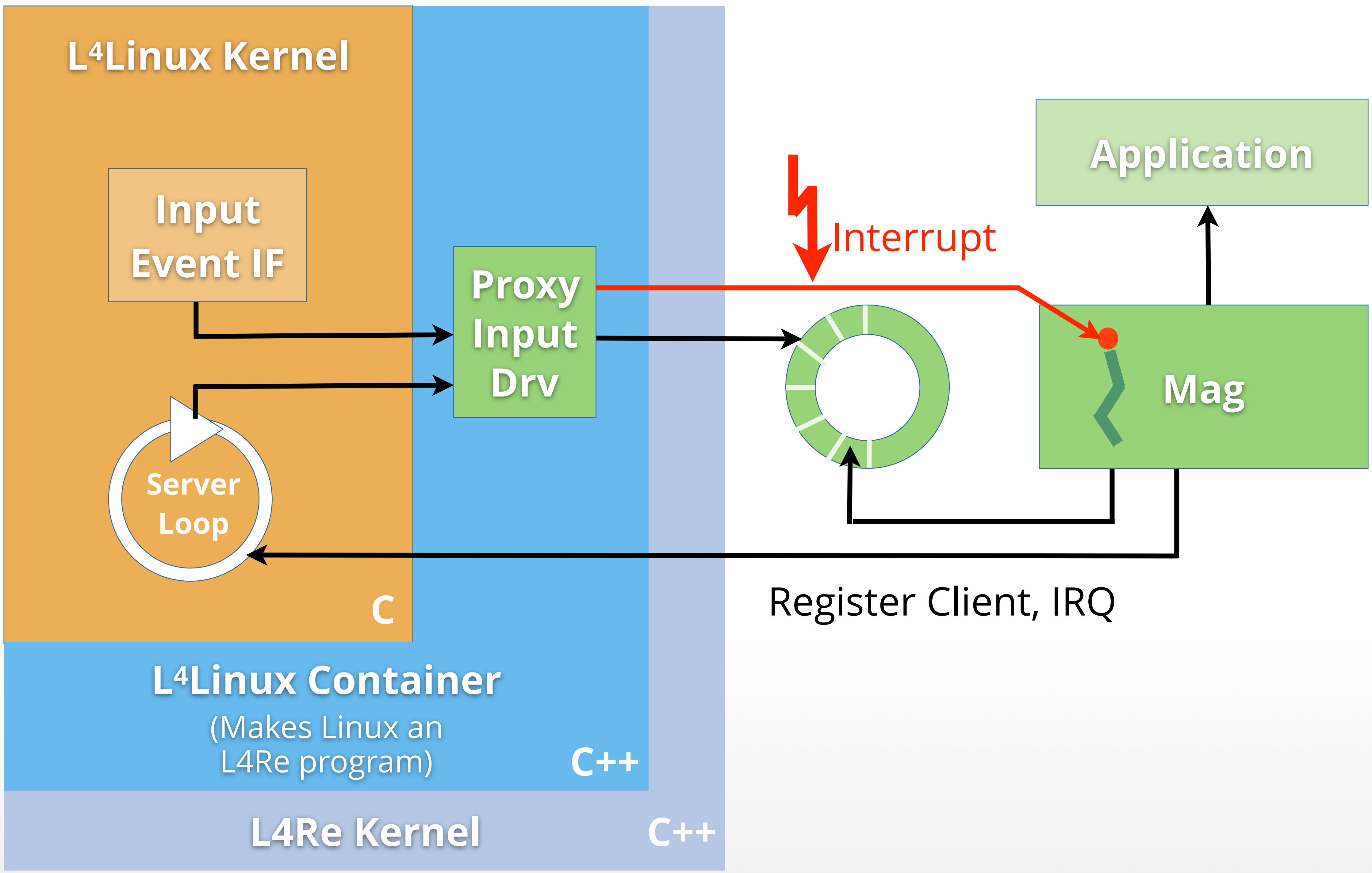
GENERAL IDEA



ACCESS L4LINUX

- L4Linux has drivers
- L4Re has great infrastructure for servers:
  - IPC framework
  - Generic server loop
- **Problems:** C vs. C++, symbol visibility
- **Bridge:** allow calls from L4Linux to L4Re
  - L4Re exports C functions to L4Linux
  - L4Linux kernel module calls them

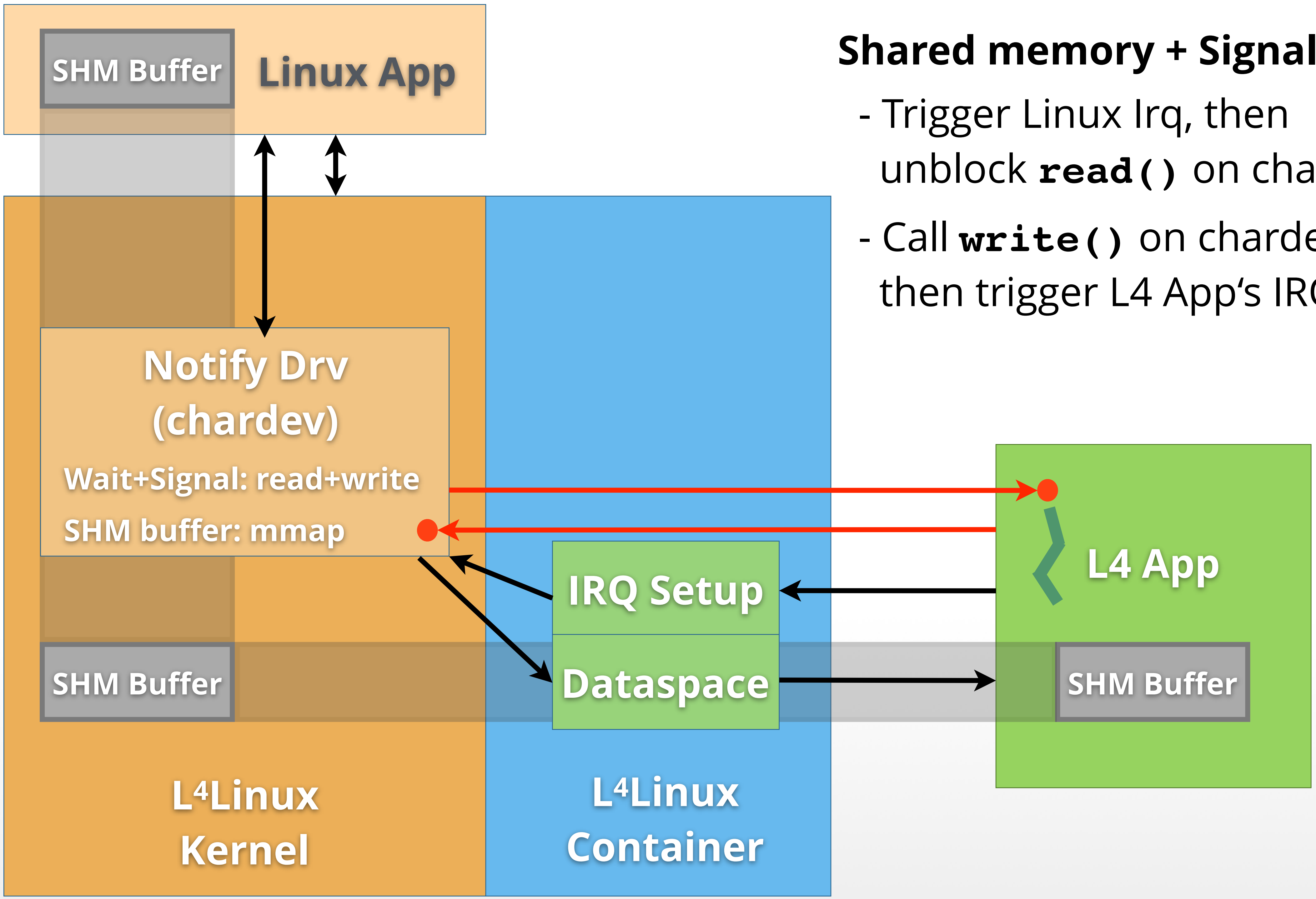
INPUT DRIVER



PRISON BREAK

- **Idea:** „enlightened“ applications
  - Know that they run on L4Re
  - Talk to L4Re servers via L^4Linux
- **Proxy driver** in L^4Linux provides:
  - Shared memory: Linux app + L4Re server
  - Signaling: Interrupt objects
  - Enables synchronous and asynchronous zero-copy communication (e.g., ring buffer)

