XXX

Tolerating Malicious Drivers in Linux

Silas Boyd-Wickizer and Nickolai Zeldovich

How could a device driver be malicious?

- Today's device drivers are highly privileged
  - Write kernel memory, allocate memory, ...
- Drivers are complex; developers write buggy code

- Result: Attackers exploit vulnerabilities

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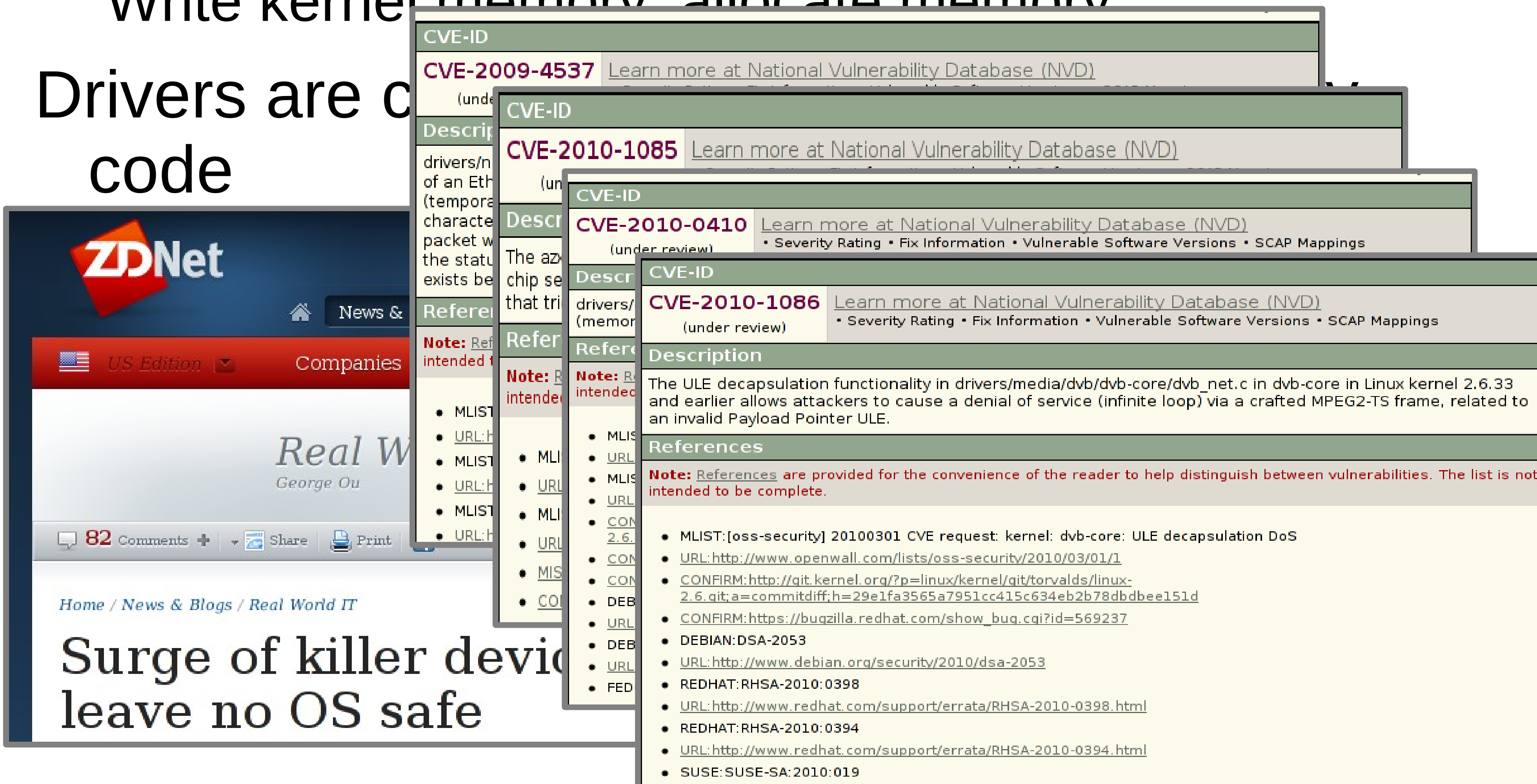


Current approach

User-space drivers in μkernels (Minix, L4, ...)

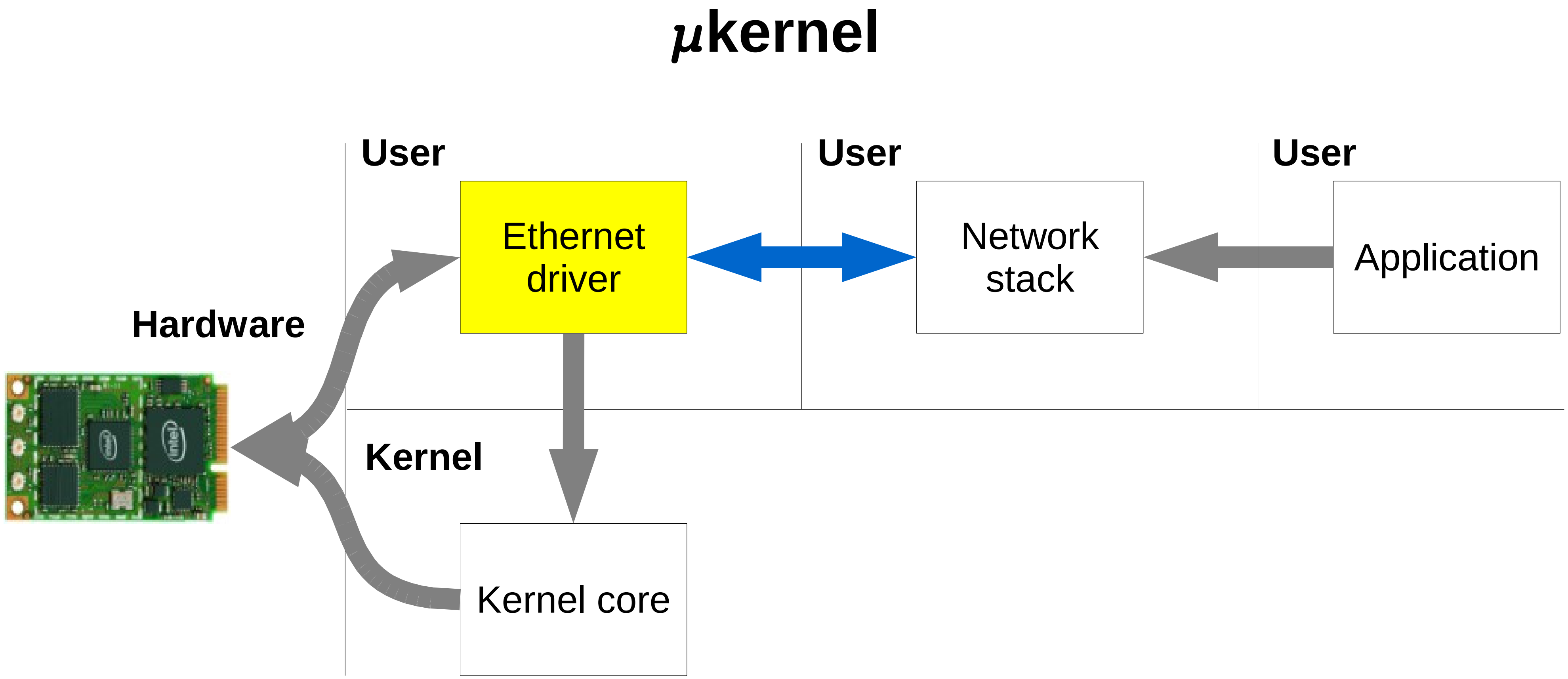
Write device driver in new language (Termite)

Handle common faults (Nooks, microdrivers, ...)

Goal

Secure, efficient, & unmodified drivers on Linux

Previous user-space drivers



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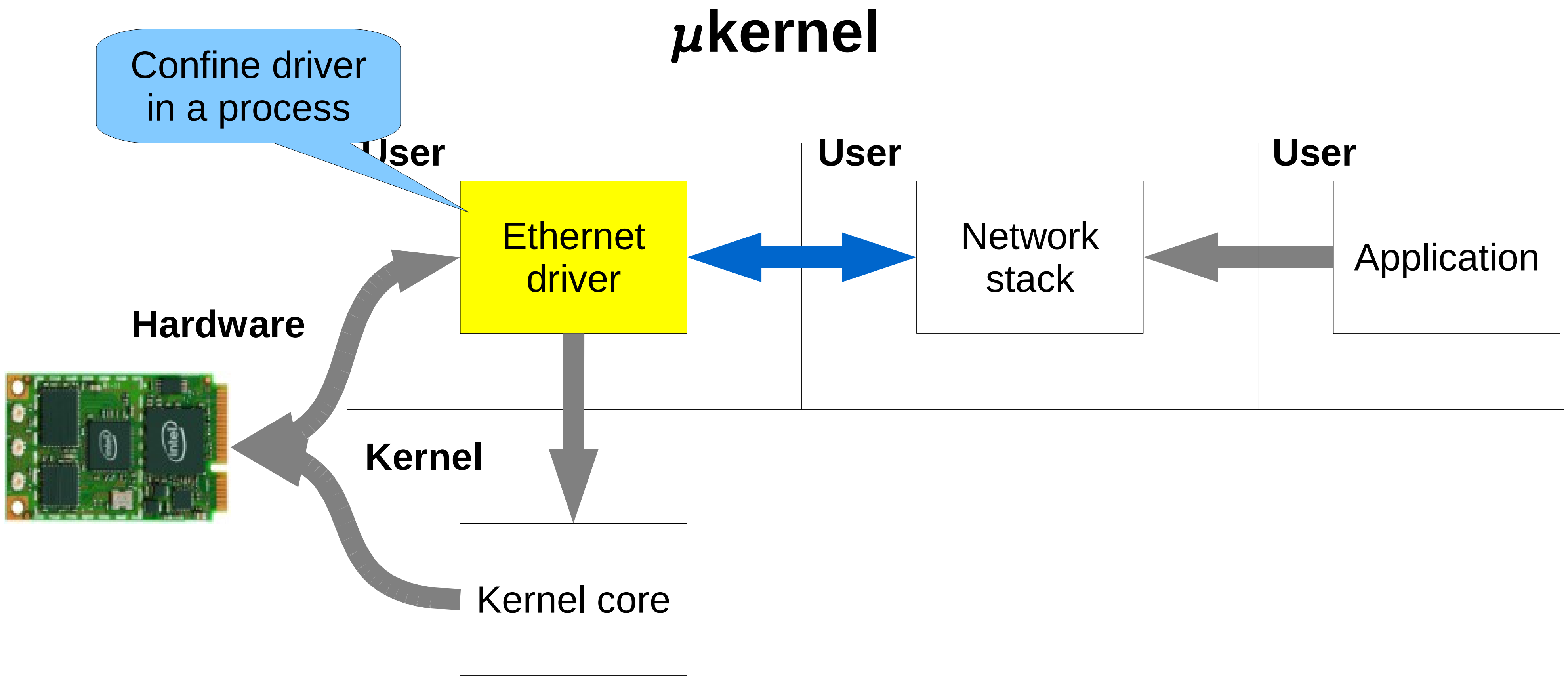

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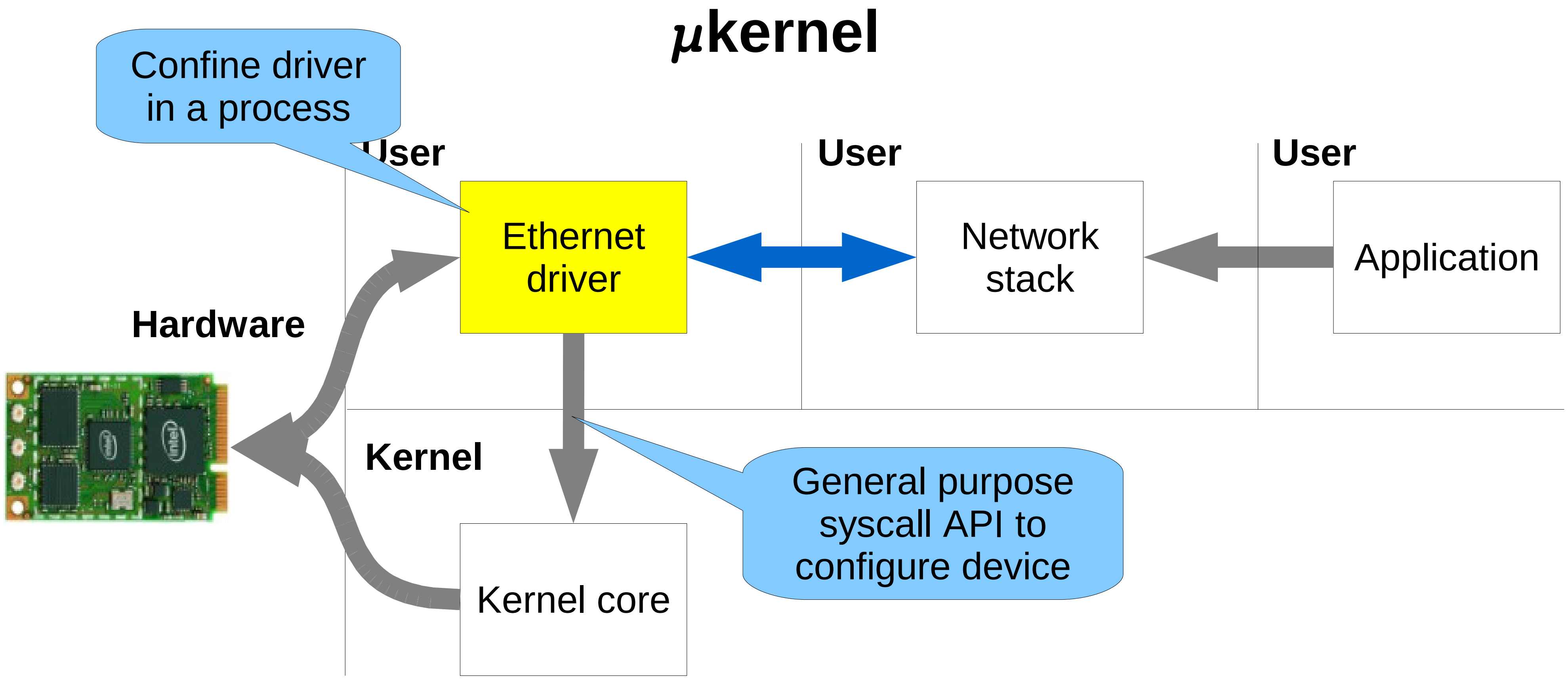

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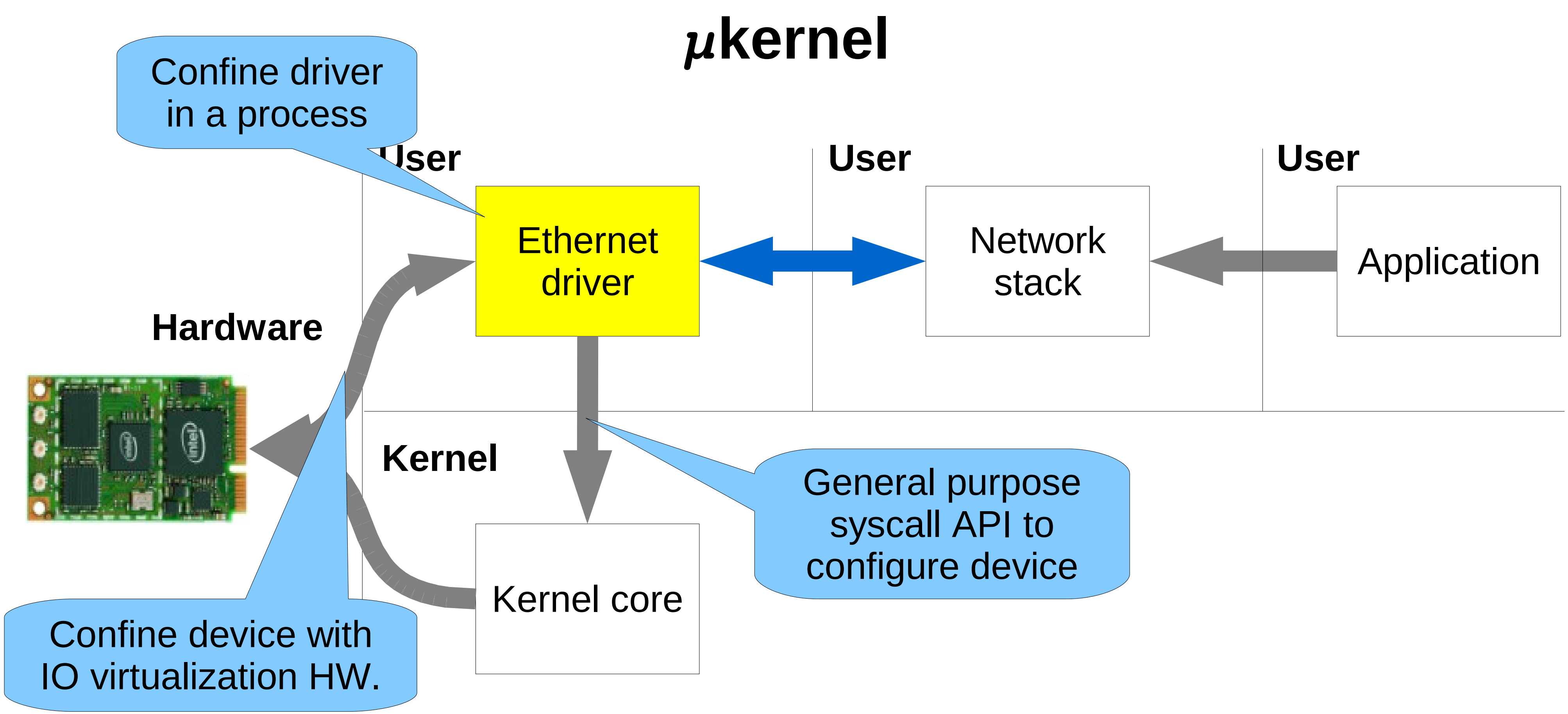

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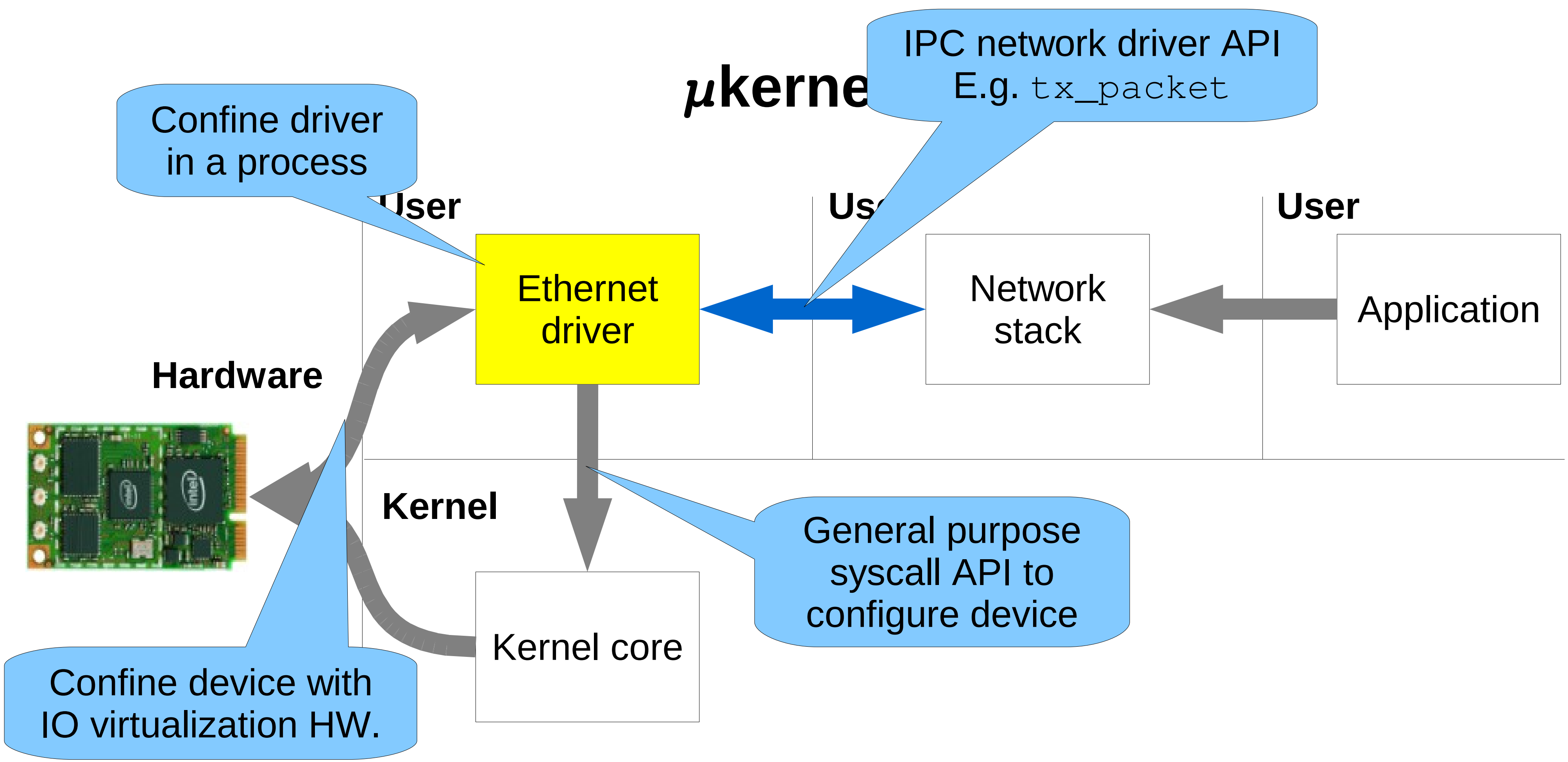