PROXY DRIVER



Shared memory + Signaling:

- Trigger Linux Irq, then unblock `read()` on chardev
- Call `write()` on chardev, then trigger L4 App's IRQ

SPLIT SERVICES

- Proxy driver suitable for many scenarios:
  - Producer/consumer (either direction)
  - Split applications:
    - Reuse application on either side
    - Trusted / untrusted parts
  - Split services:
    - Block device / file system / database / ...
    - Network stack
  - Split device drivers

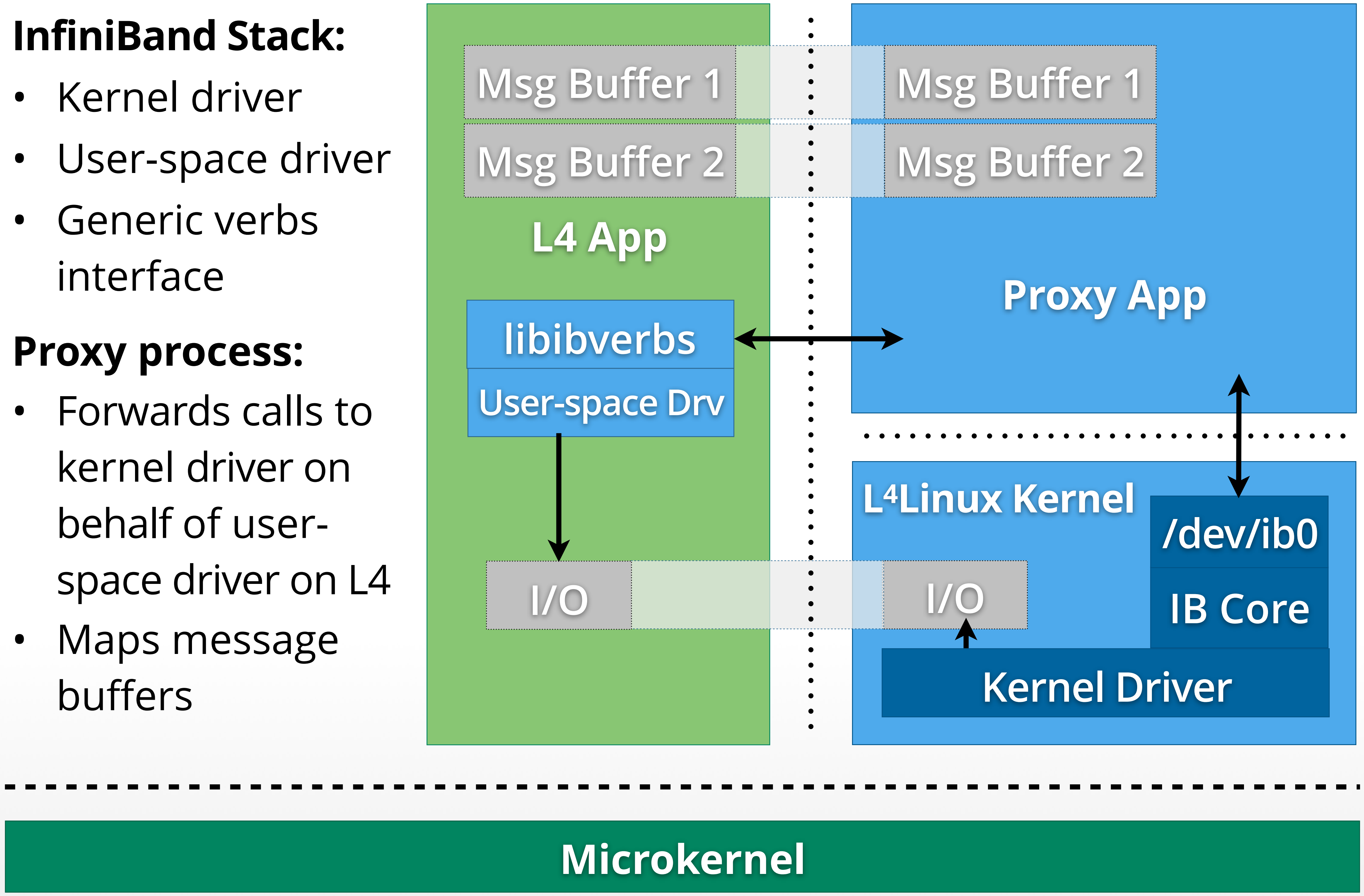
INFINIBAND

InfiniBand Stack:

- Kernel driver
- User-space driver
- Generic verbs interface

Proxy process:

- Forwards calls to kernel driver on behalf of user-space driver on L4
- Maps message buffers



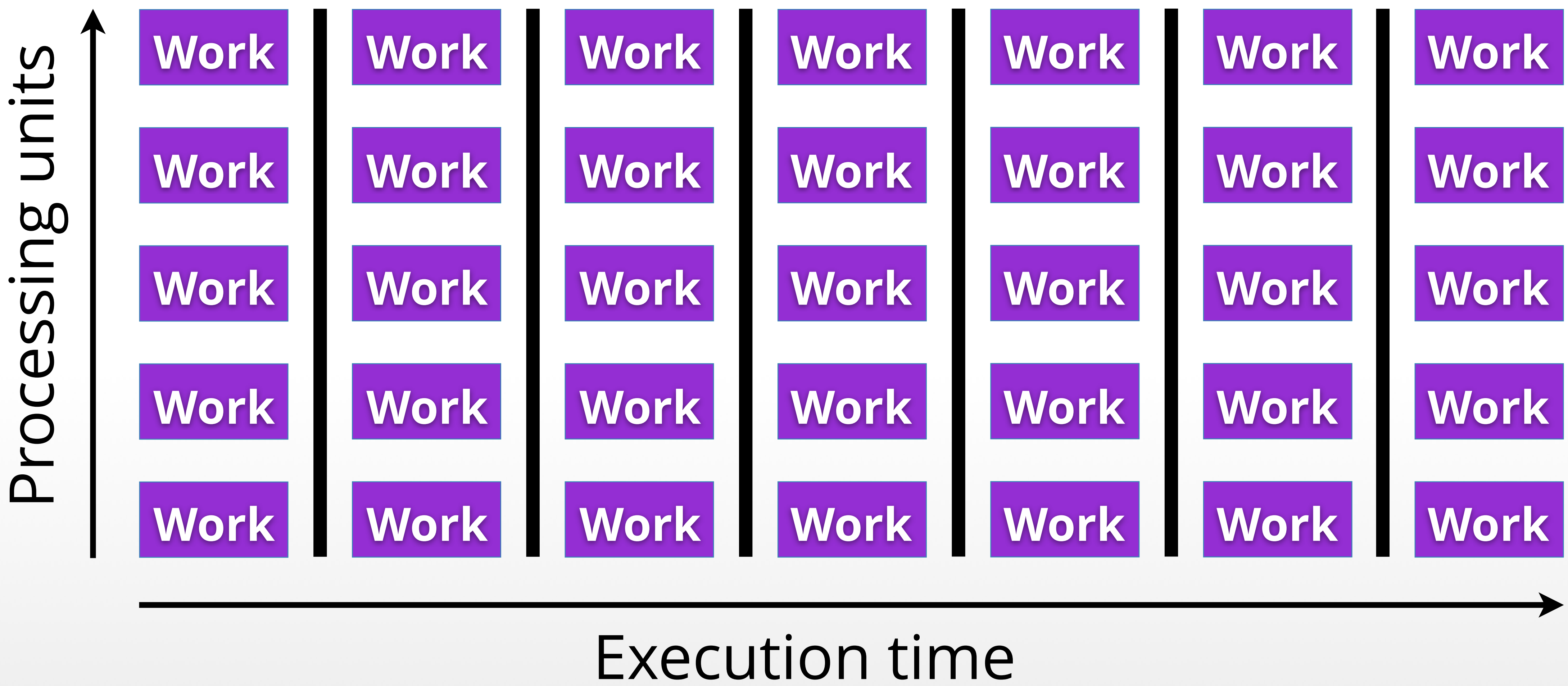
HYBRID OPERATING SYSTEMS

WHY HYBRID OS?

- **Problem:**
  - Some applications need a lot of functionality from a legacy OS like Linux ...
  - ... and a few strong guarantees that Linux cannot provide due to its complexity
- **Examples:**
  - Security-critical applications
  - Real-time & high-performance computing
- **Solution:** Combine Microkernel and Linux

NO DELAYS!!!

- Real-time: Prevent deadline miss
- Bulk-synchronous programs: Avoid straggler



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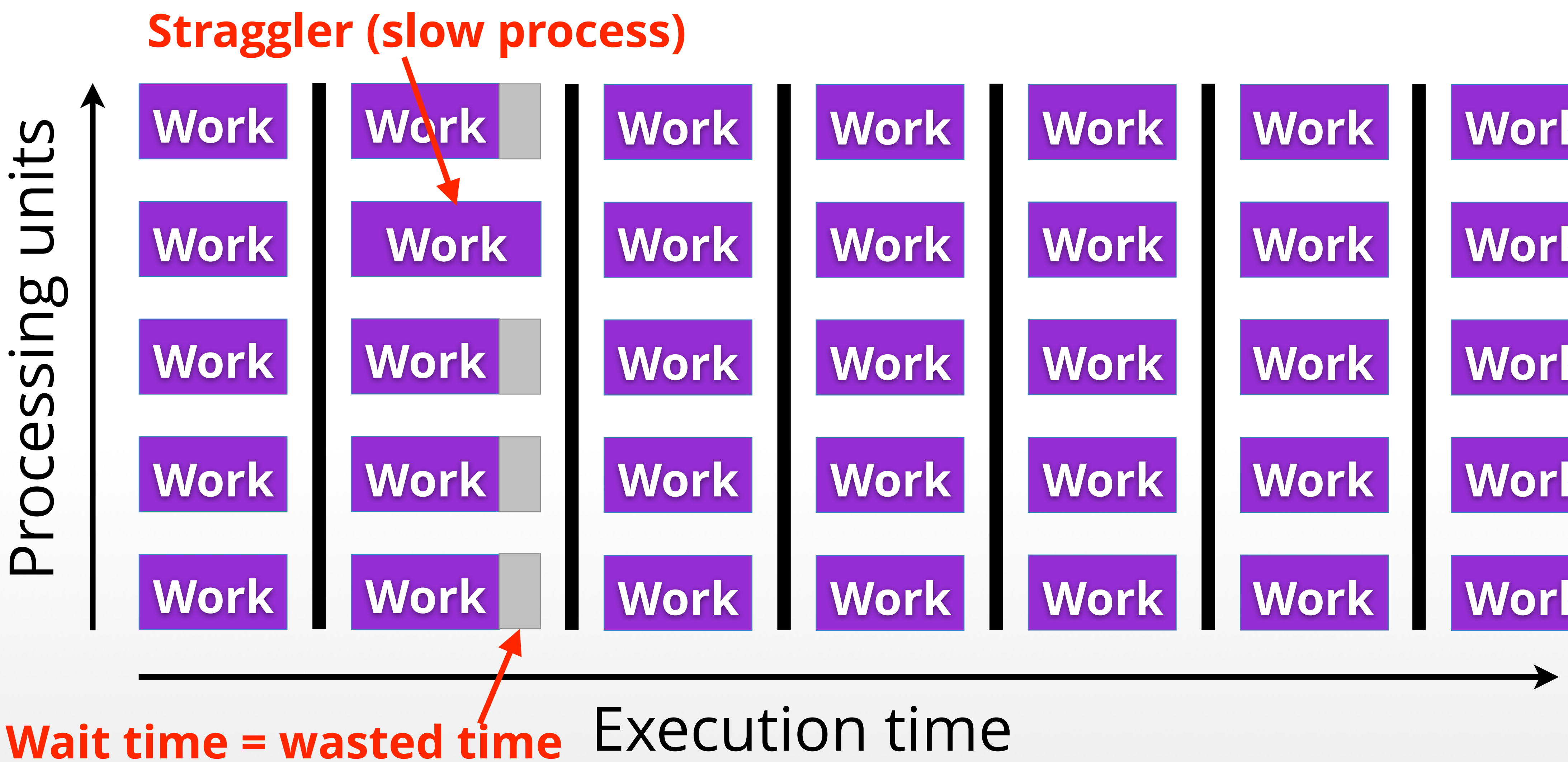
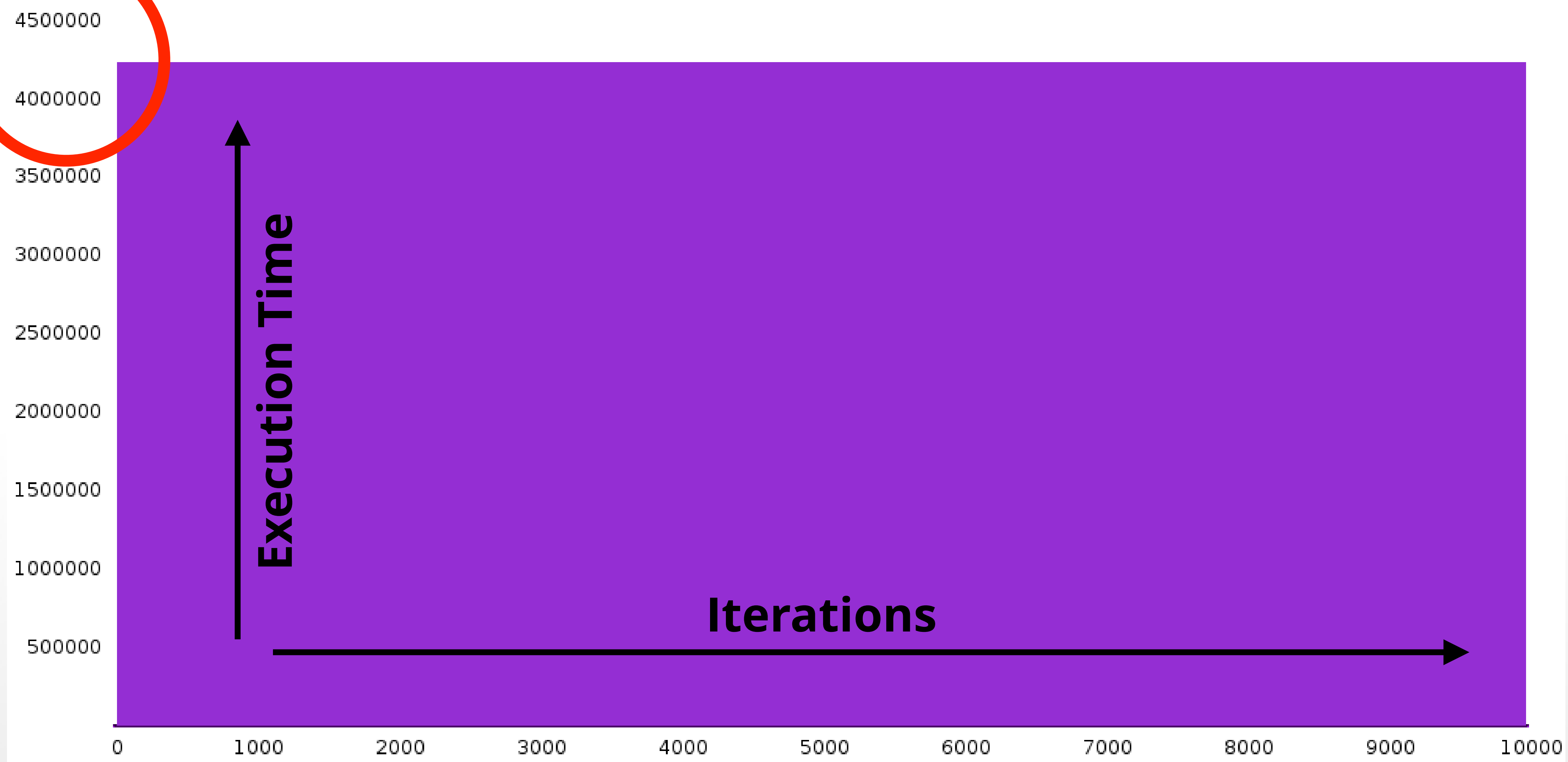