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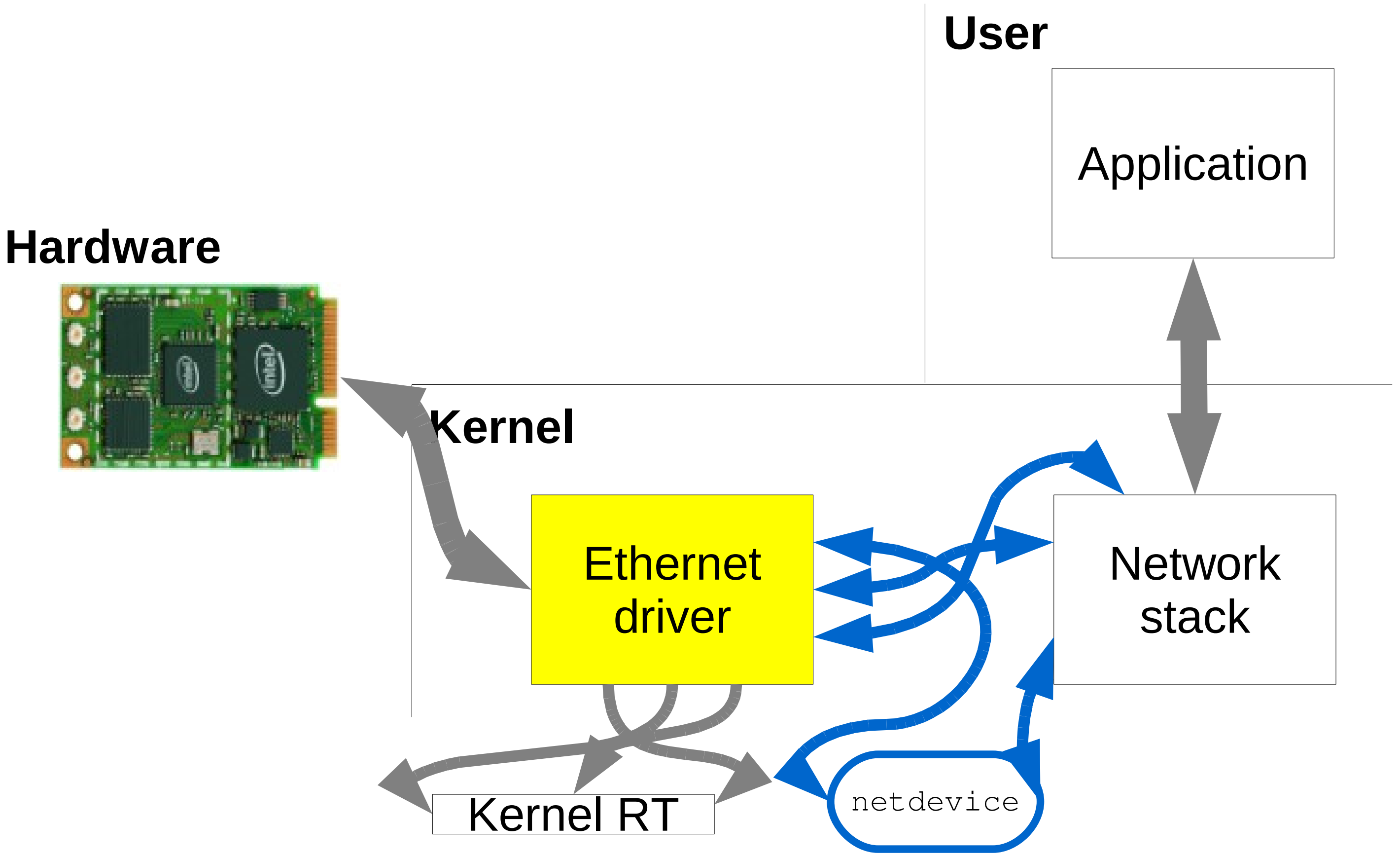

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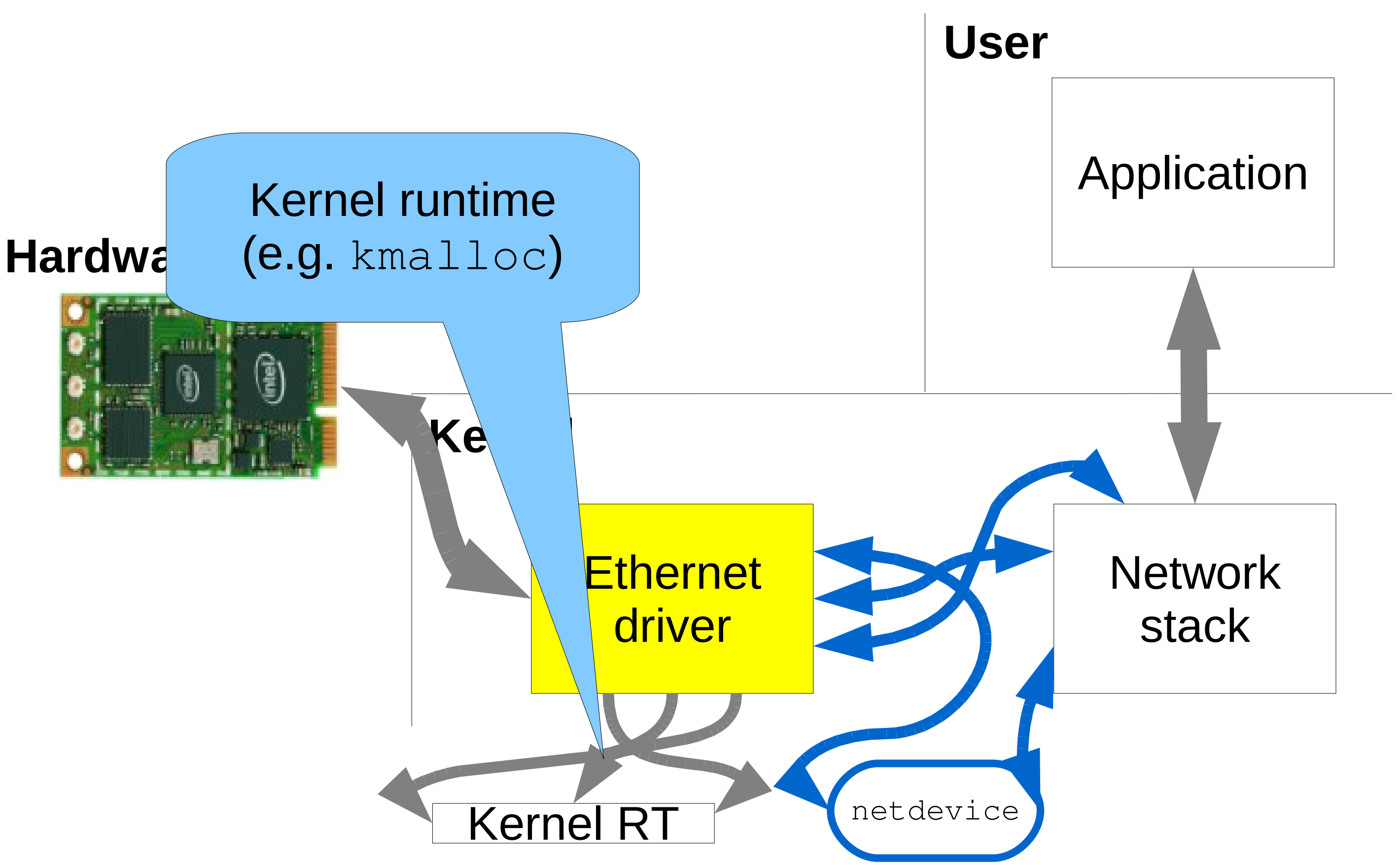

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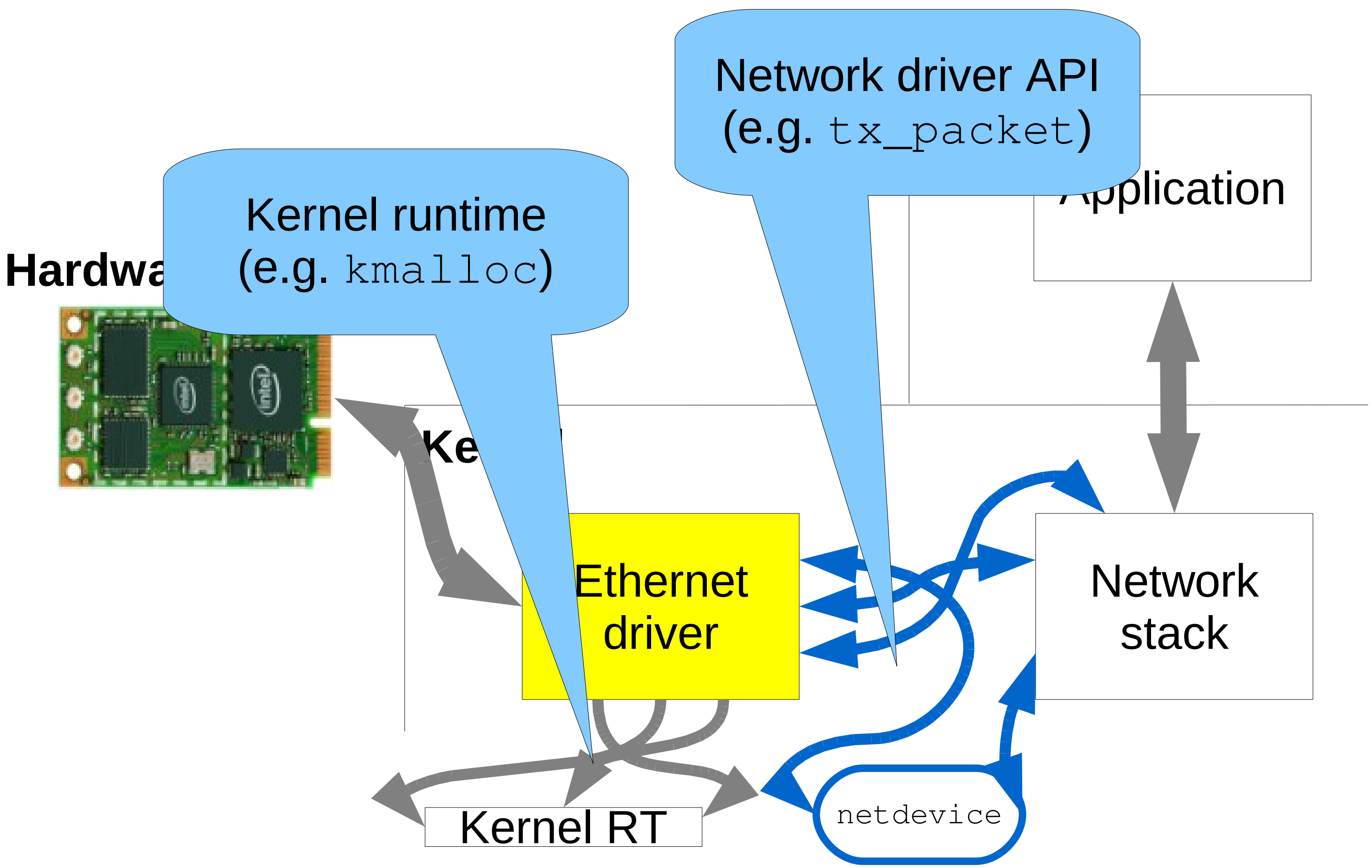
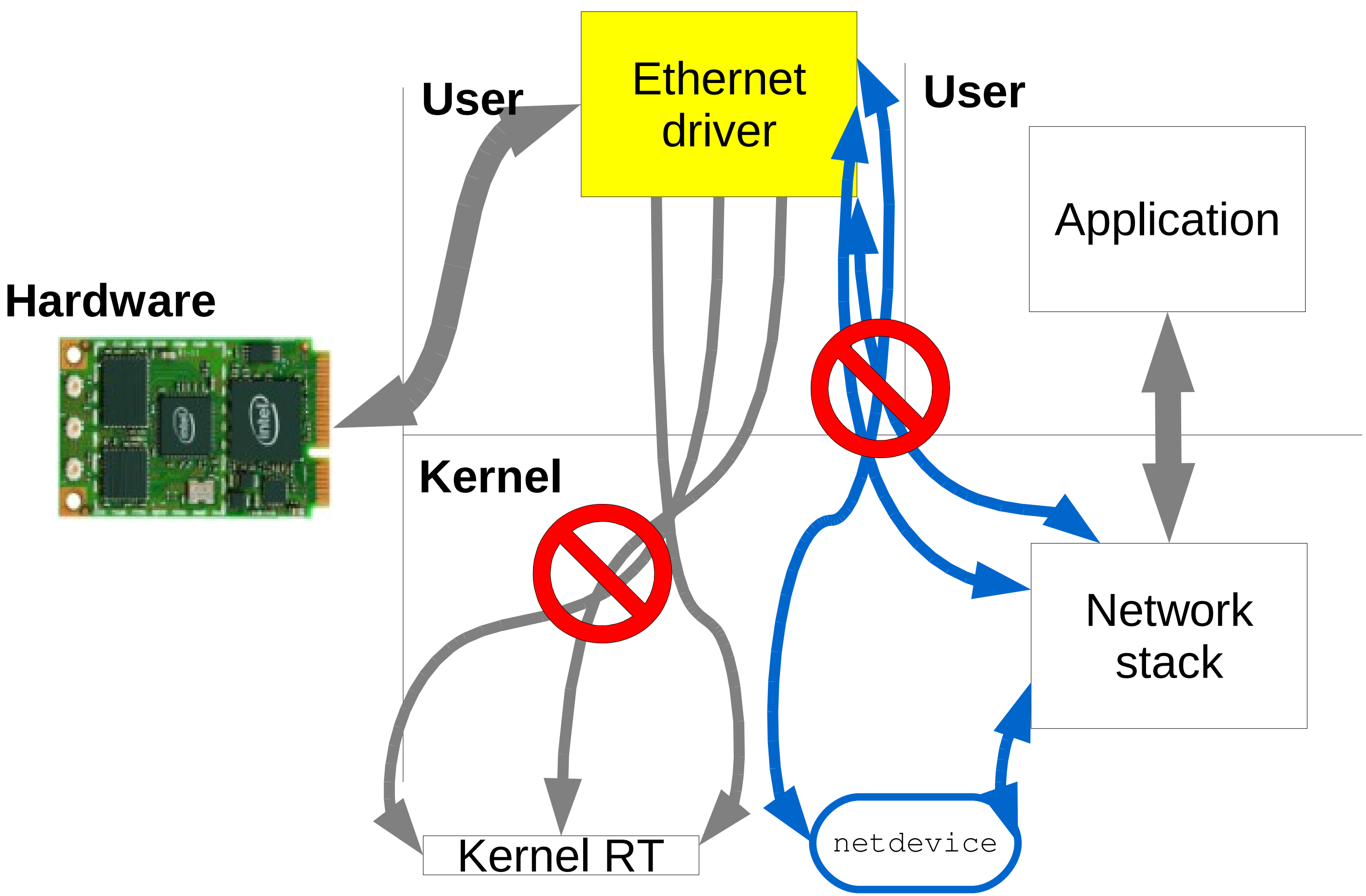
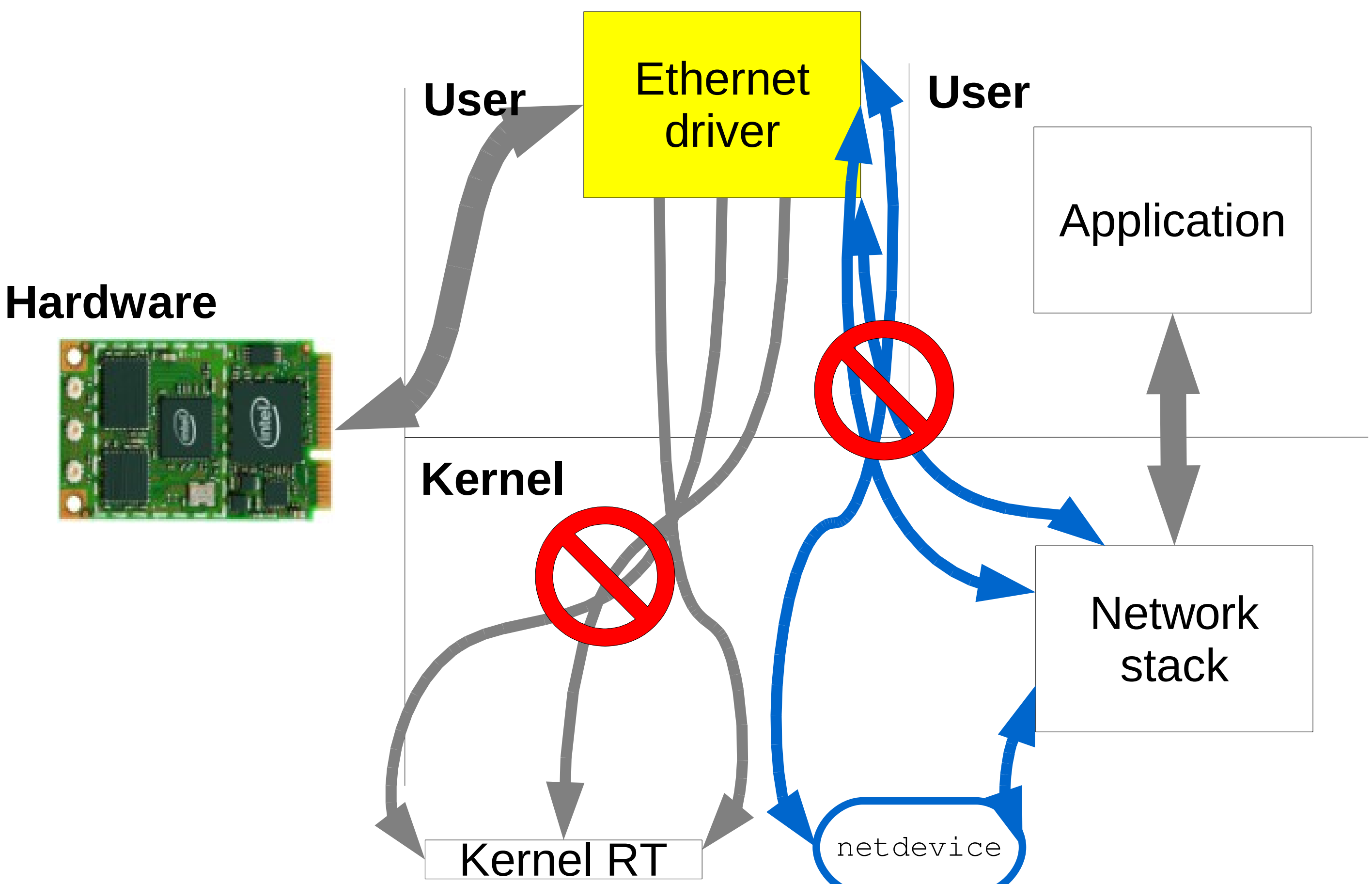