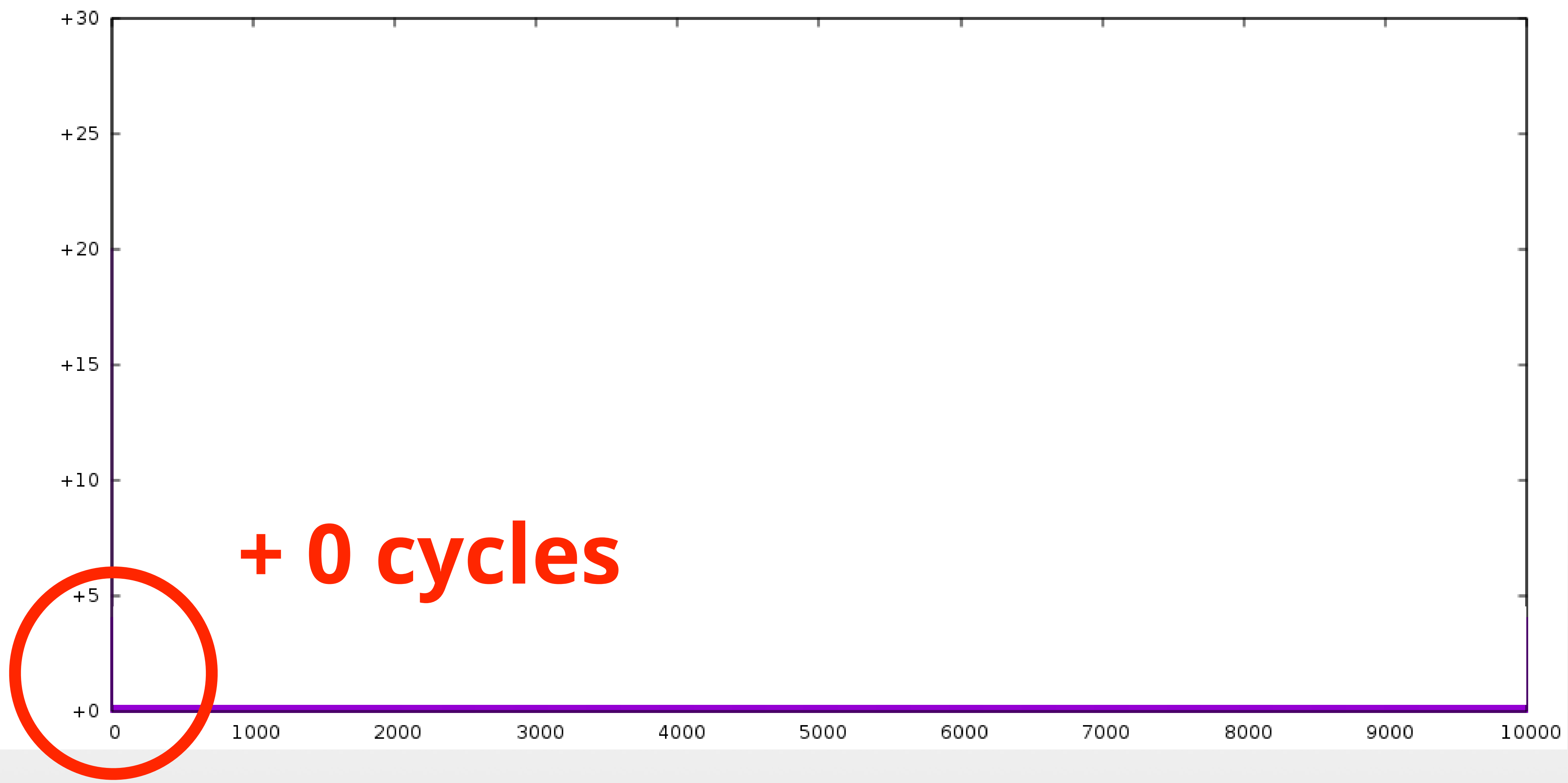
FWQ BENCHMARK

Fixed work quantum (FWQ): repeatedly measure execution time for same work

4.25 million cycles (constant work)

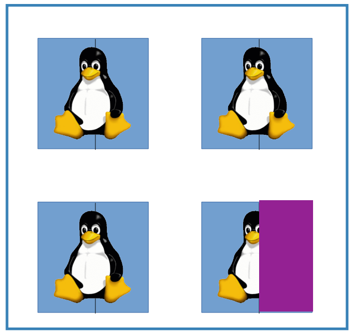


Ideal: zero extra cycles

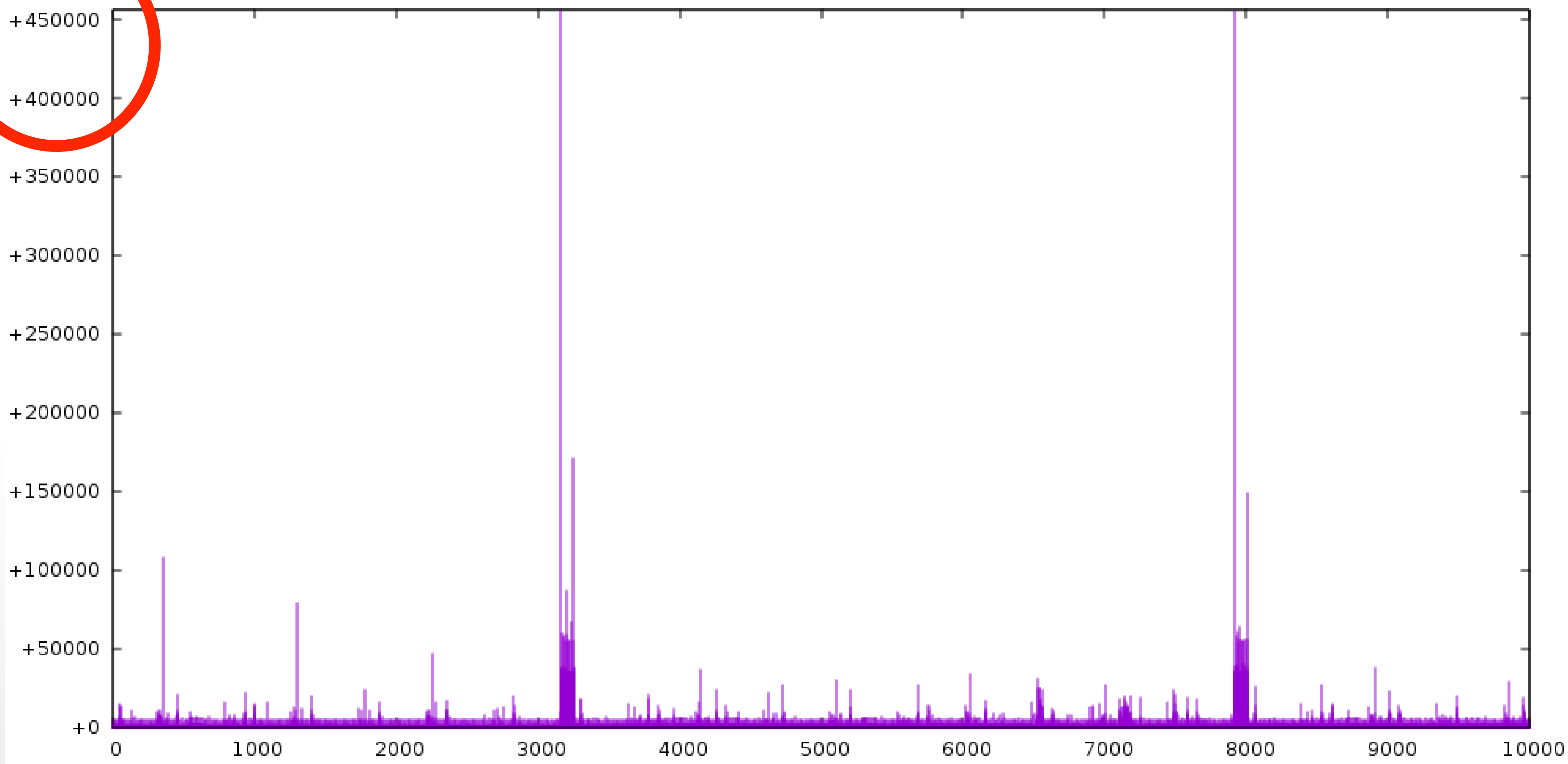


NOISY LINUX?

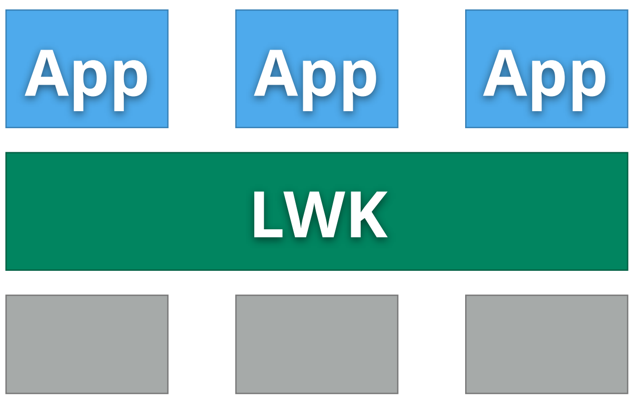
Real-World HPC Linux



+450,000 cycles ≈ 10%



APPROACHES

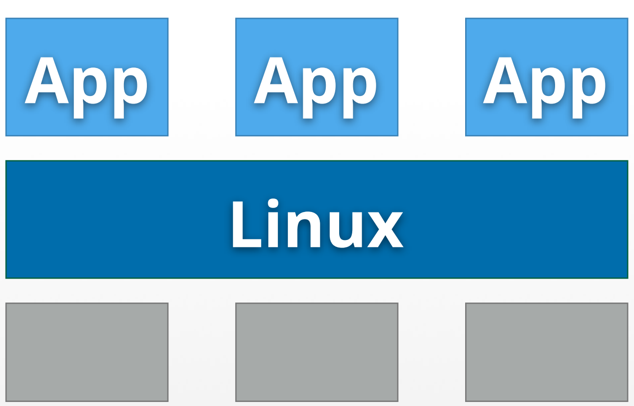


Light-Weight Kernel (LWK)

⊕ No Noise

⊖ Compatibility

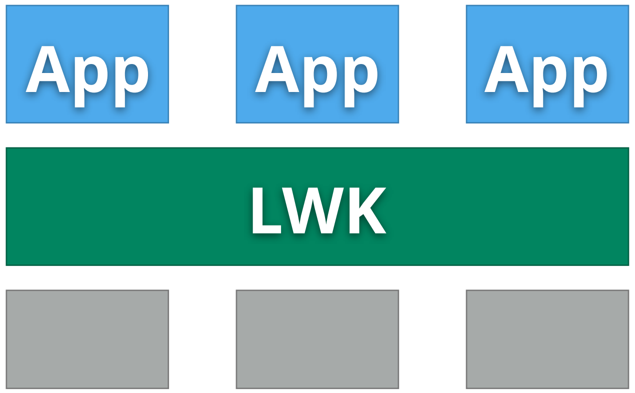
⊖ Features



Tweaked Linux

⊙ Low Noise
⊕ Compatibility
⊕ Features
⊖ Fast moving target

APPROACHES



Light-Weight Kernel (LWK)

- ⊕ No Noise
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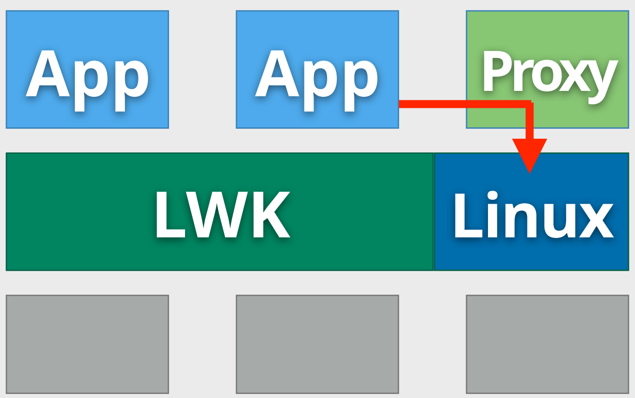
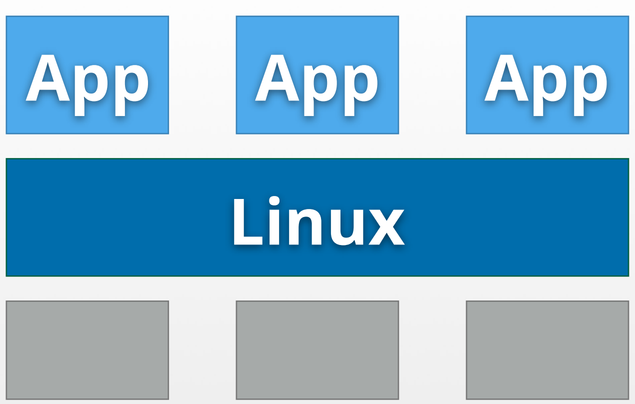
- ⊖ Features