Linux user-space driver problem

Kernel RT and driver APIs won't work for untrusted drivers in a different AS

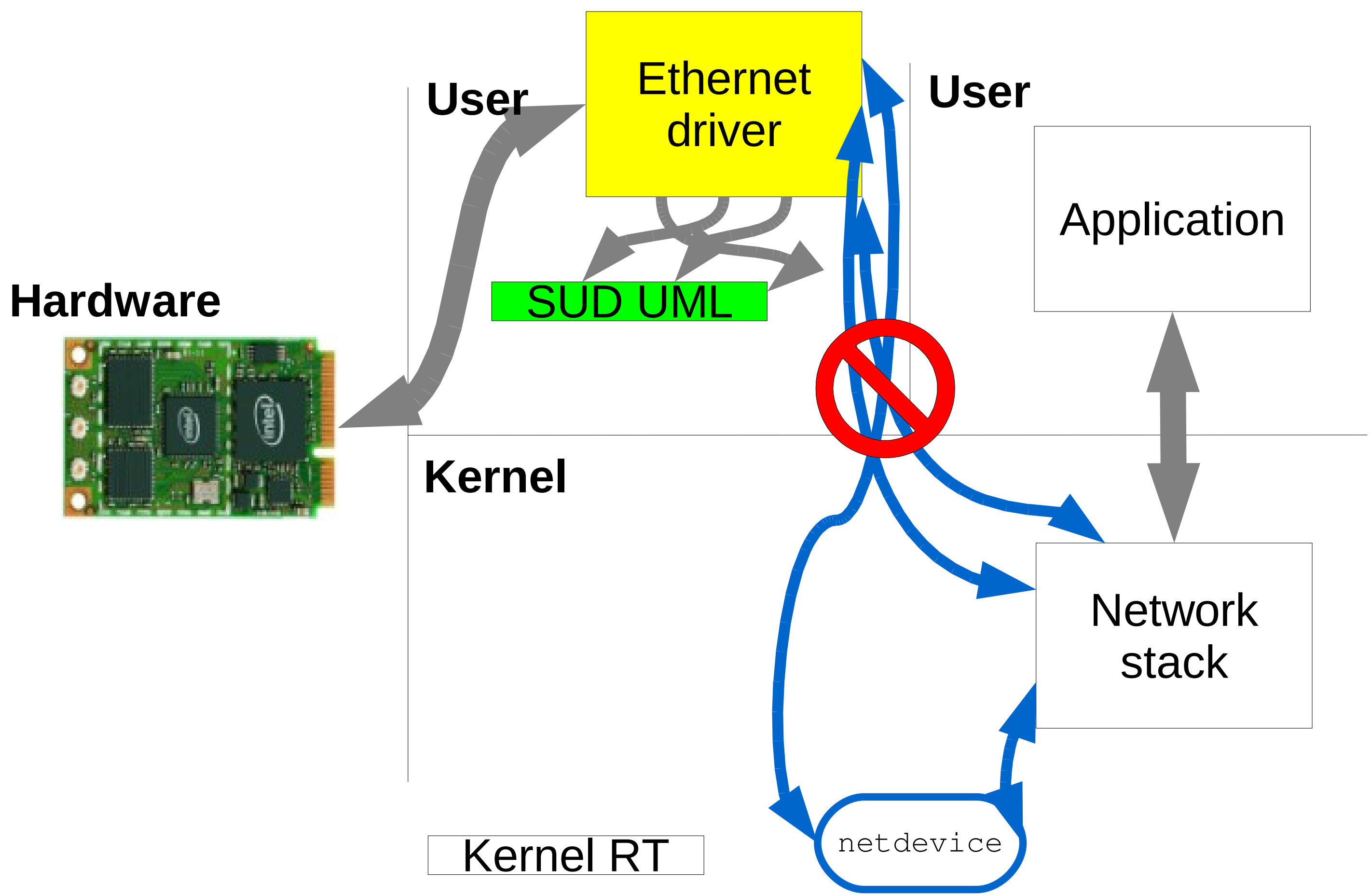


SUD's approach



SUD's approach

SUD UML handles calls to kernel RT



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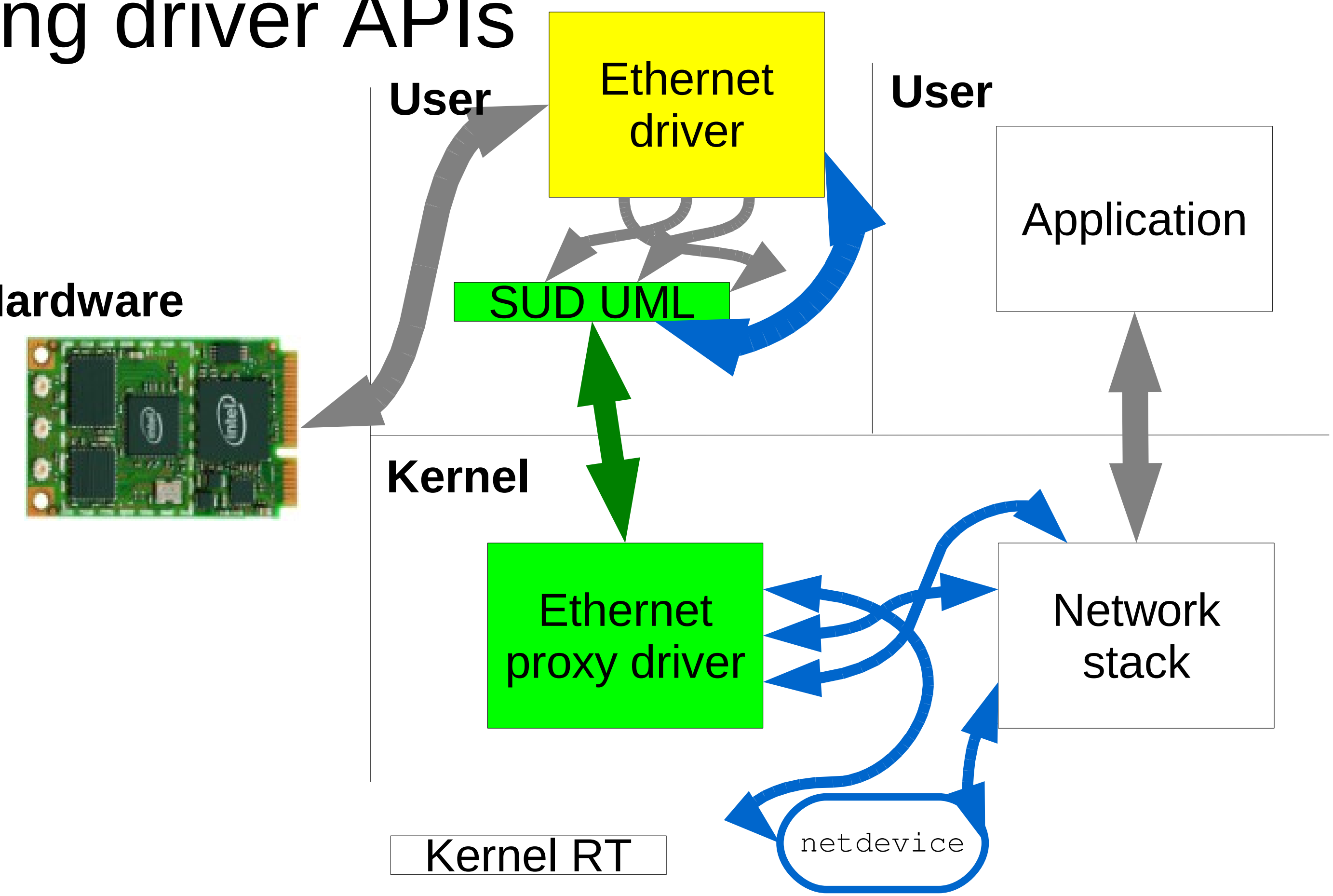
Proxy driver and SUD UML allow reuse of existing driver APIs



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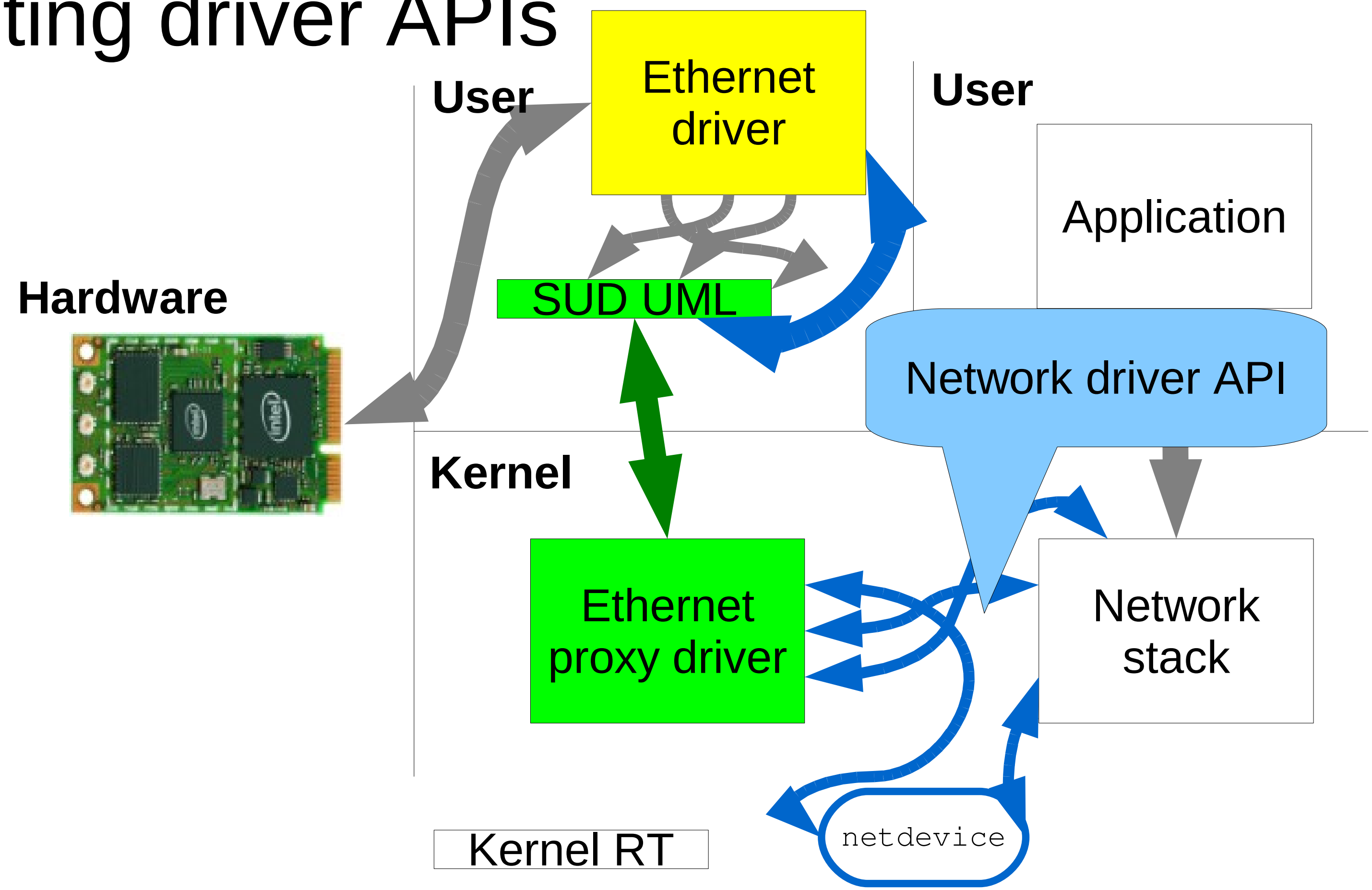

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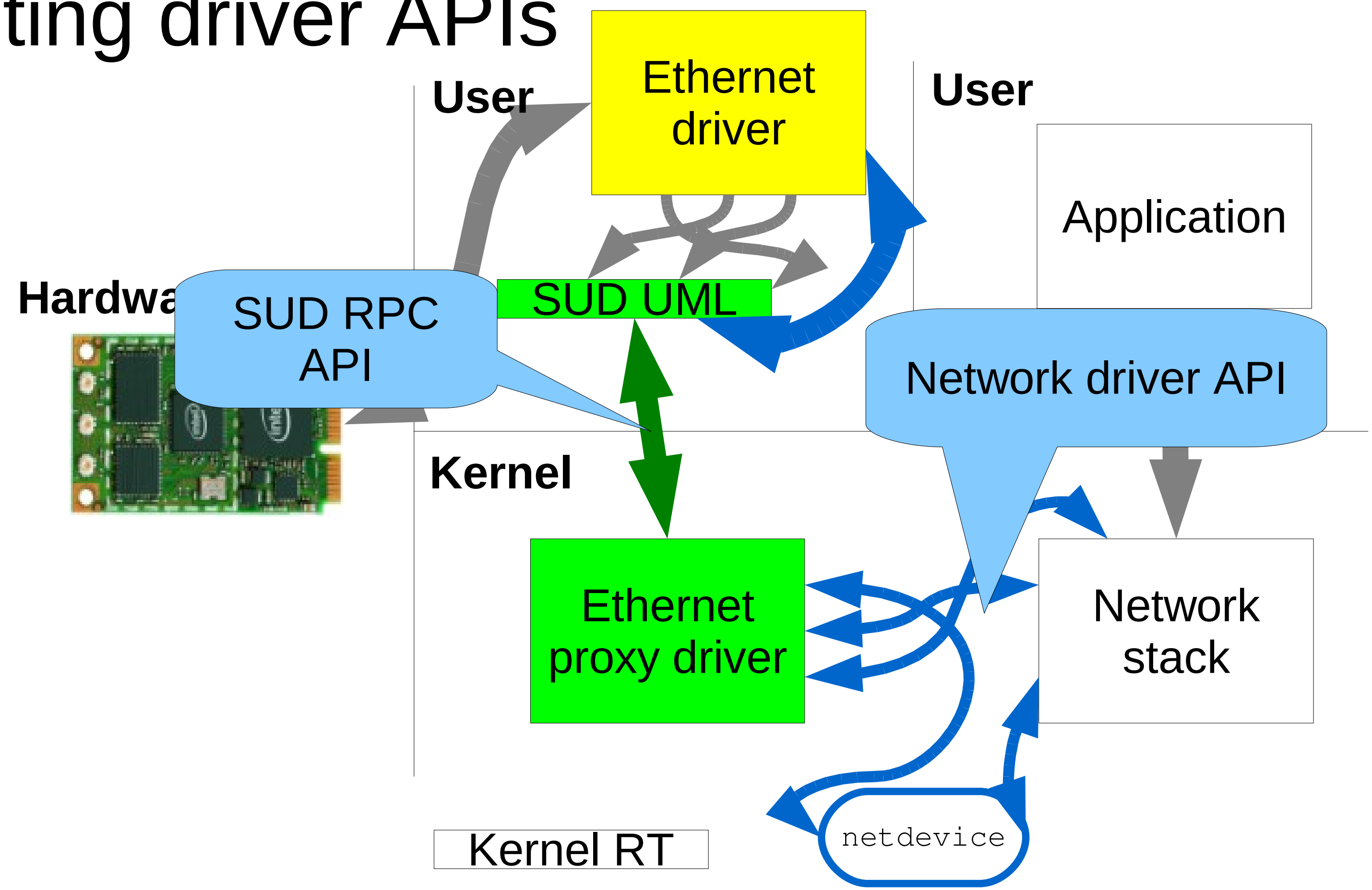

SUD's approach

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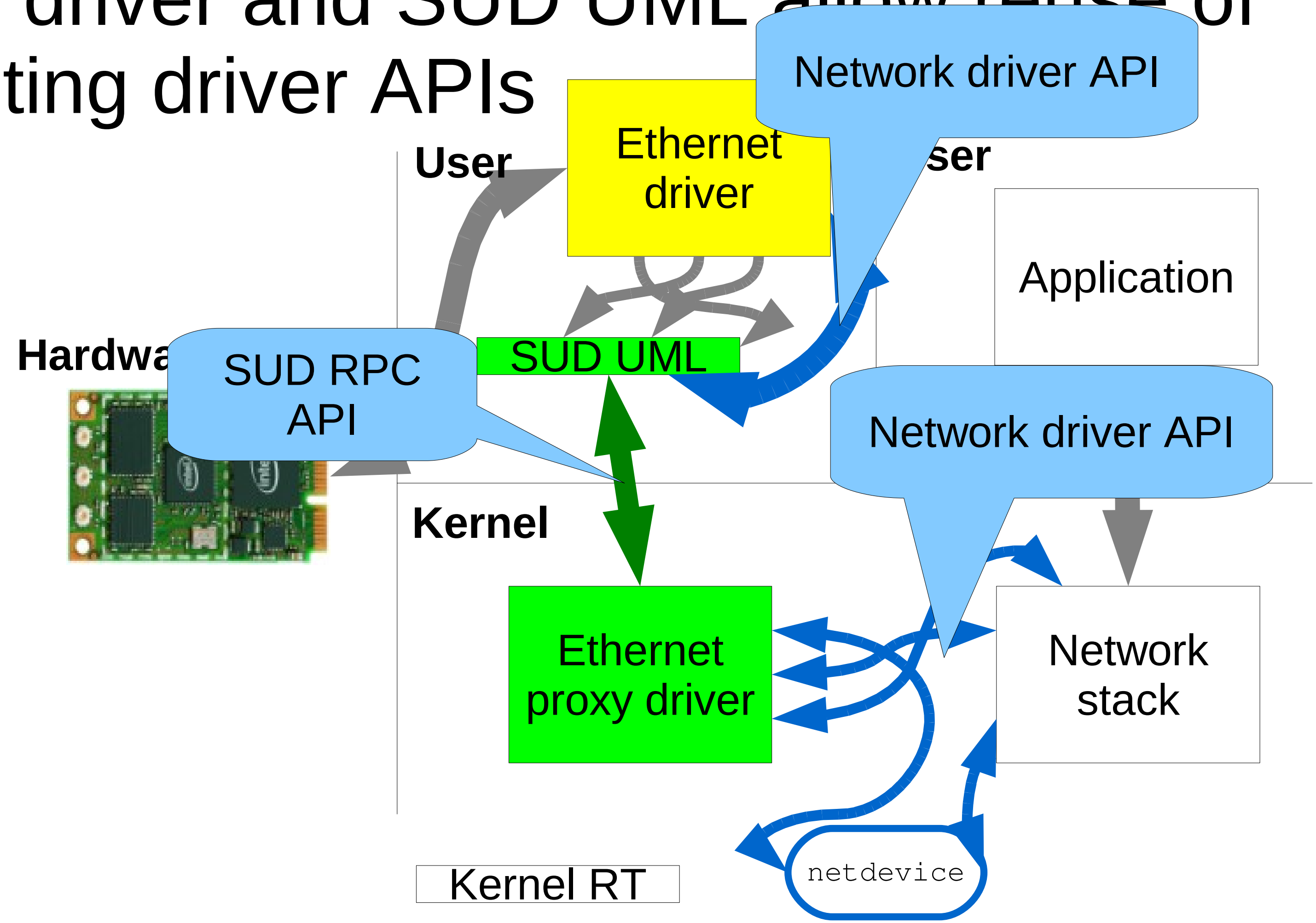


SUD's results

Tolerate malicious device drivers

Proxy drivers small (~500 LOC)

One proxy driver per device class

Few kernel modifications (~50 LOC)

Unmodified drivers (6 test drivers)

High performance, low overhead

No need for new OS or language

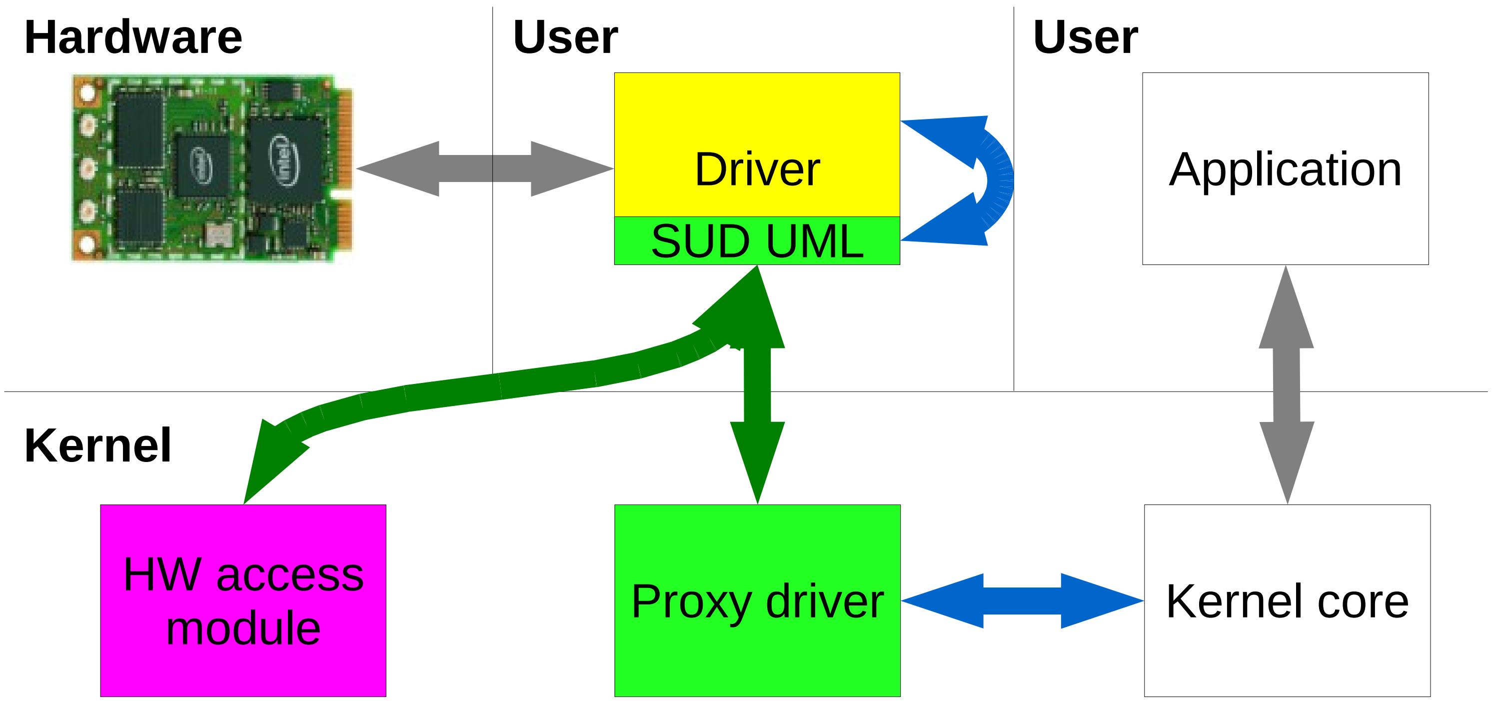
Security challenge: prevent attacks

- Problem: driver must perform privileged operations
  - Memory access, driver API, DMA, interrupts, …
- Attacks from driver code:
  - Direct system attacks: memory corruption, ...
  - Driver API attacks: invalid return value, deadlock, ...
- Attacks from device:
  - DMA to DRAM, peer-to-peer attacks, interrupt storms

Practical challenges

- High performance, low overhead
  - Challenge: interact with hardware and kernel at high rate, kernel-user switch expensive
  - E.g. Ethernet driver ~100k times a second
- Reuse existing drivers and kernel
  - Challenge: drivers assume fully-privileged kernel env.
  - Challenge: kernel driver API complex, non-uniform

SUD overview



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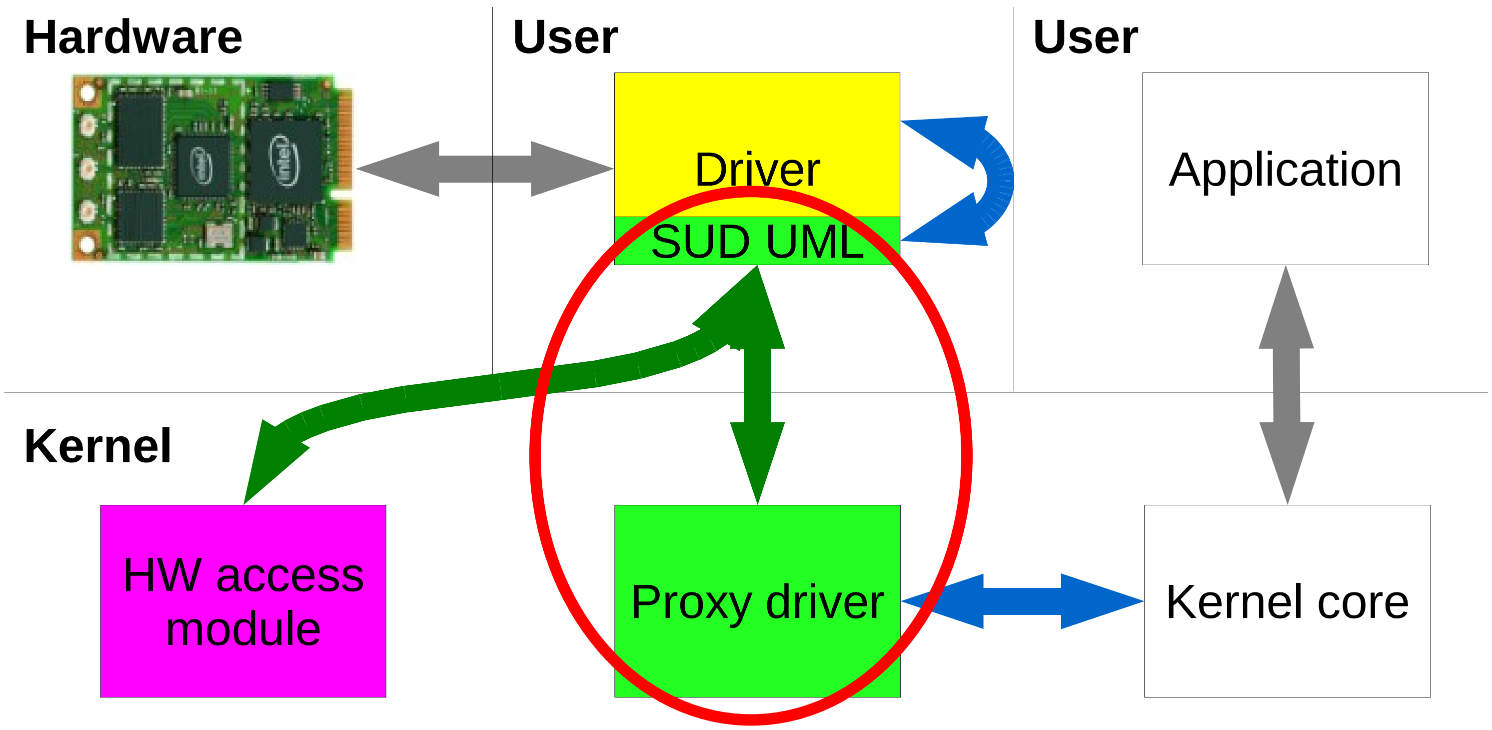

Linux driver APIs

- Linux defines a driver API for each device class
  - Driver and kernel functions and variables

Example: wireless driver API

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- Driver and kernel functions and variables

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struct wireless_ops {
    int (*tx)(struct sk_buff*);
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Called in a non-preemptable context

Driver API variable

Proxy drivers and SUD-UML convert API to RPCs

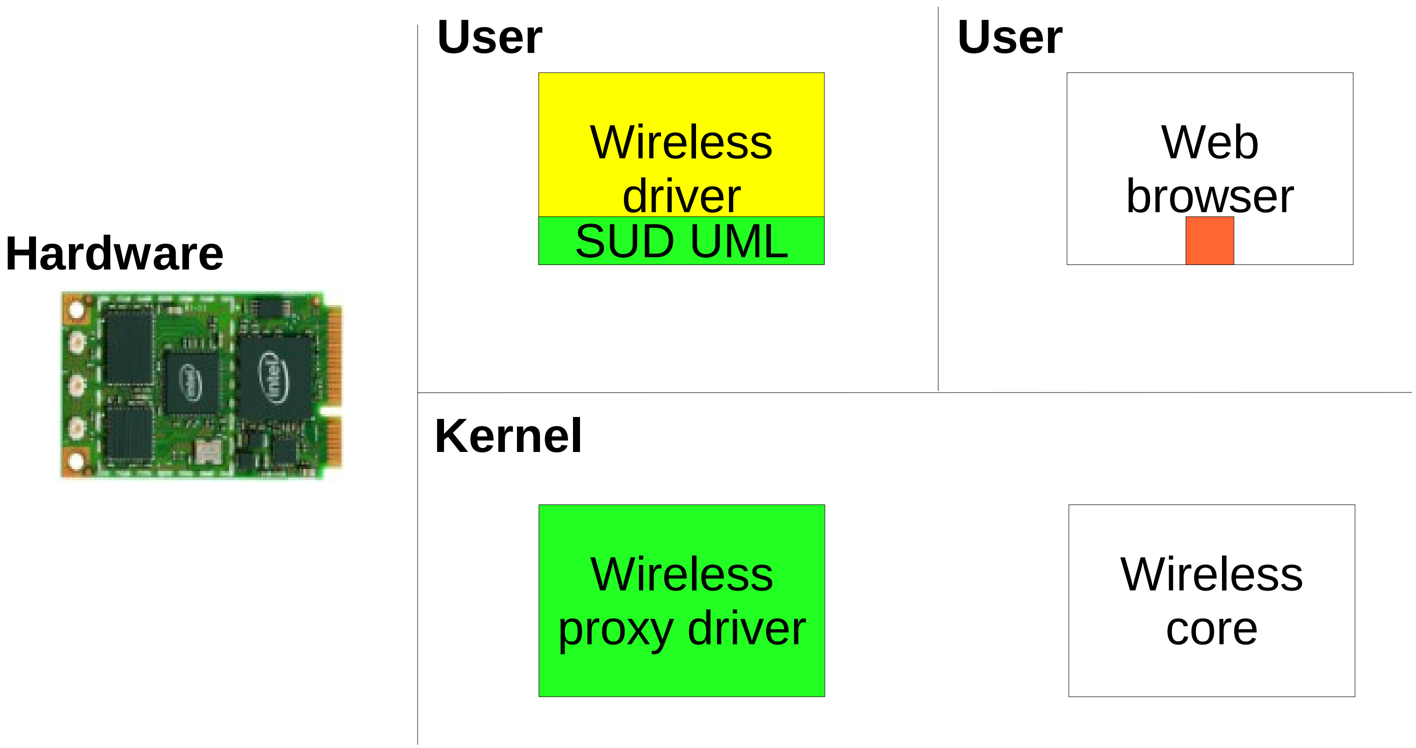
Wireless driver in SUD

Basic driver API → SUD RPC API → driver API

Non-preemptable function: implement in proxy

Driver API variable: shadow variables

Example 1: transmit a packet



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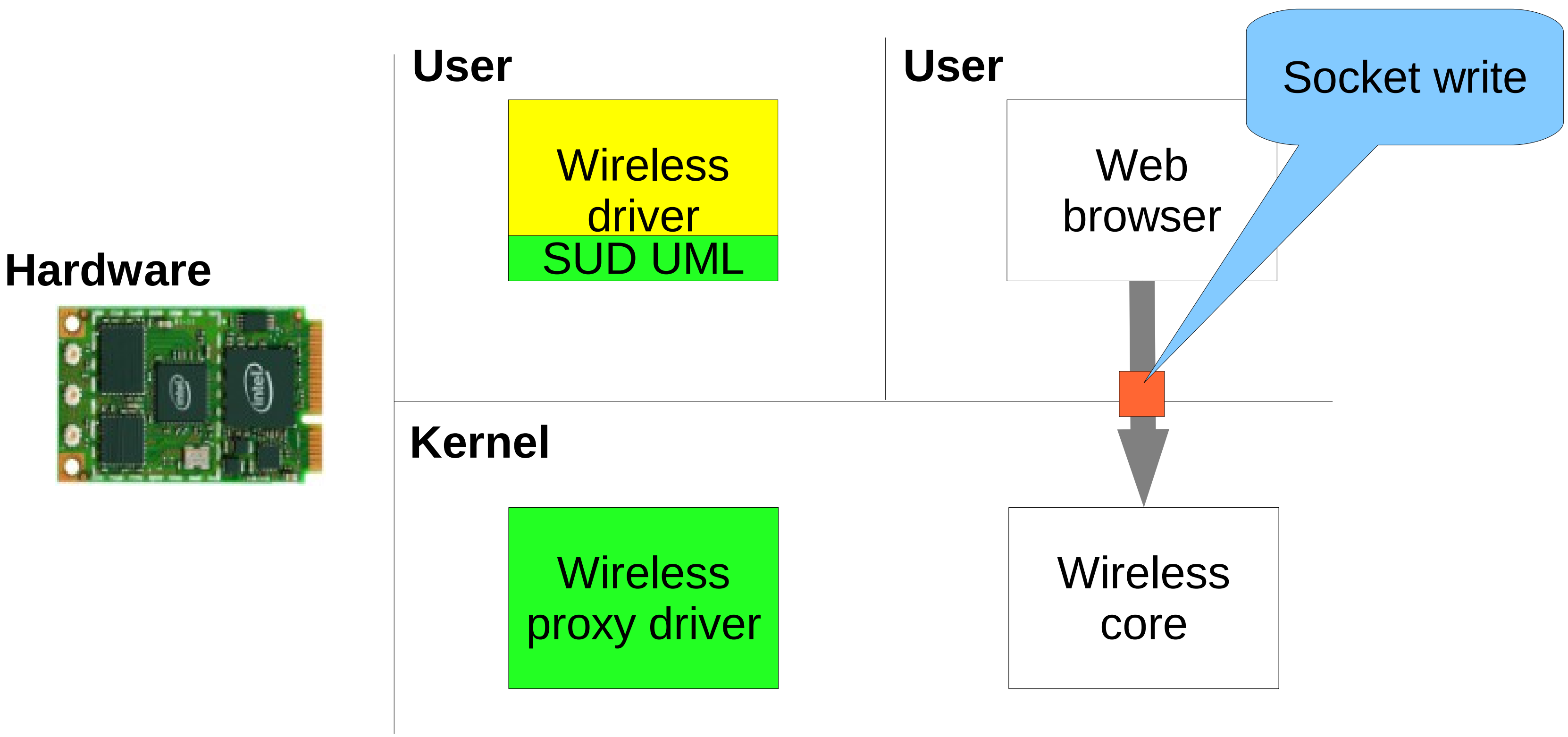

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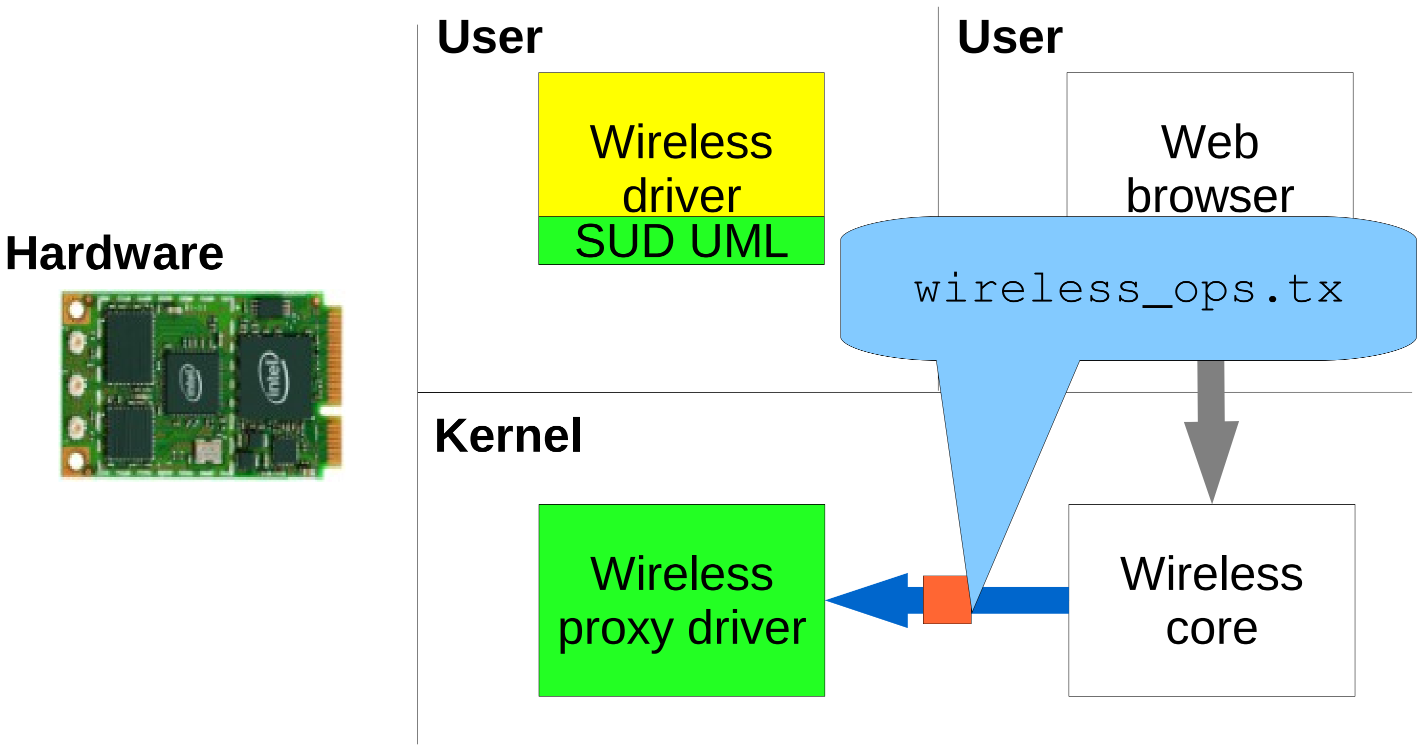

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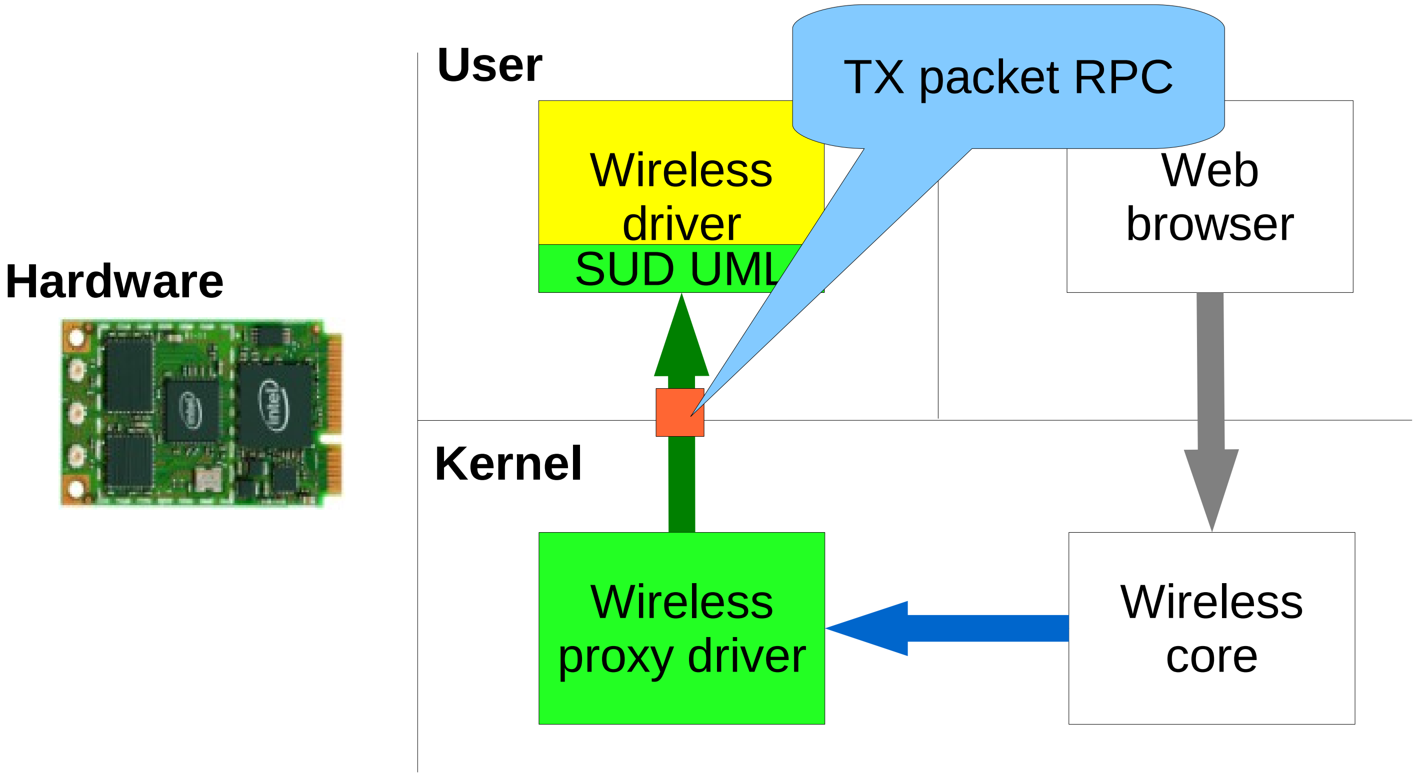

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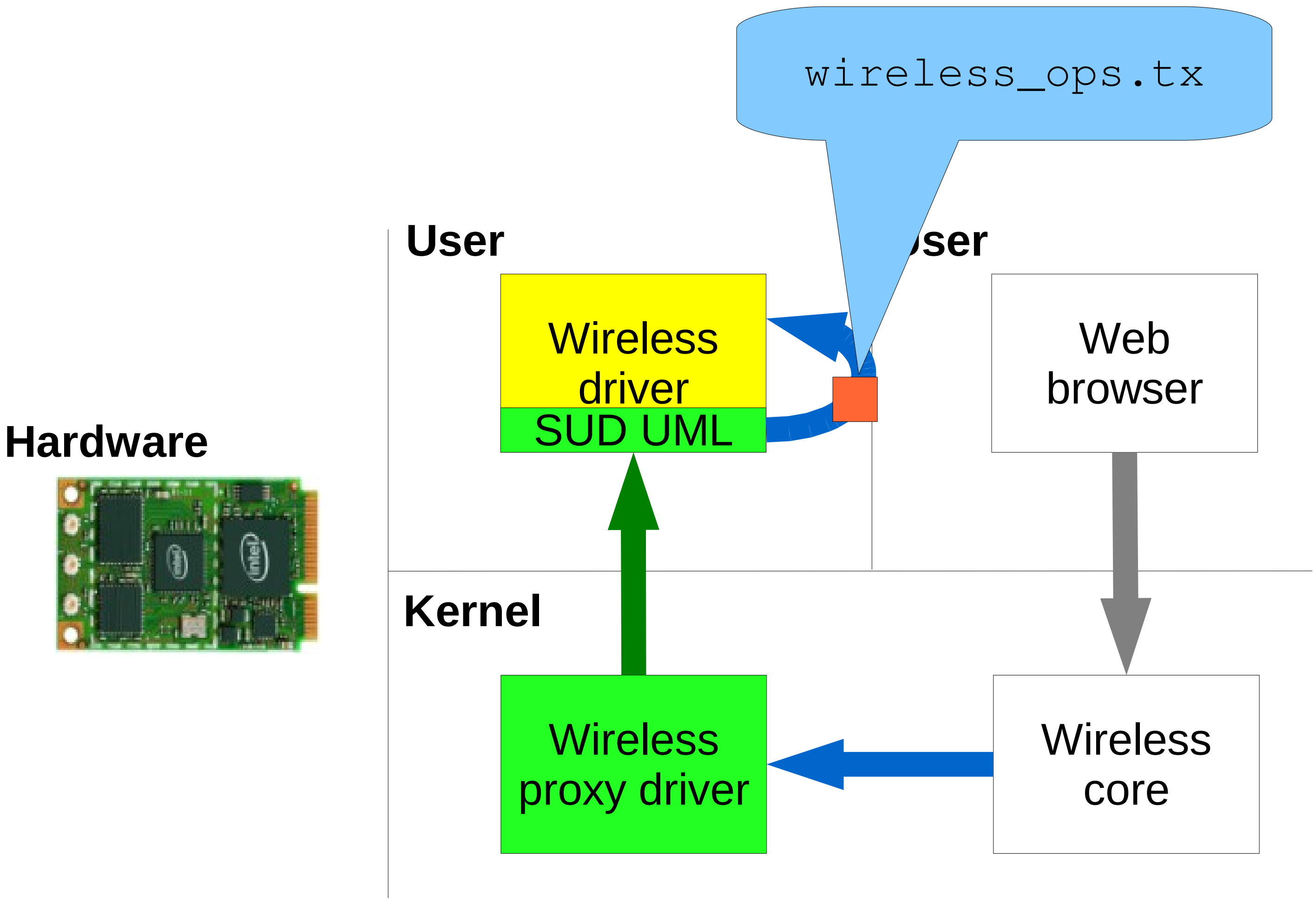