Light-Weight Kernel + Linux

- ⊕ No Noise
- ⊕ Compatibility
- ⊕ Features
- ⊖ **Much effort? Not if we can reuse a lot …**

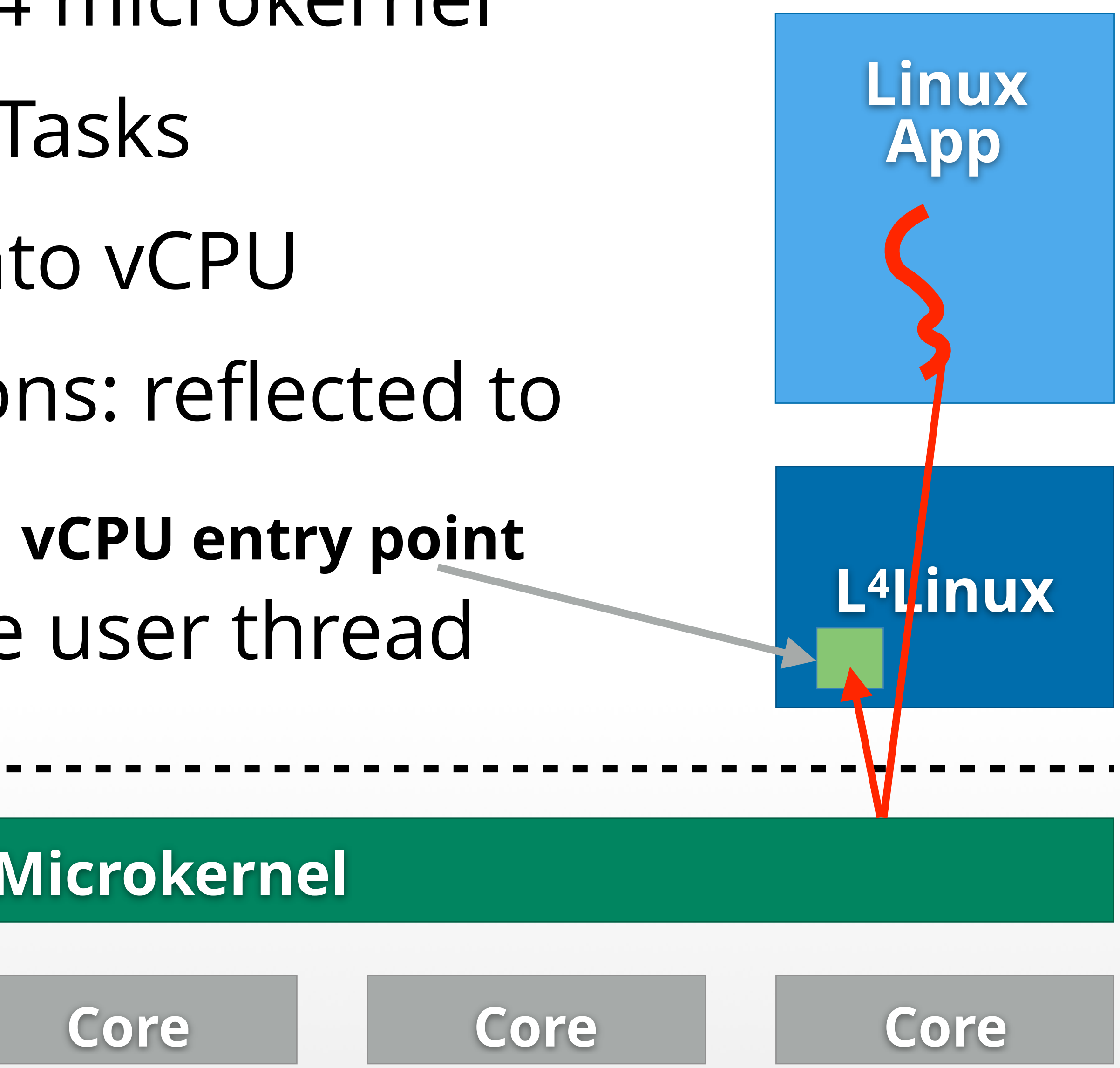


Tweaked Linux

- ⊙ Low Noise
- ⊕ Compatibility
- ⊕ Features
- ⊖ Fast moving target

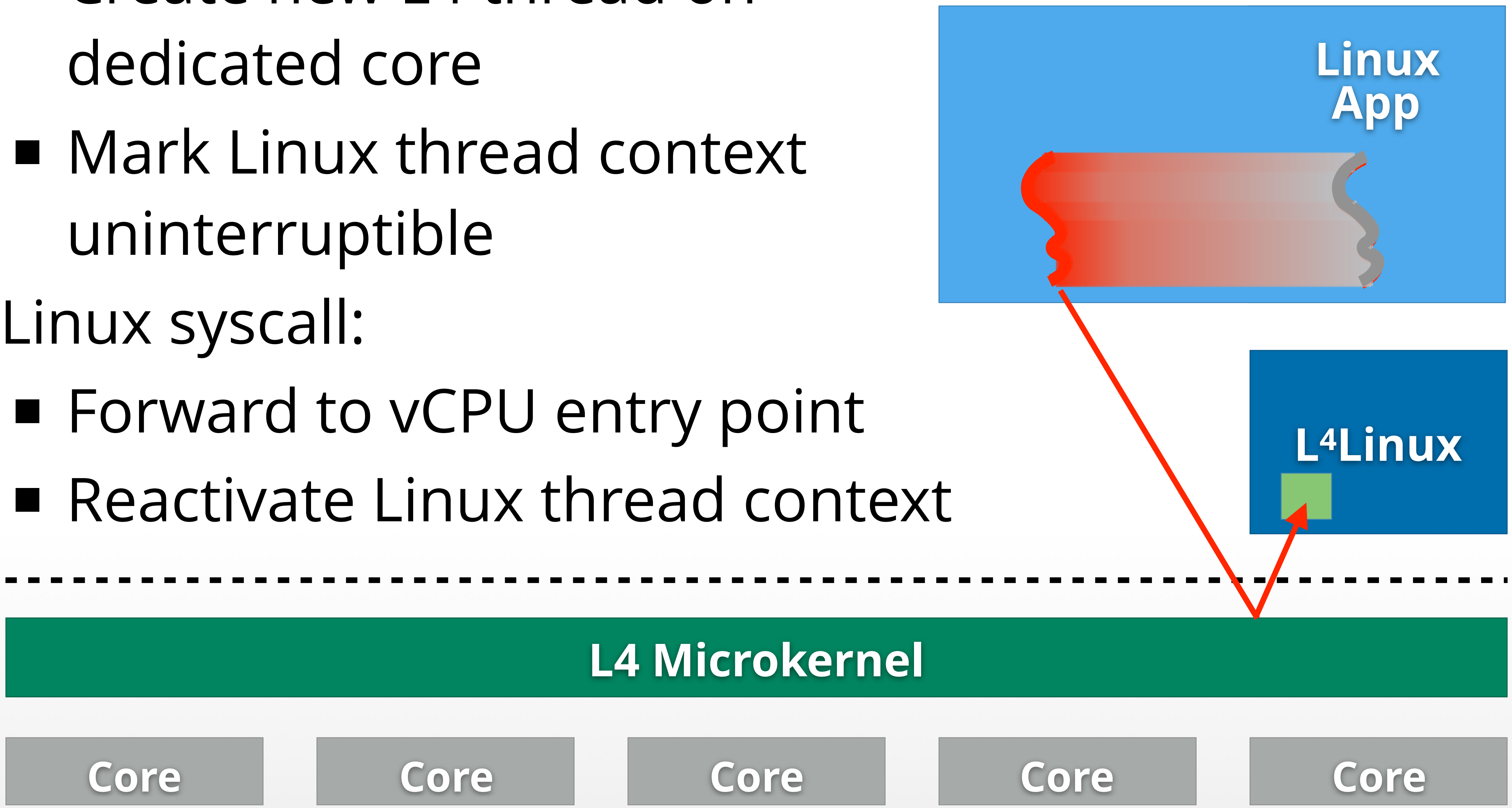
L4RE + L4LINUX

- L4Linux is paravirtualized: `arch/l4`
- Tight integration with L4 microkernel
- Linux processes are L4 Tasks
- Threads multiplexed onto vCPU
- Linux syscalls / exceptions: reflected to vCPU entry point
- Handle syscall + resume user thread