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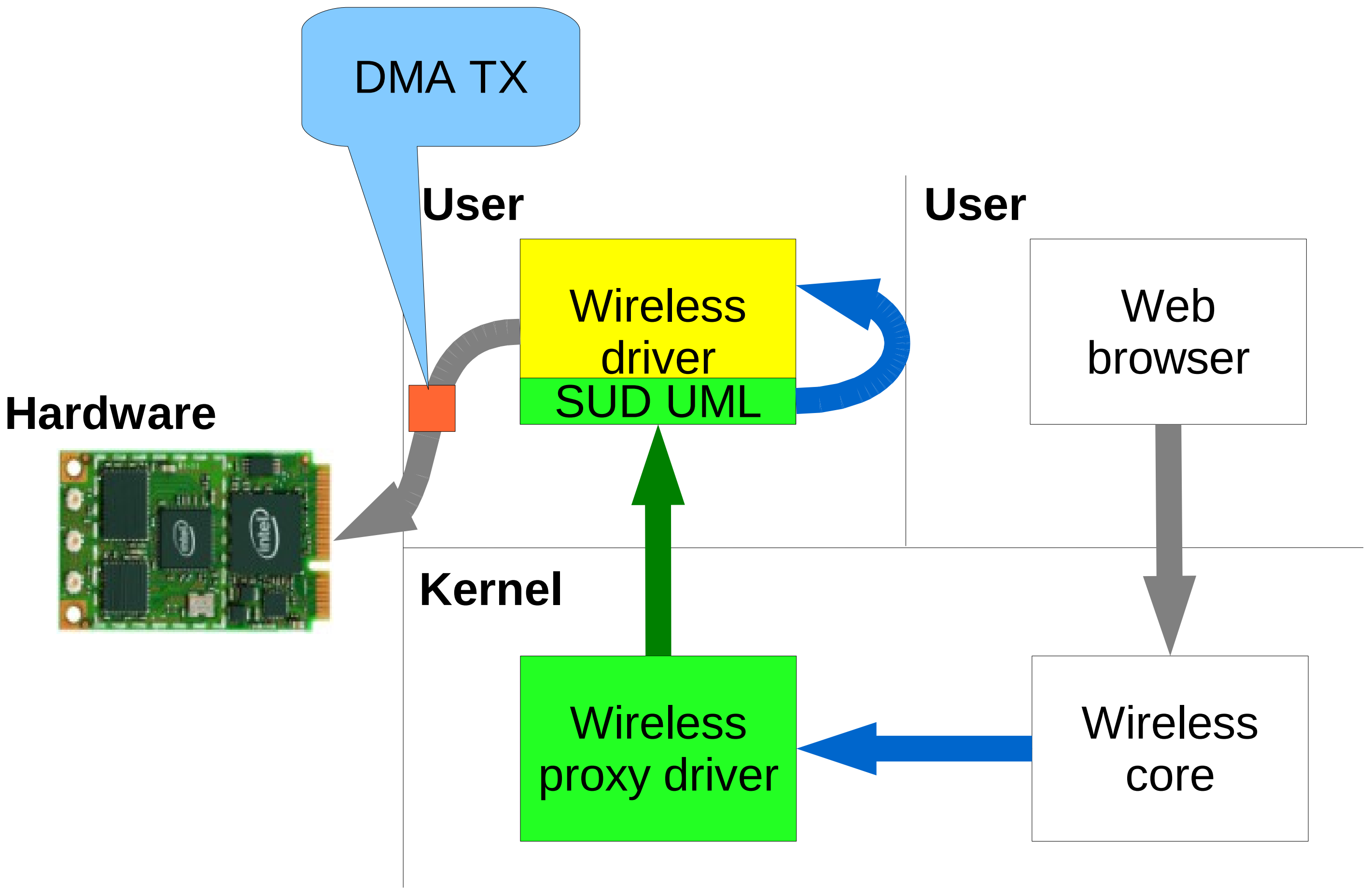
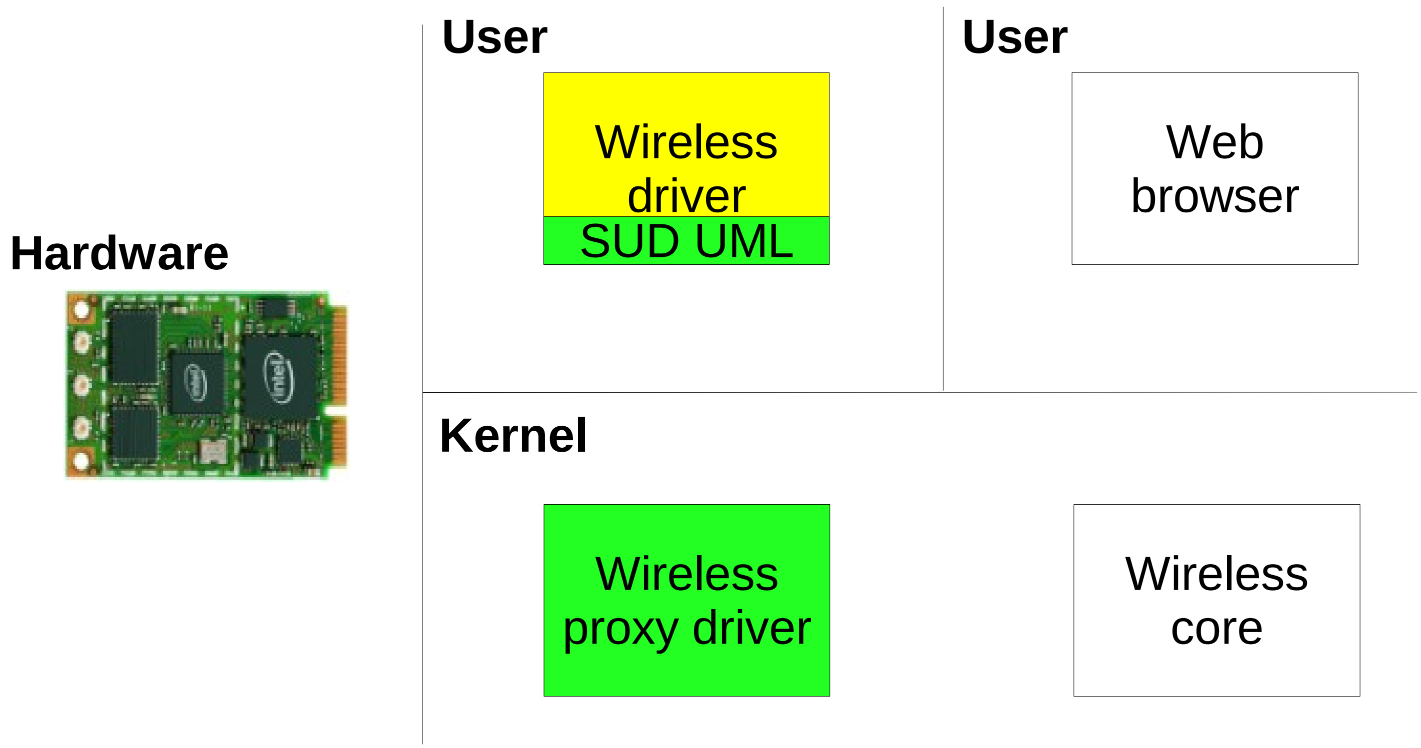


Example 2: non-preemptable callback

Problem: unable to switch to user-space



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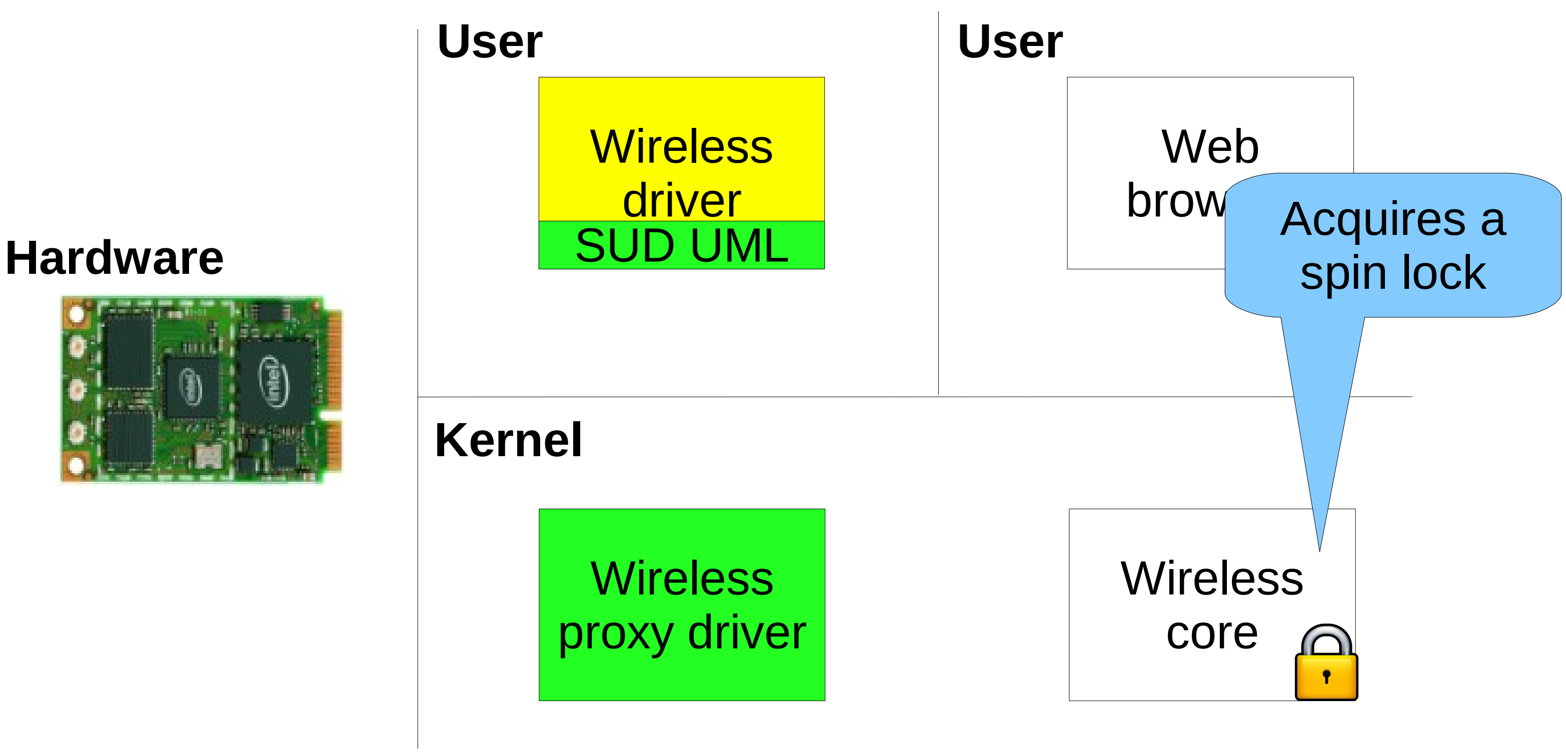

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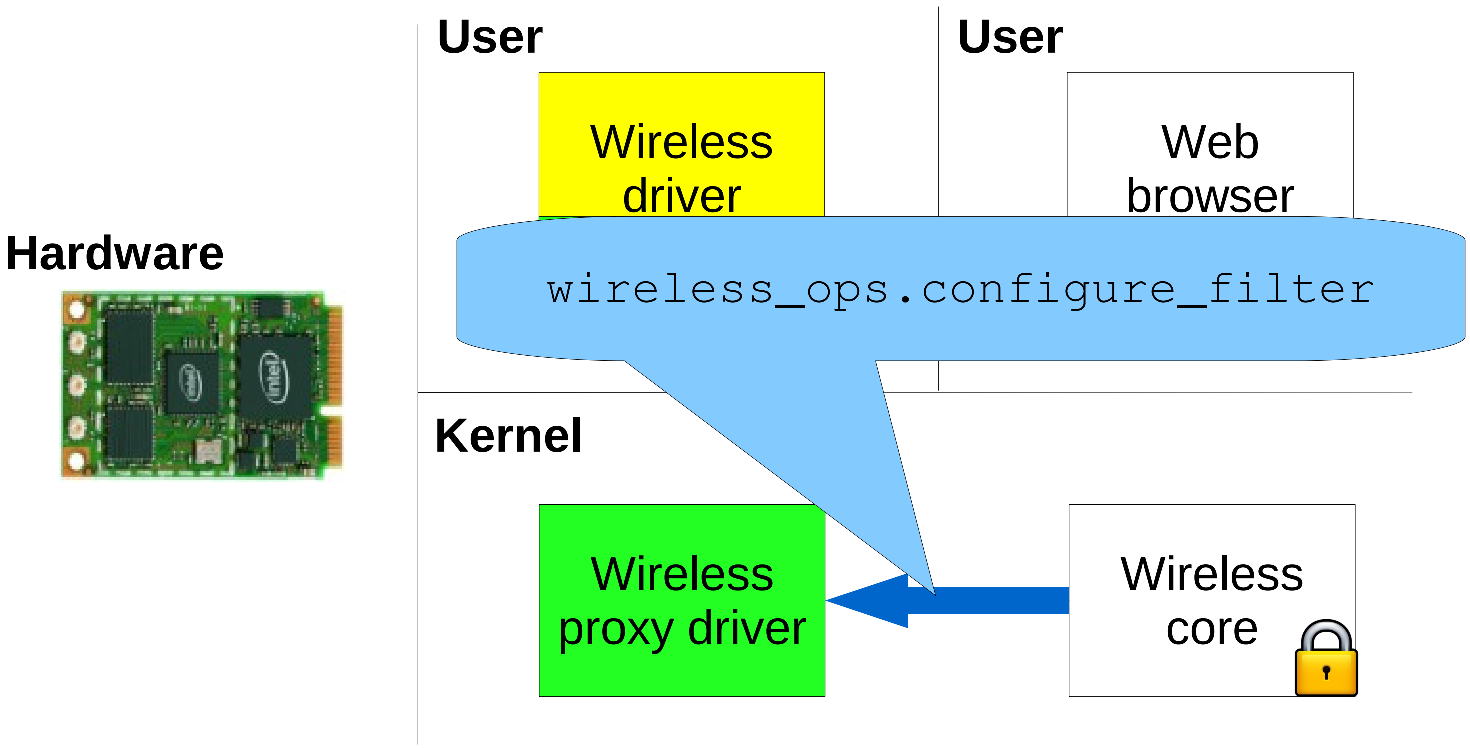

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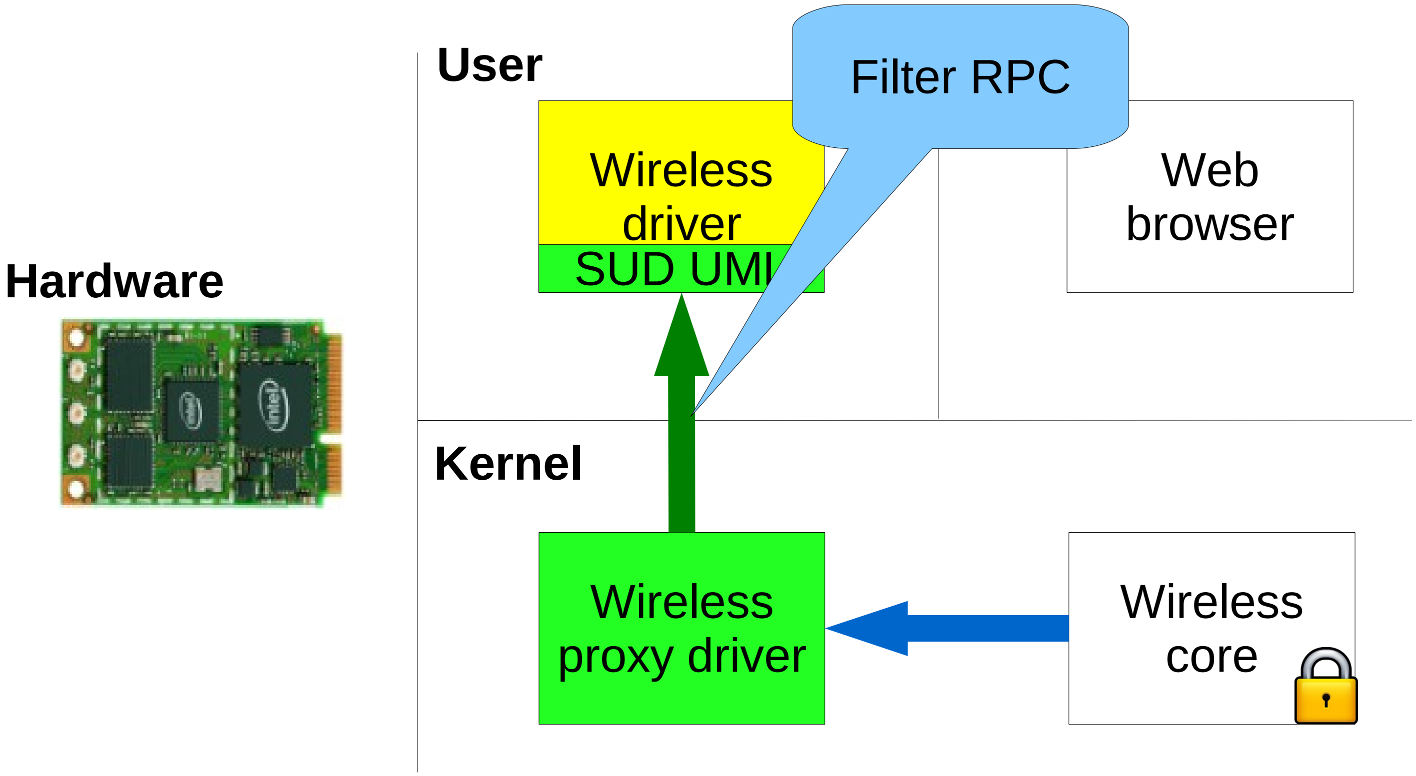

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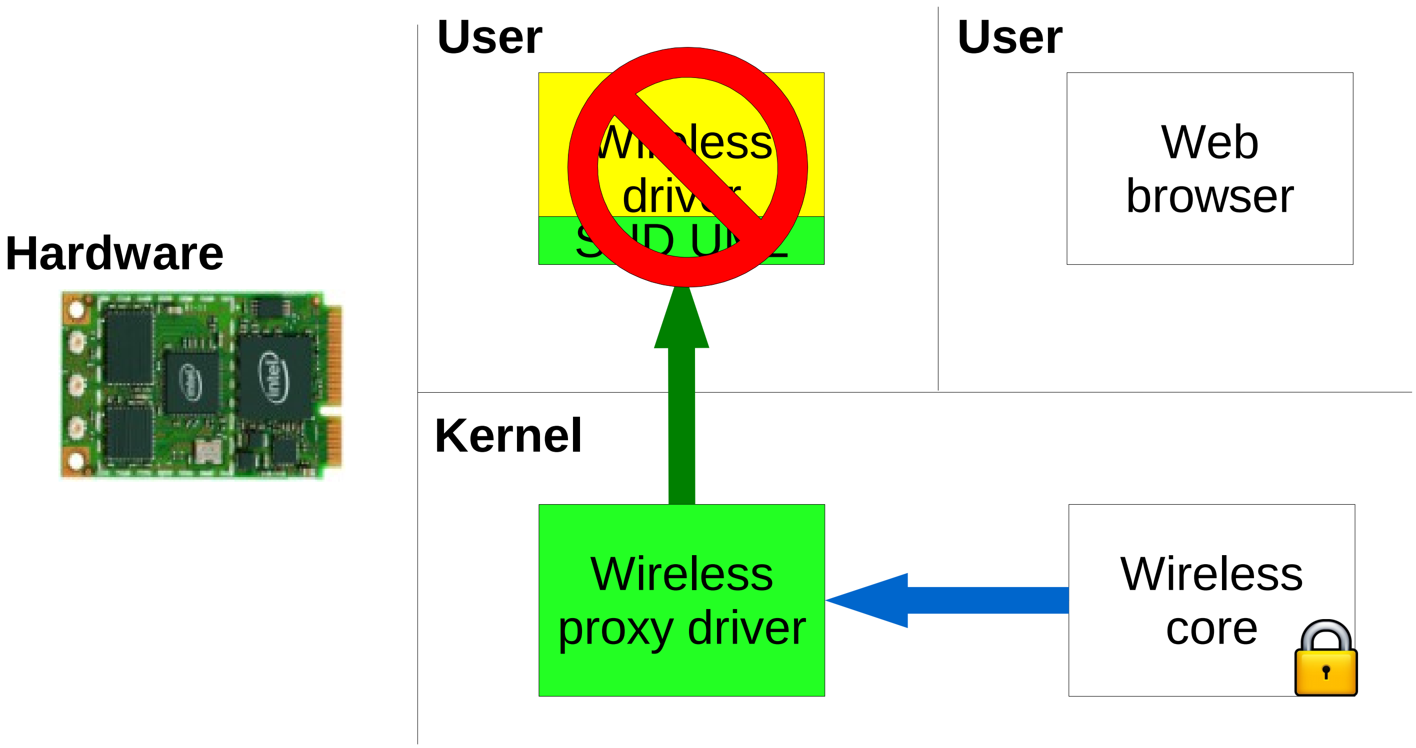

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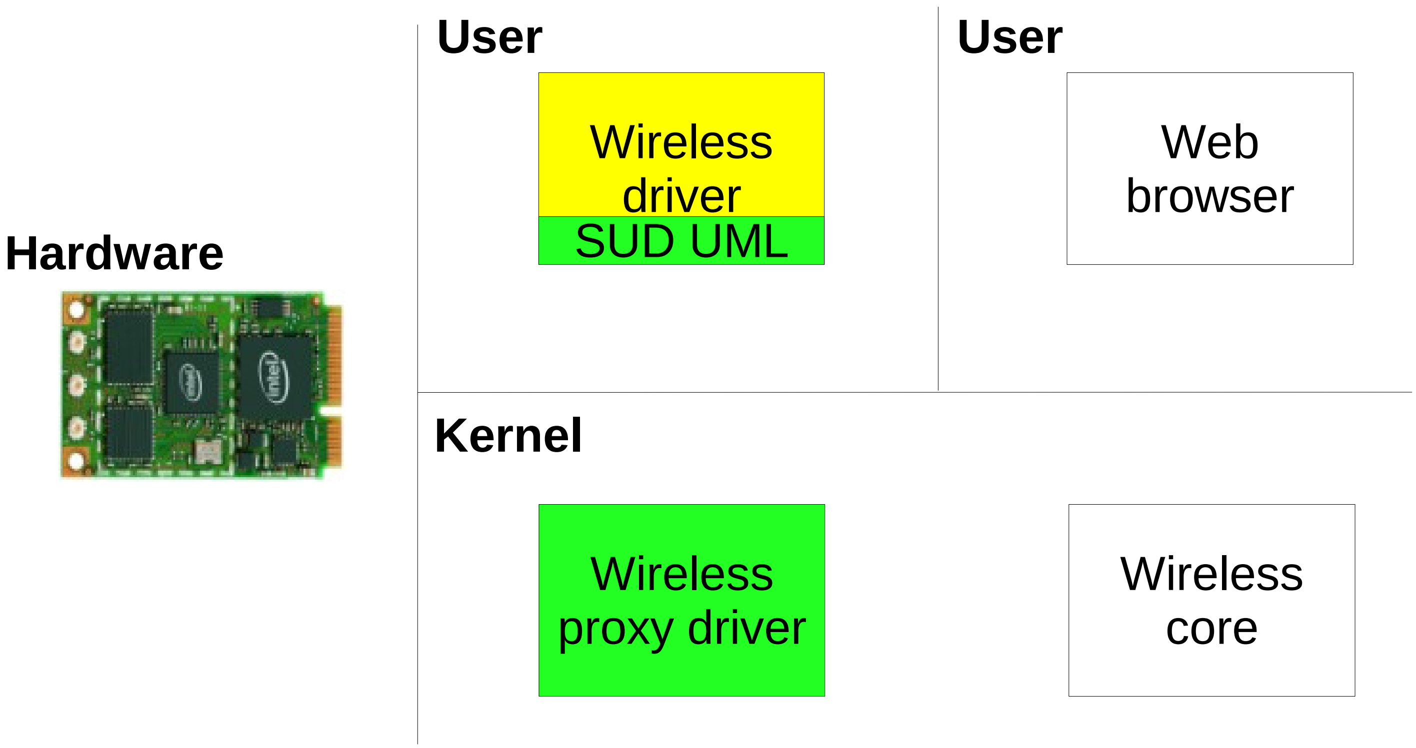

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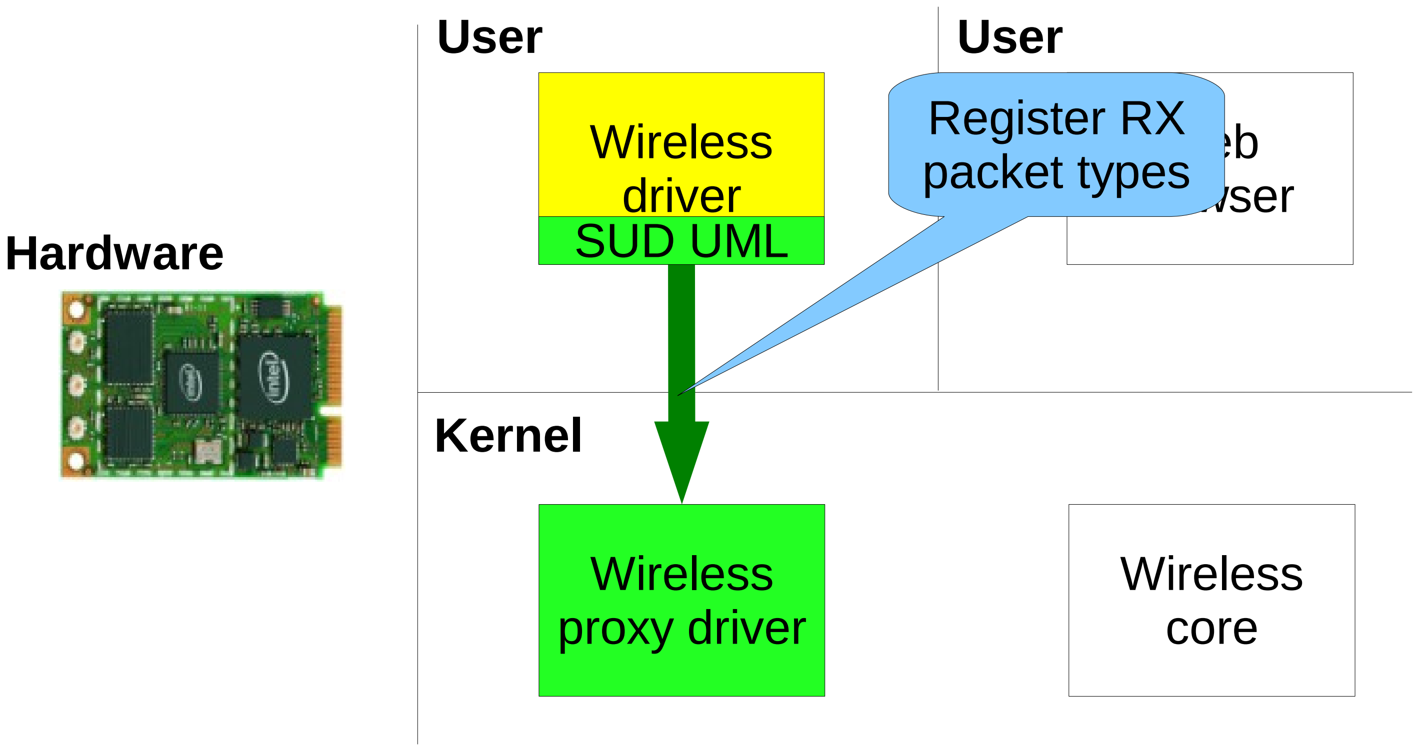

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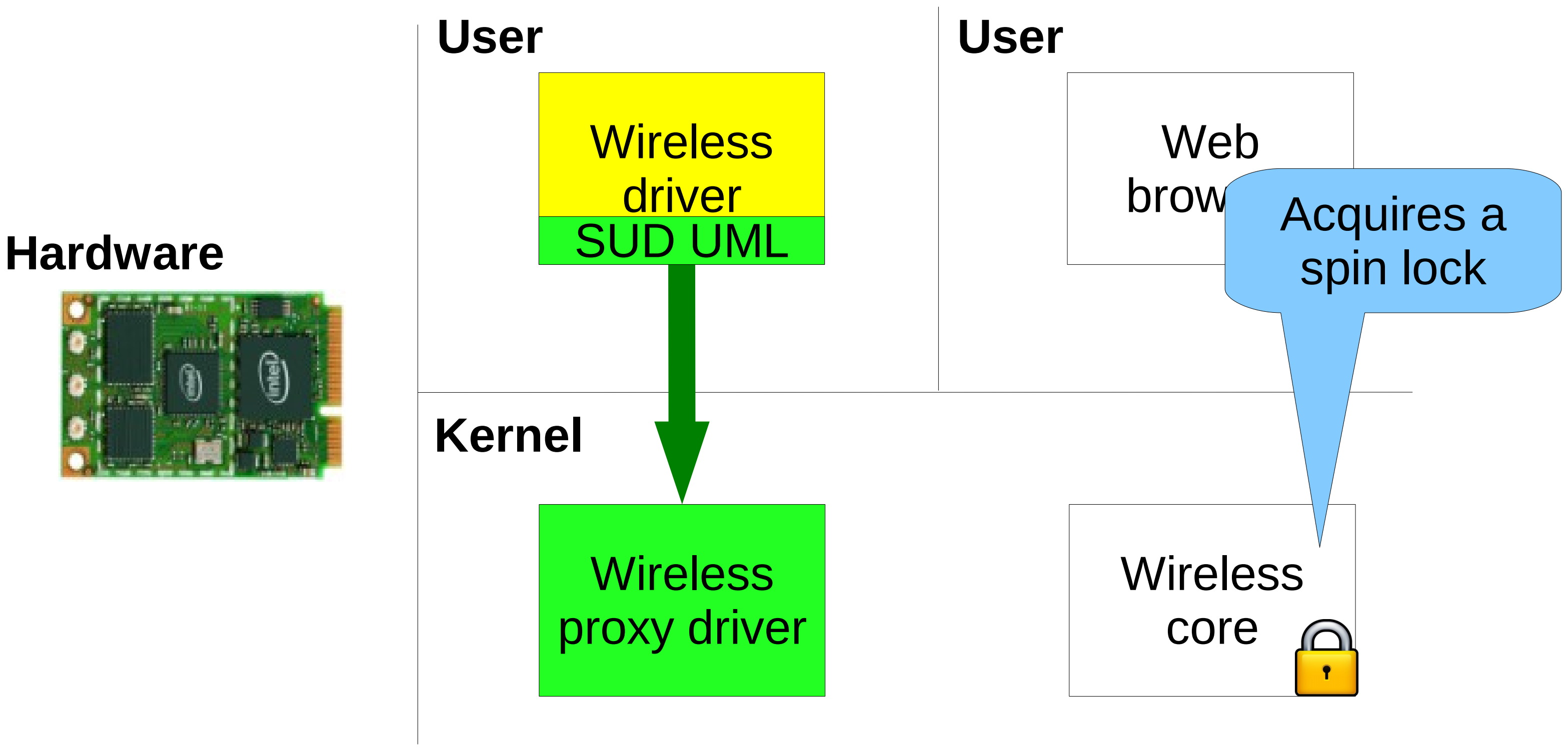

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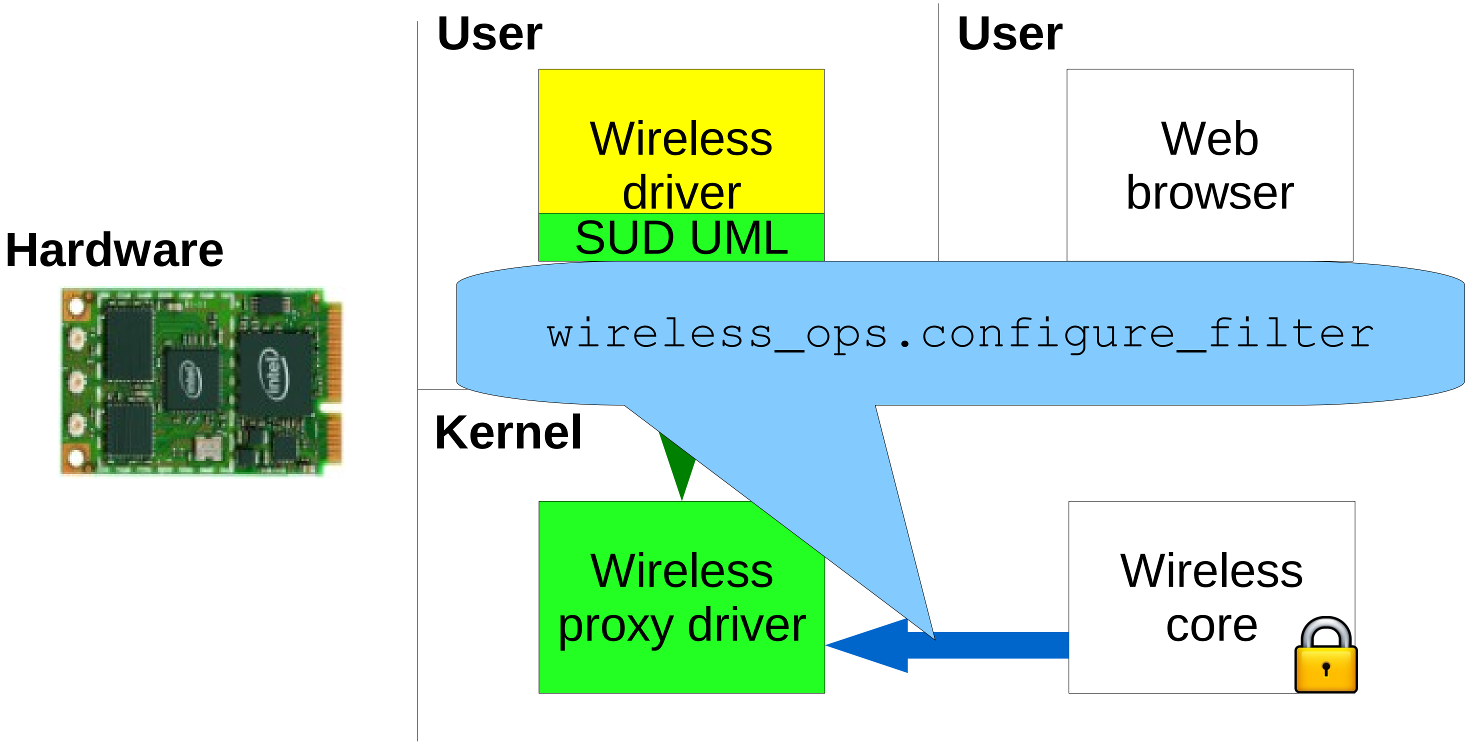

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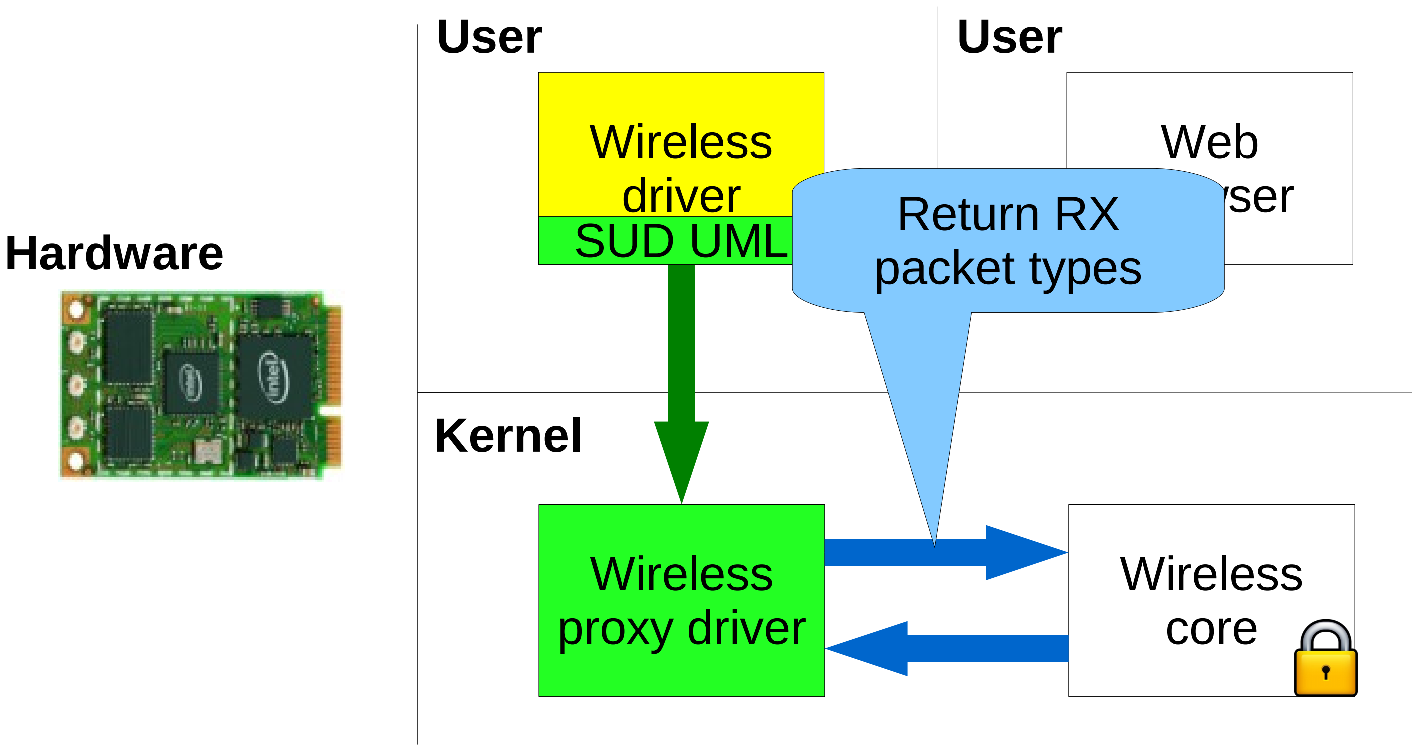

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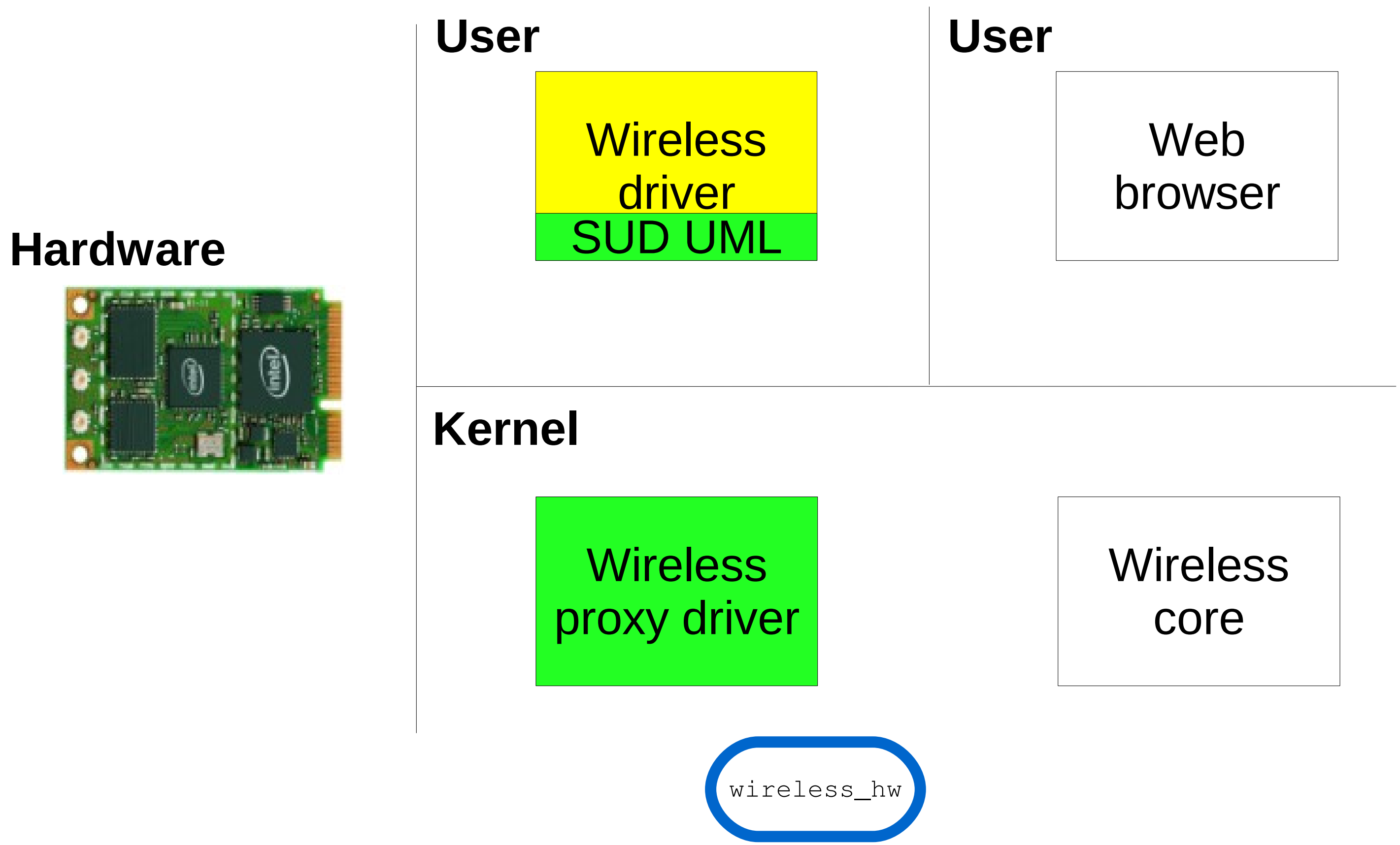

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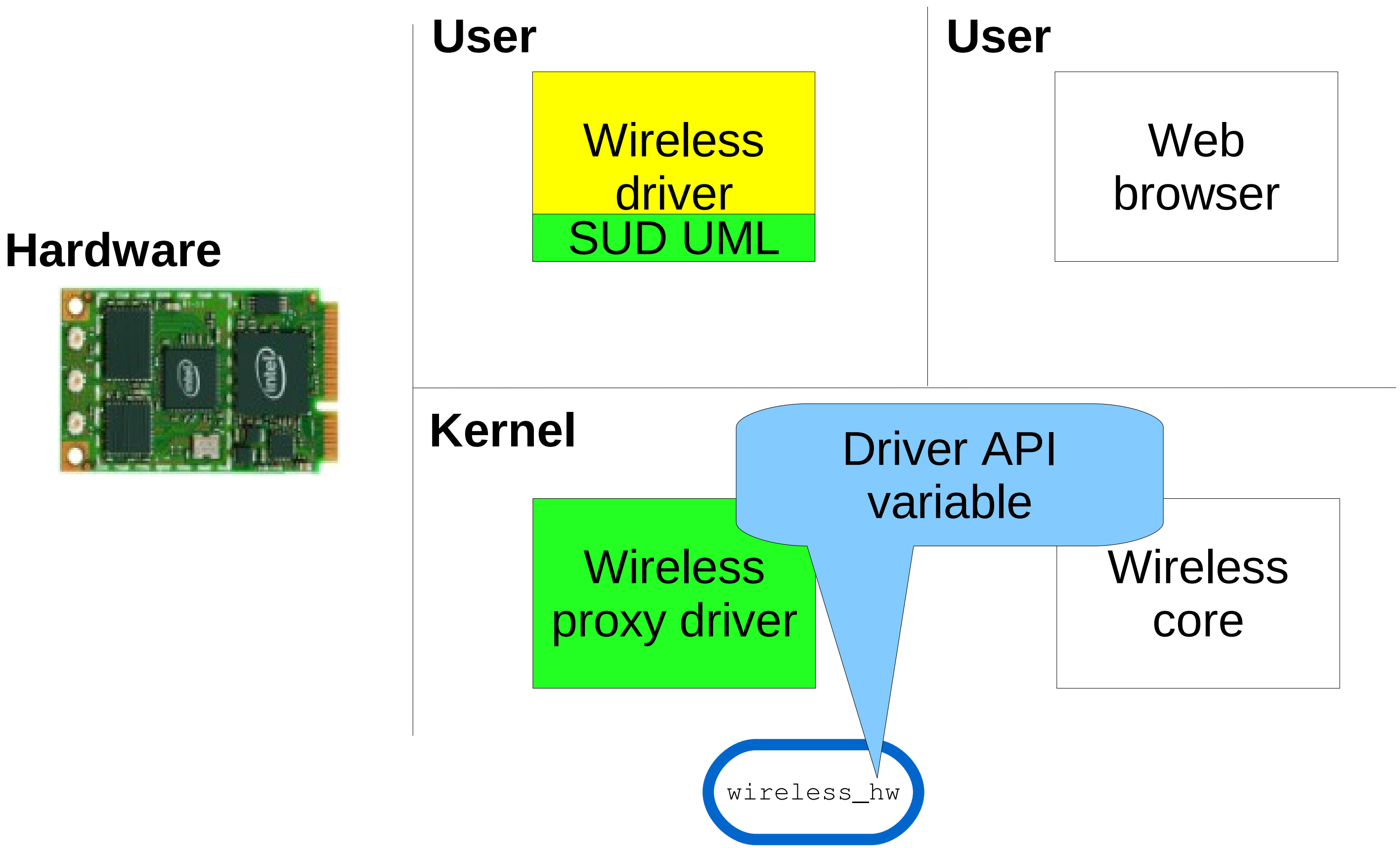