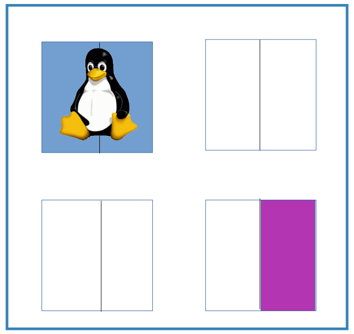


DECOUPLING

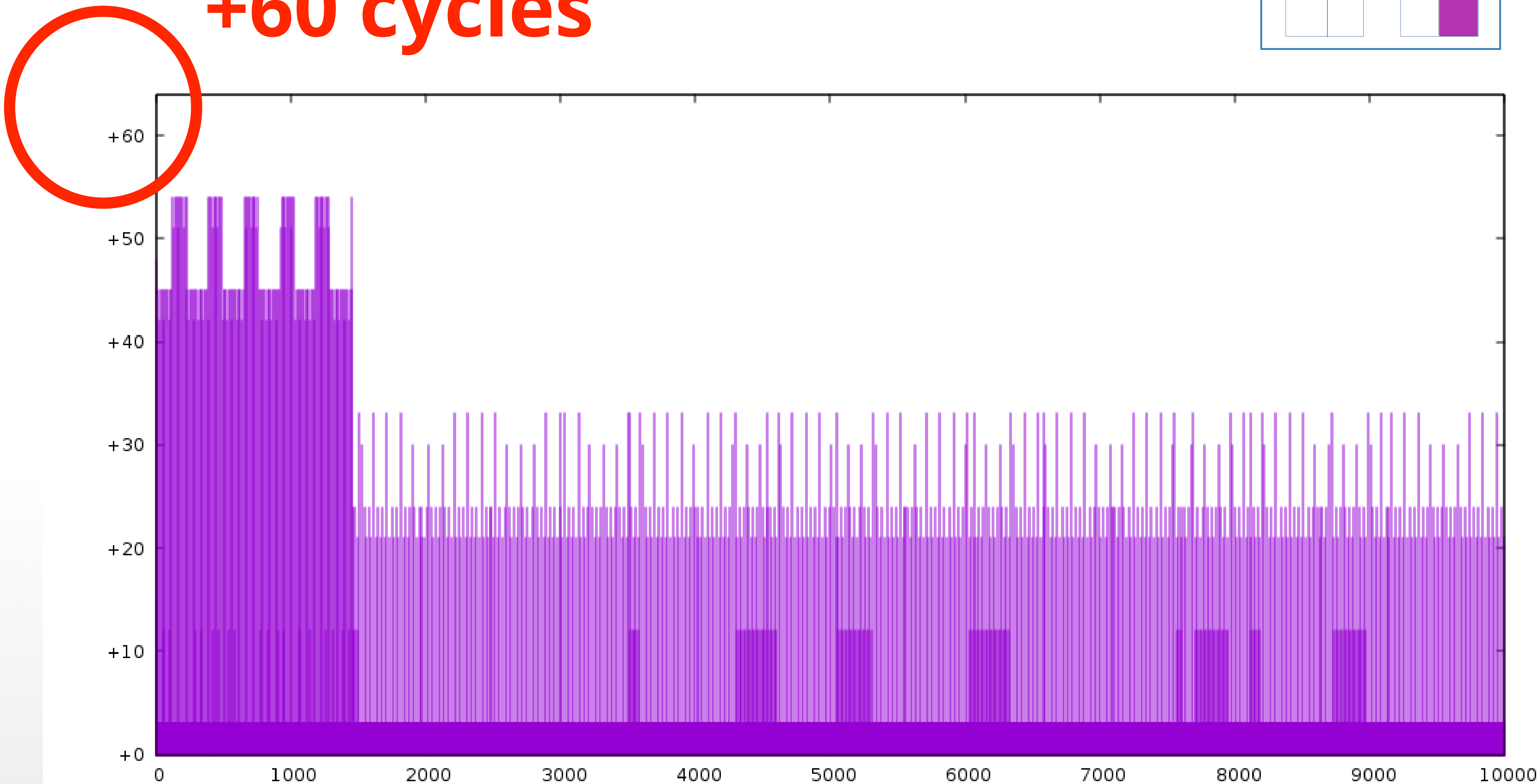
- Decoupling:
  - Create new L4 thread on dedicated core
  - Mark Linux thread context uninterruptible
- Linux syscall:
  - Forward to vCPU entry point
  - Reactivate Linux thread context



Decoupled Linux thread

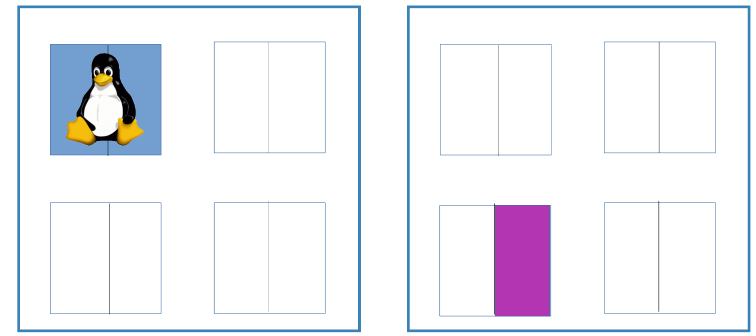


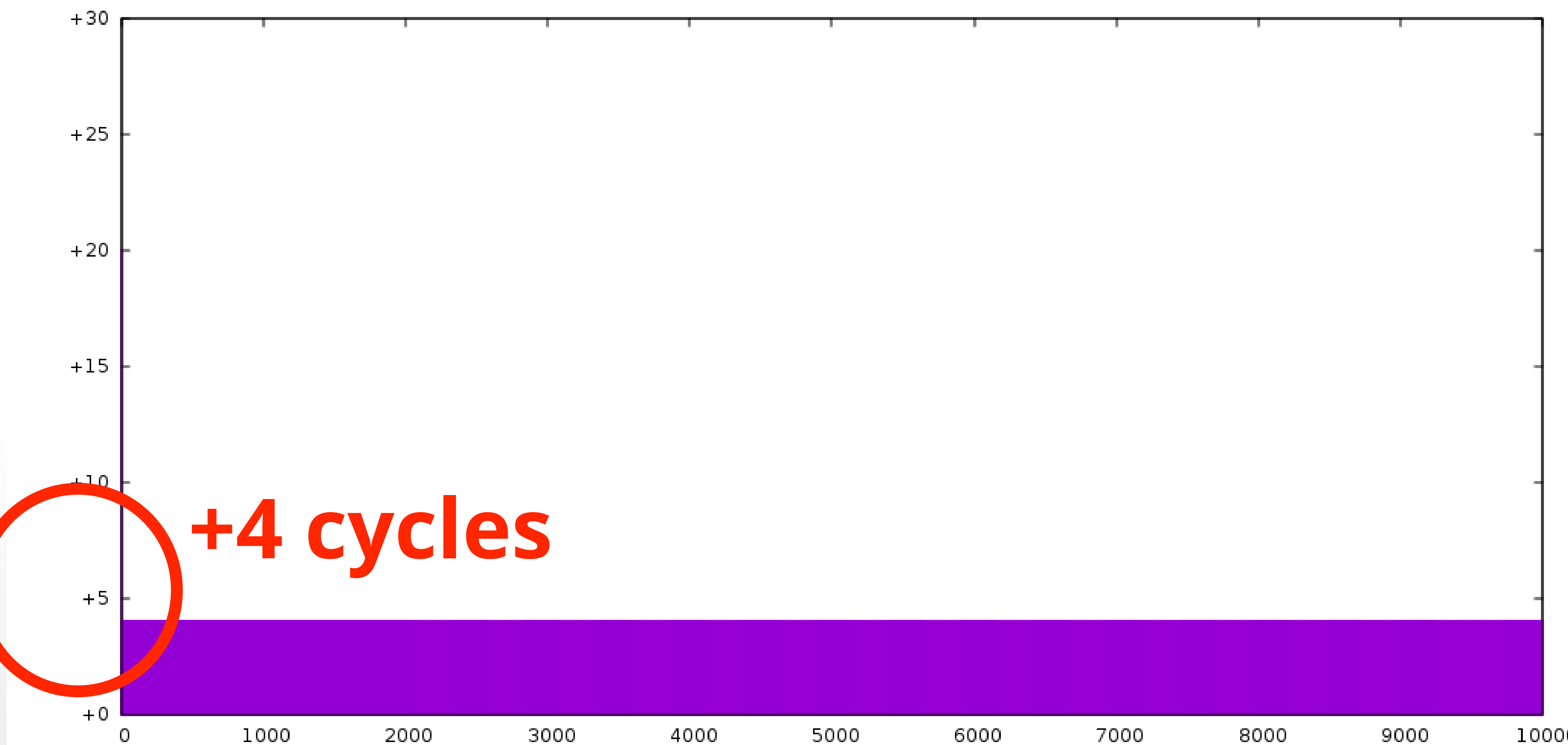
+60 cycles



DECOUPLING

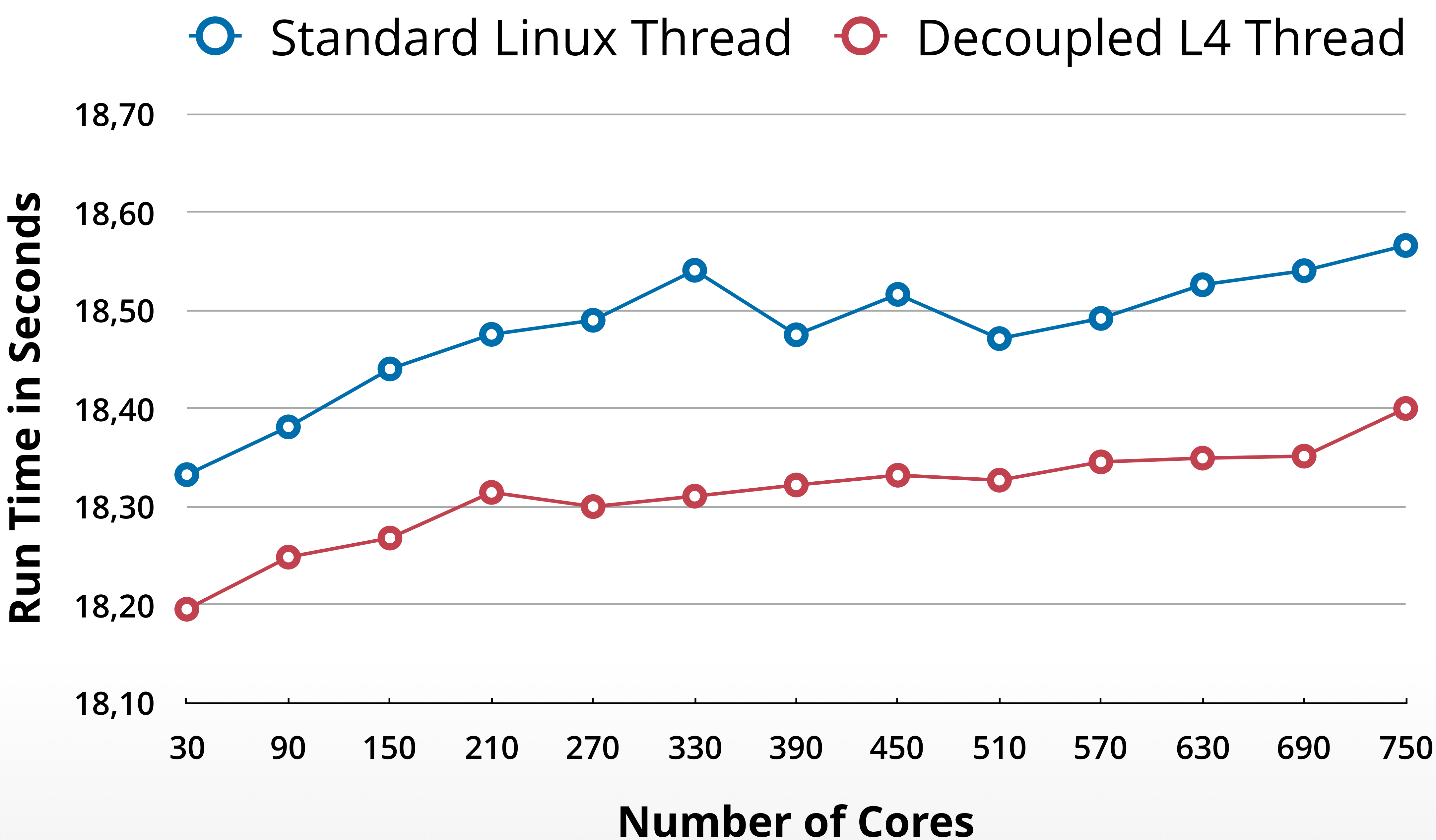
Decoupled Linux thread





- **MPI-FWQ:**
  - Simulates bulk-synchronous high-performance application
  - Alternates between: constant work on each processor and global barrier (wait-for-all)

MPI-FWQ RESULT



[1] „Decoupled: Low-Effort Noise-Free Execution on Commodity Systems", Adam Lackorzynski, Carsten Weinhold, Hermann Härtig, ROSS'16, Kyoto, Japan

UP NEXT ...

<u>Next week:</u>

- **Lecture:** *„Virtualization“*
- ***Paper reading exercise***

REFERENCES

- [1] **„Decoupled: Low-Effort Noise-Free Execution on Commodity Systems“**, Adam Lackorzynski, Carsten Weinhold, Hermann Härtig, Runtime and Operating Systems for Supercomputers (ROSS 2016), Kyoto, Japan, June 2016

- [2] Resources on POSIX standard: *http://standards.ieee.org/regauth/posix/*

- [3] **„Unmodified Device Driver Reuse and Improved System Dependability via Virtual Machines“**, by J. LeVasseur, V. Uhlig, J. Stoess, S. Götz, OSDI 2004