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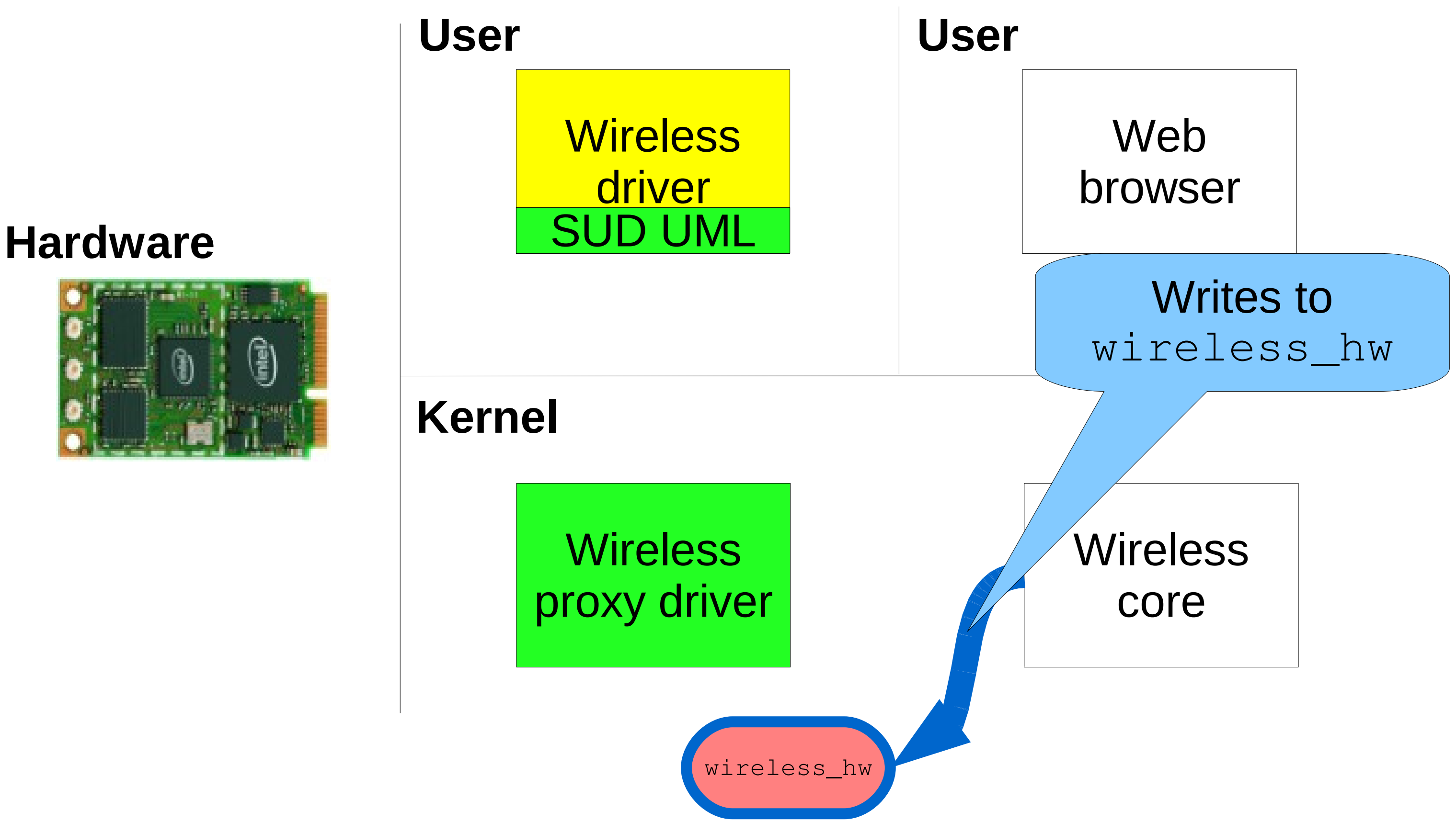

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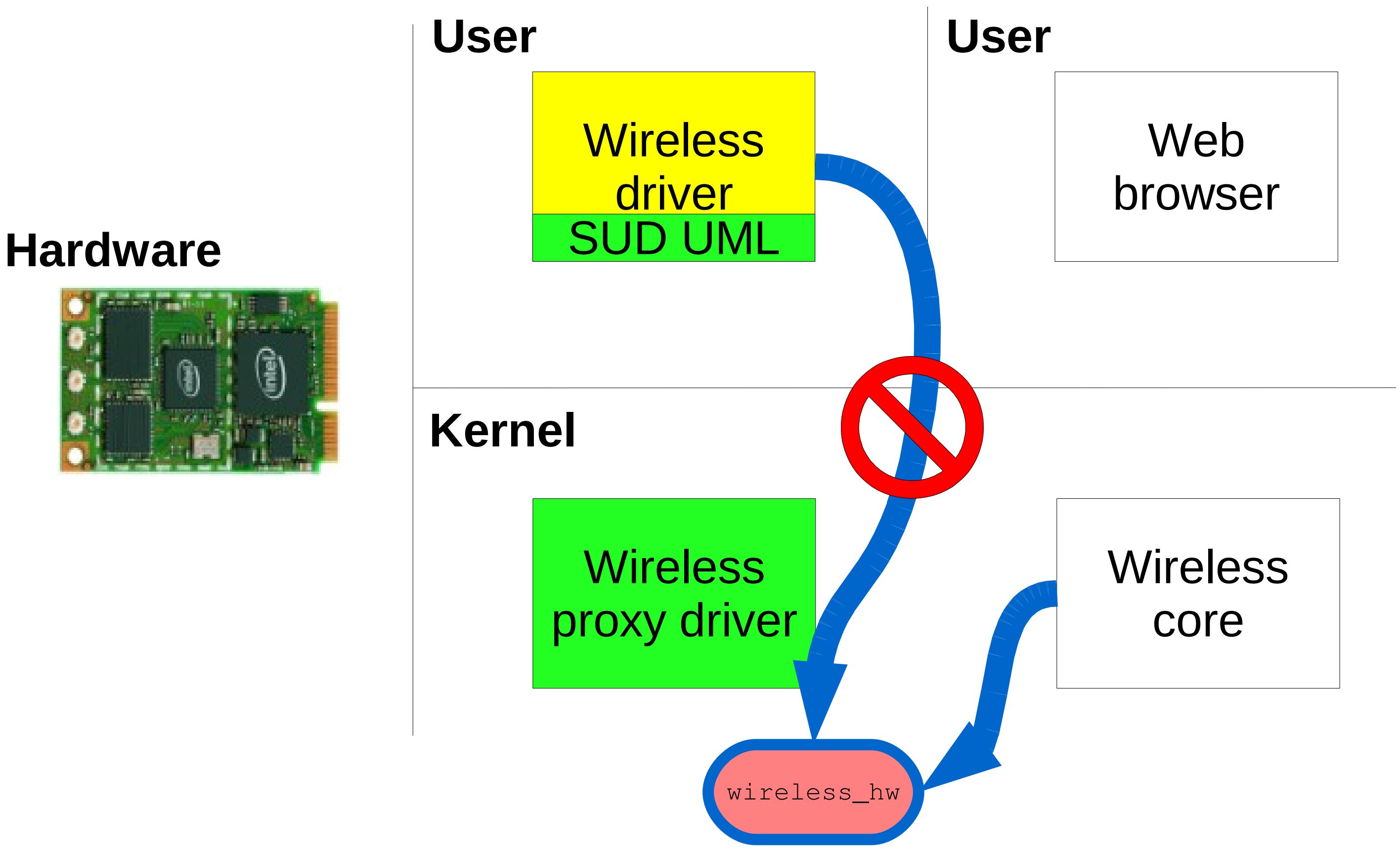

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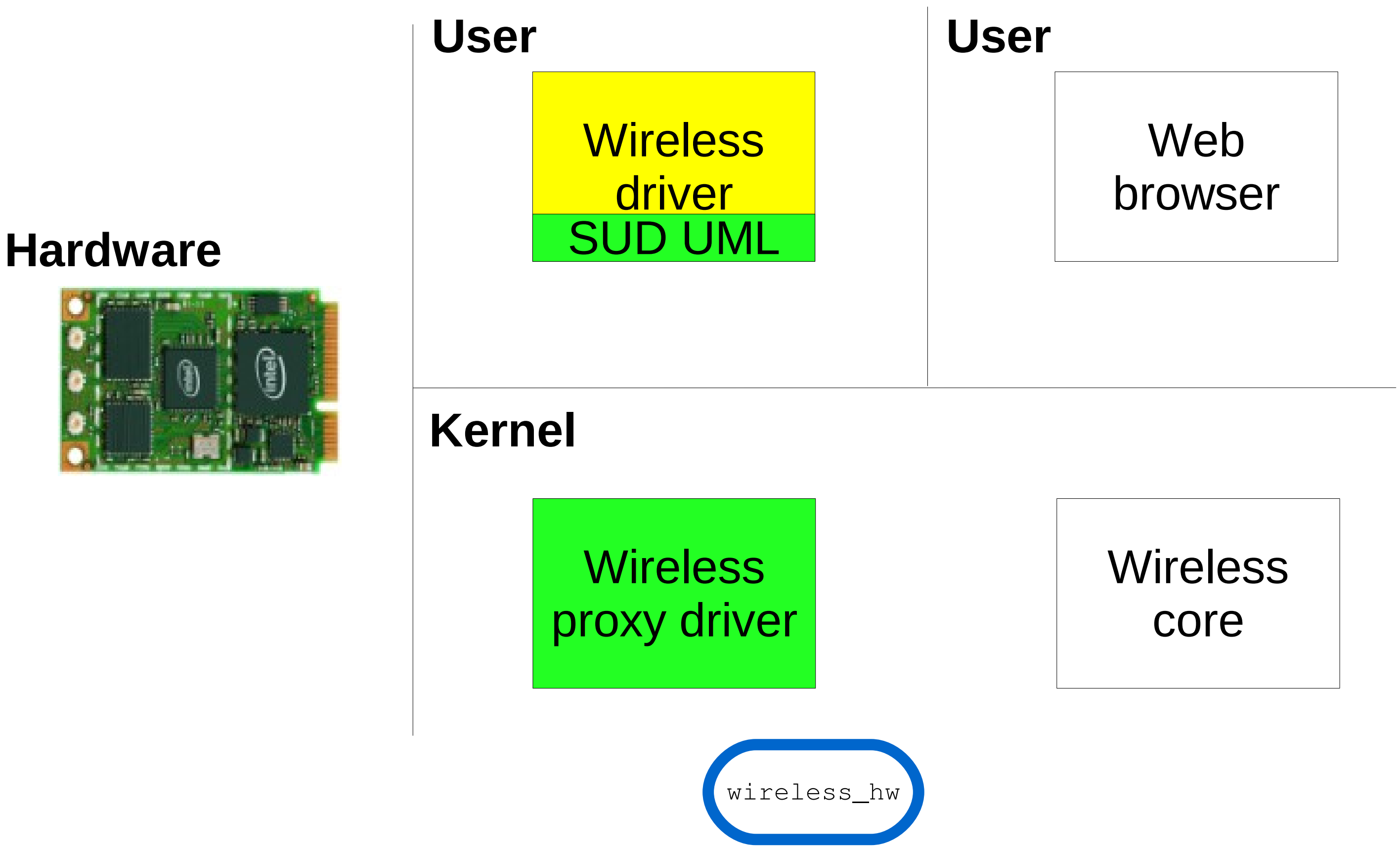

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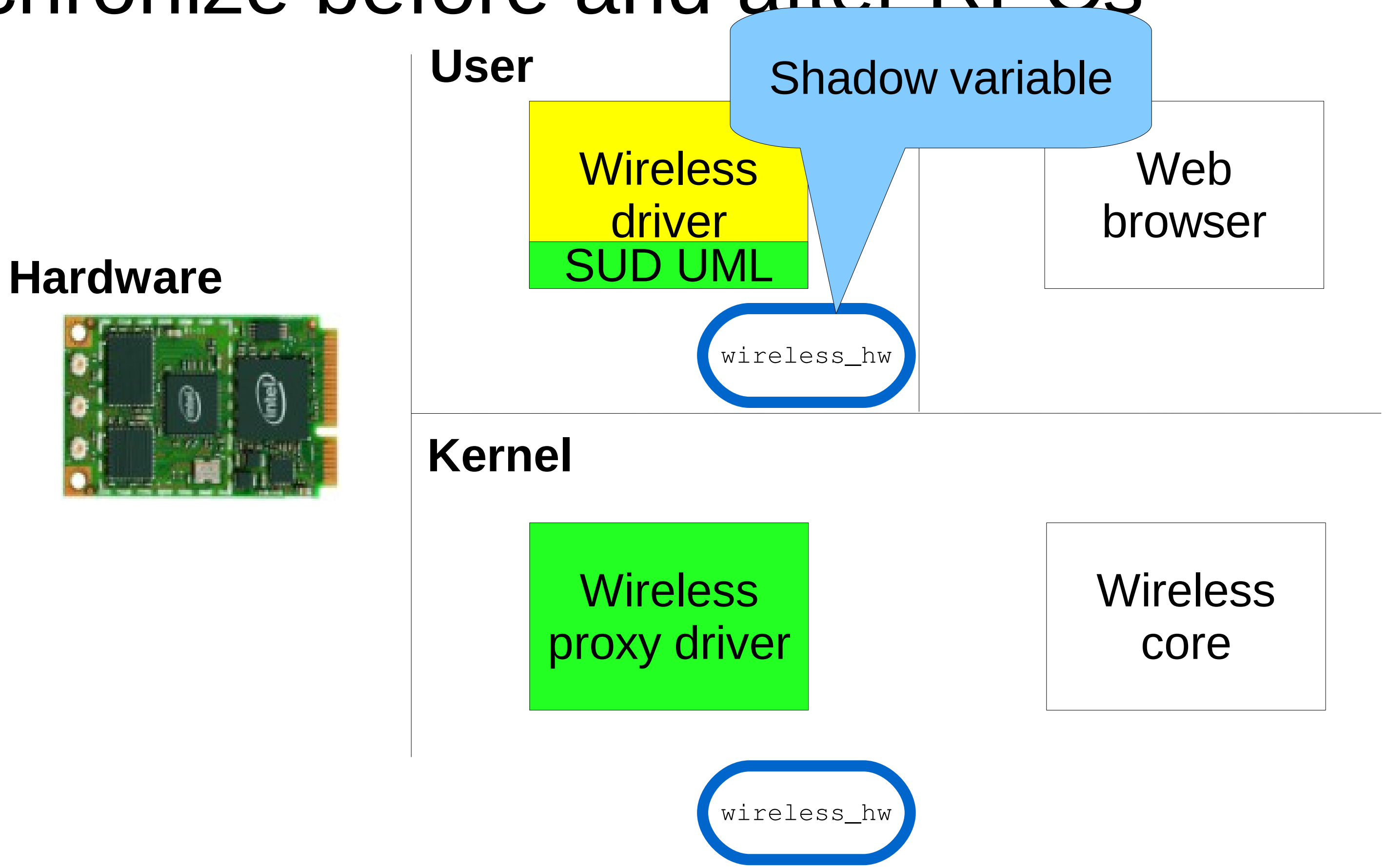

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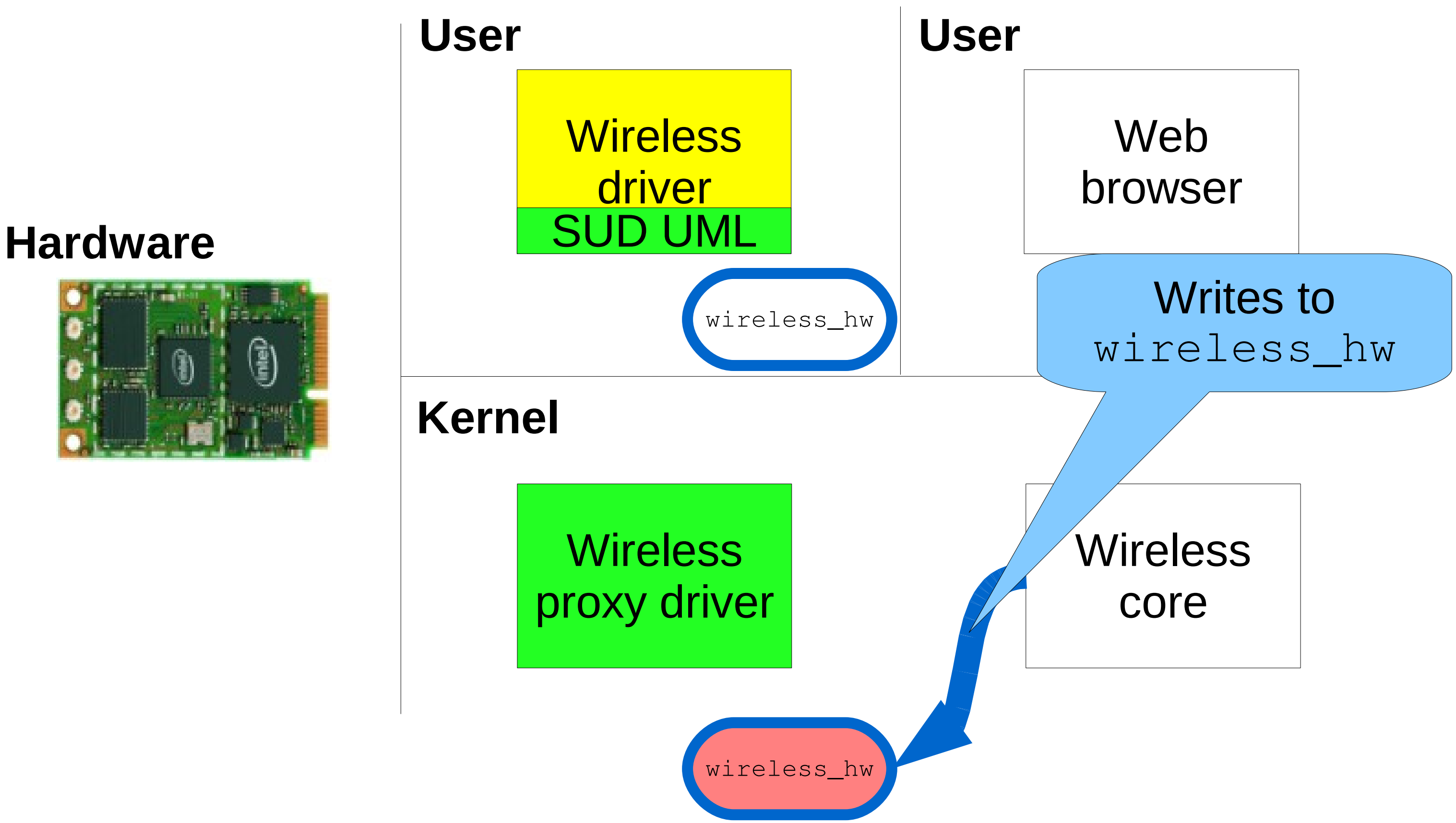

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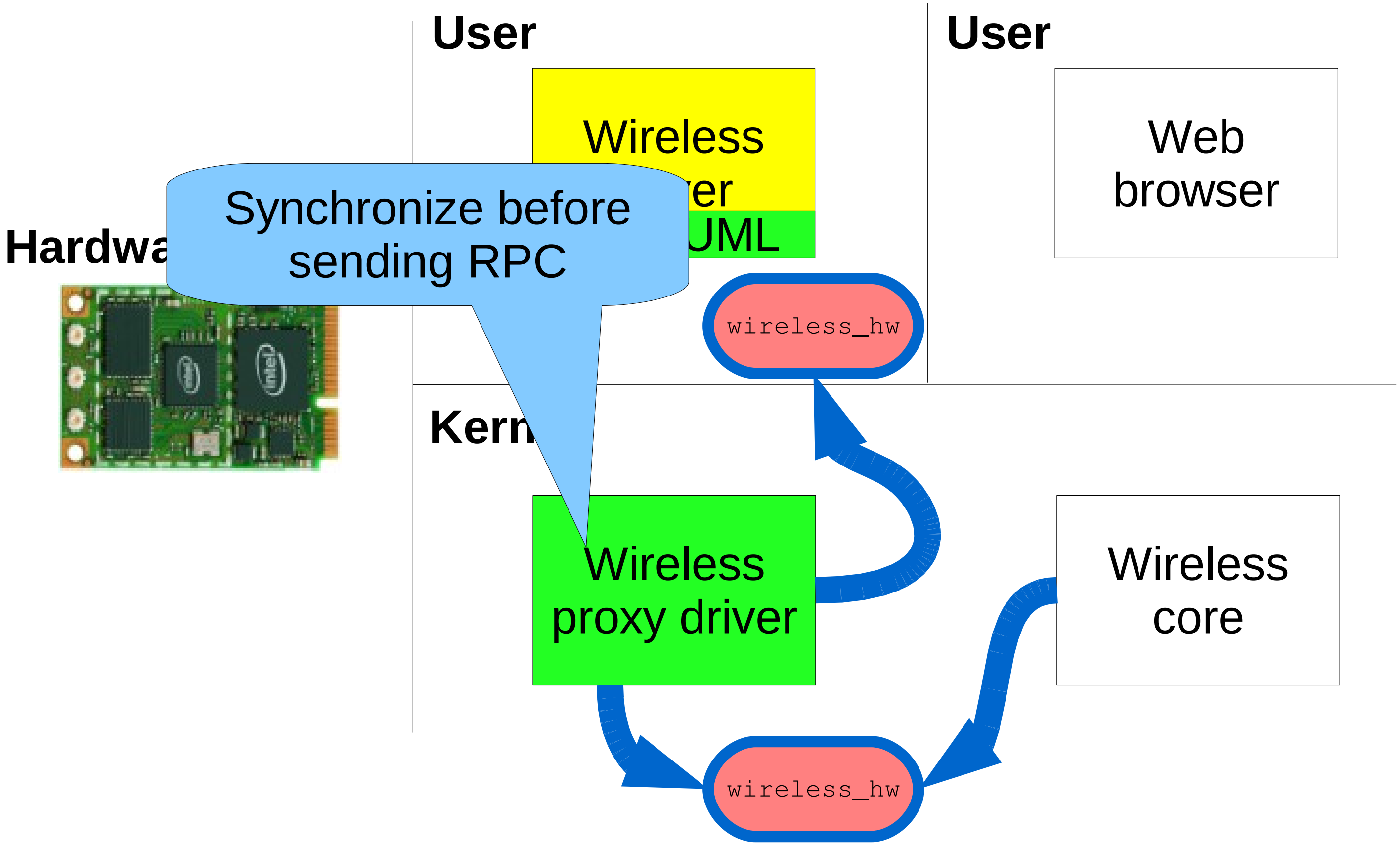

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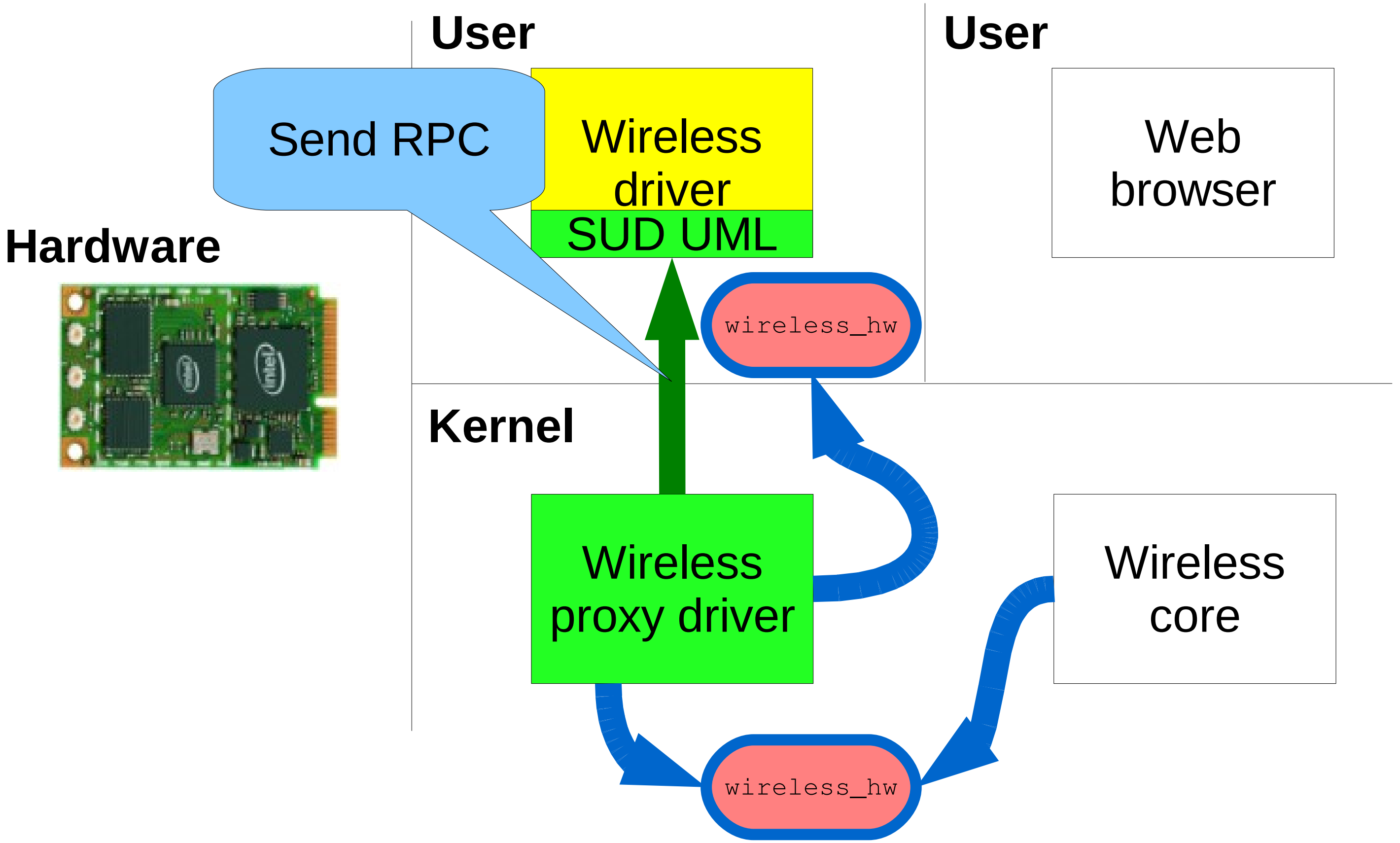

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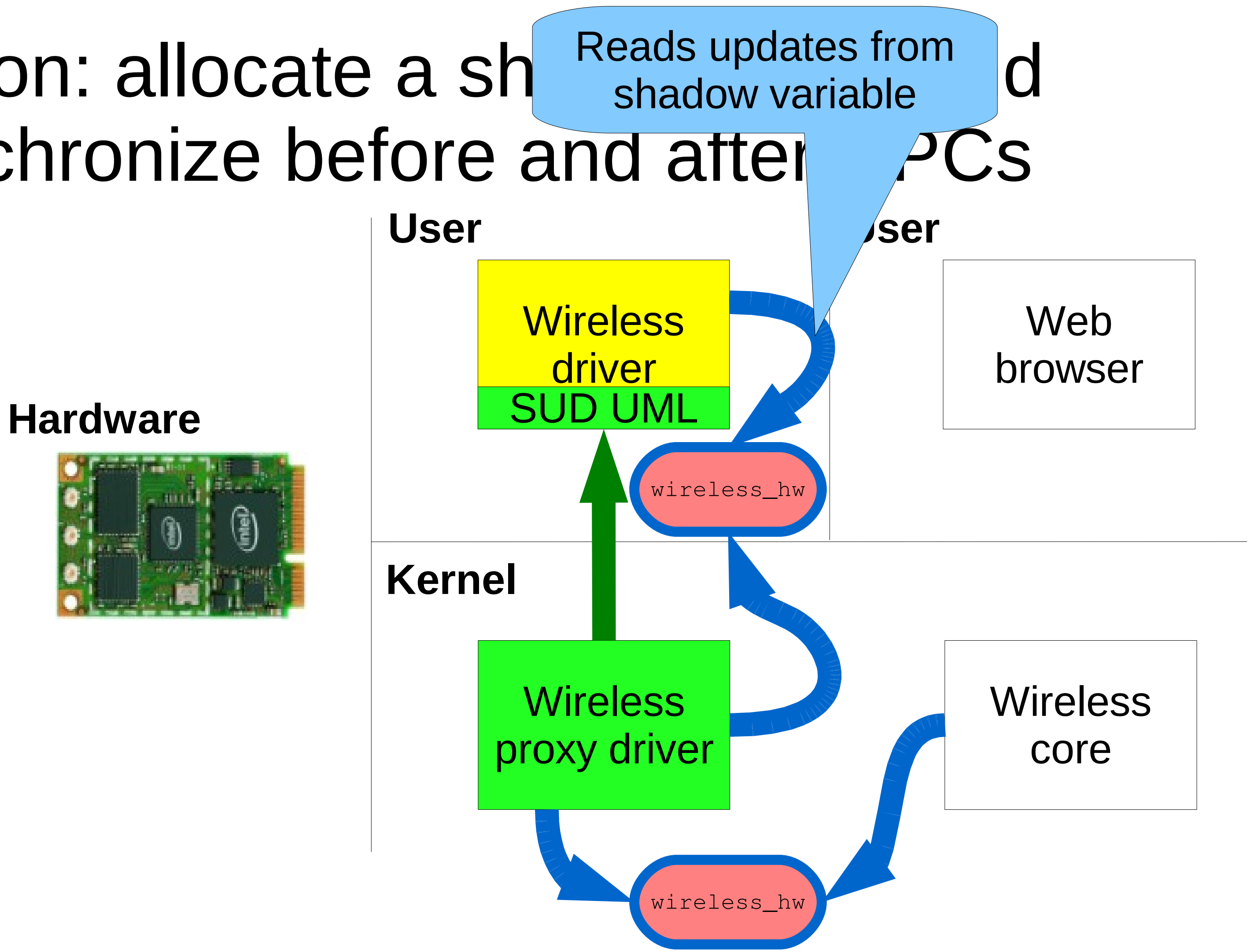

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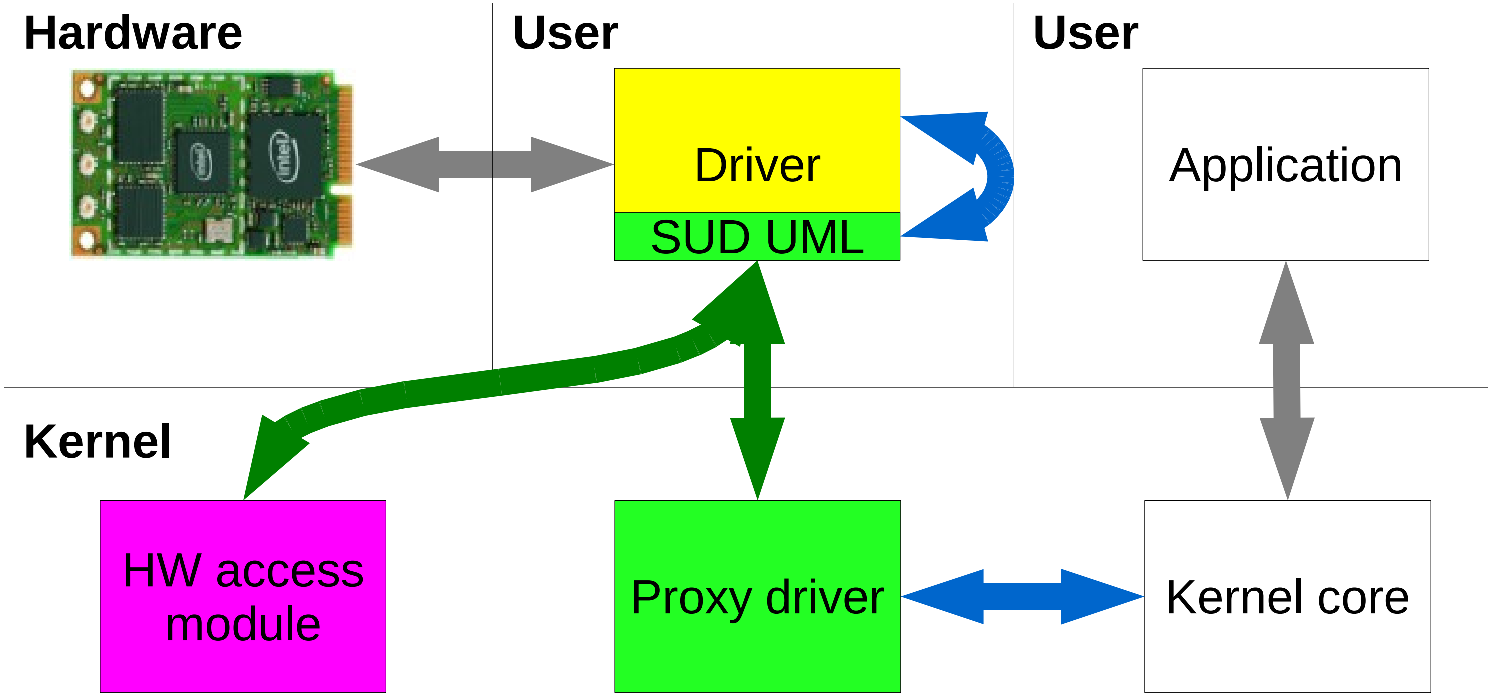

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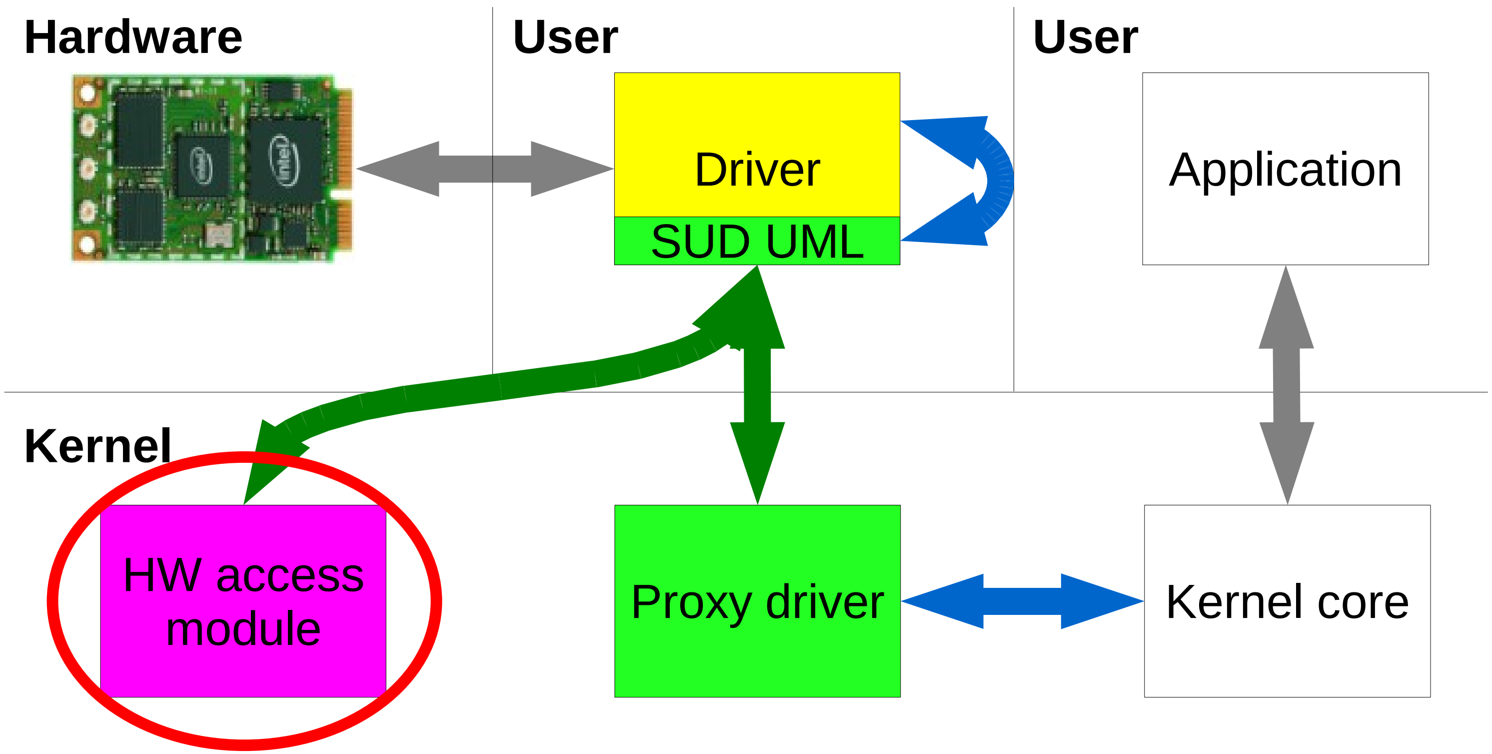
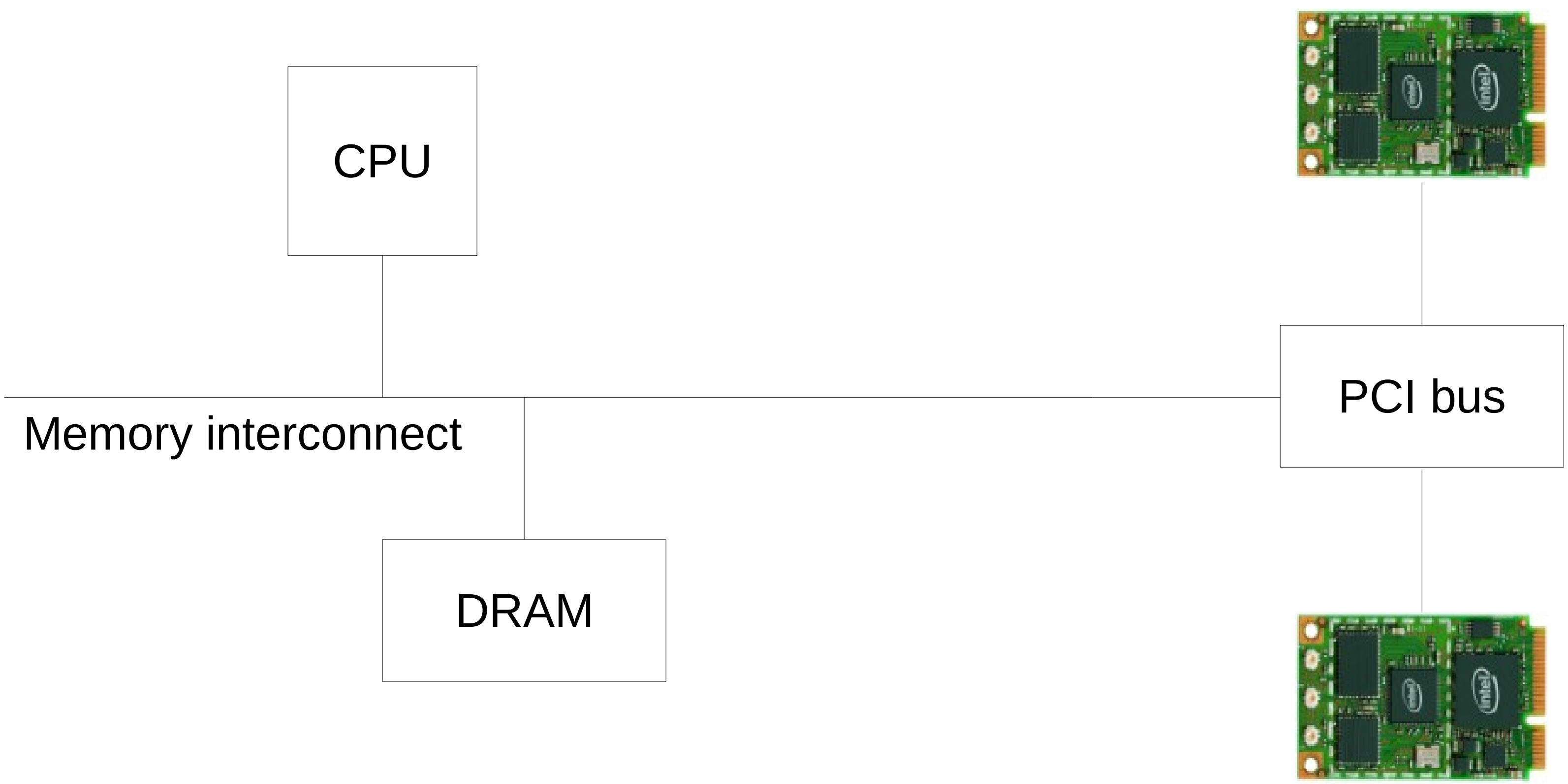
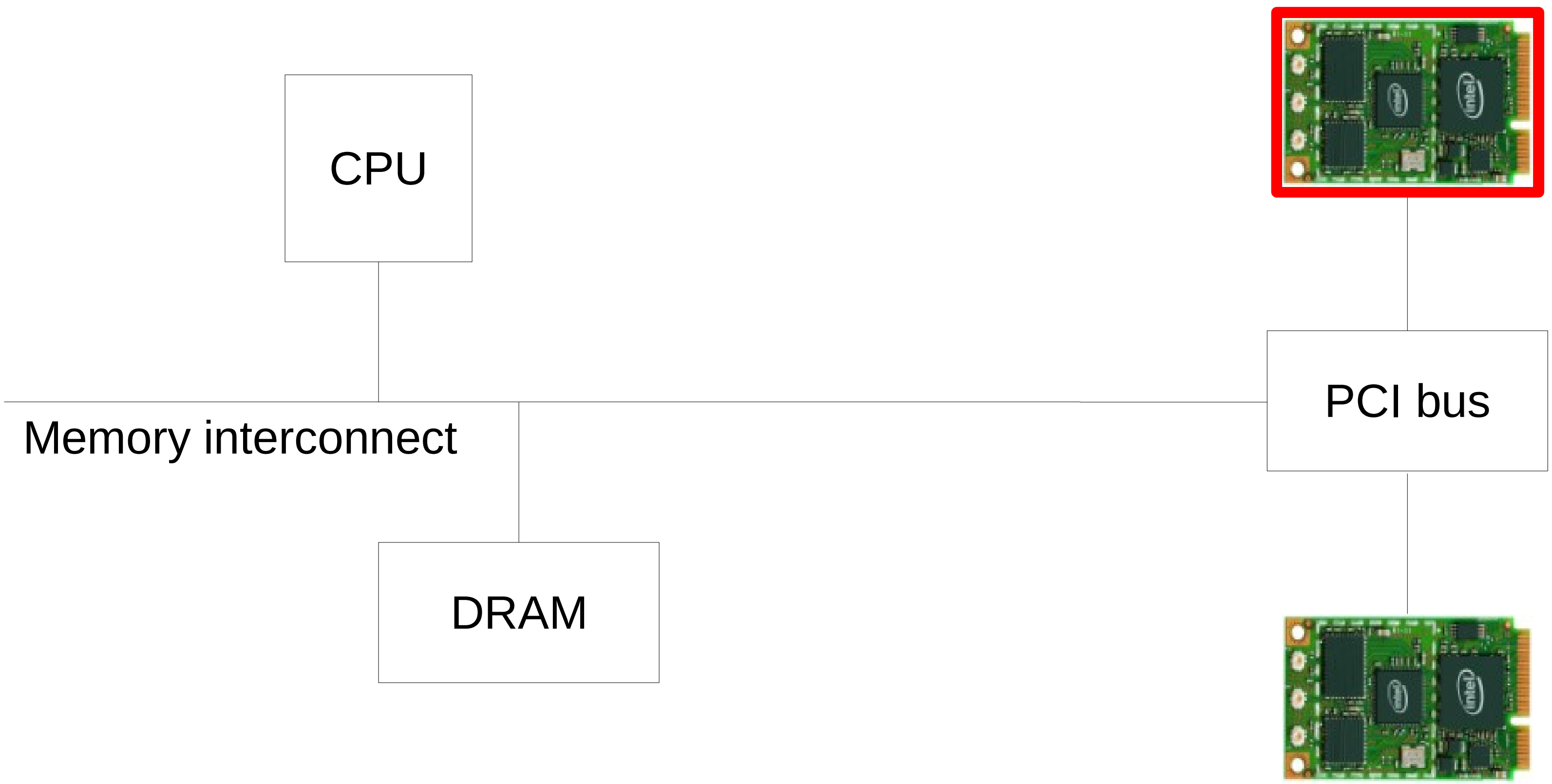


Attacks from hardware



Attacks from hardware

Driver configures the device to execute attacks



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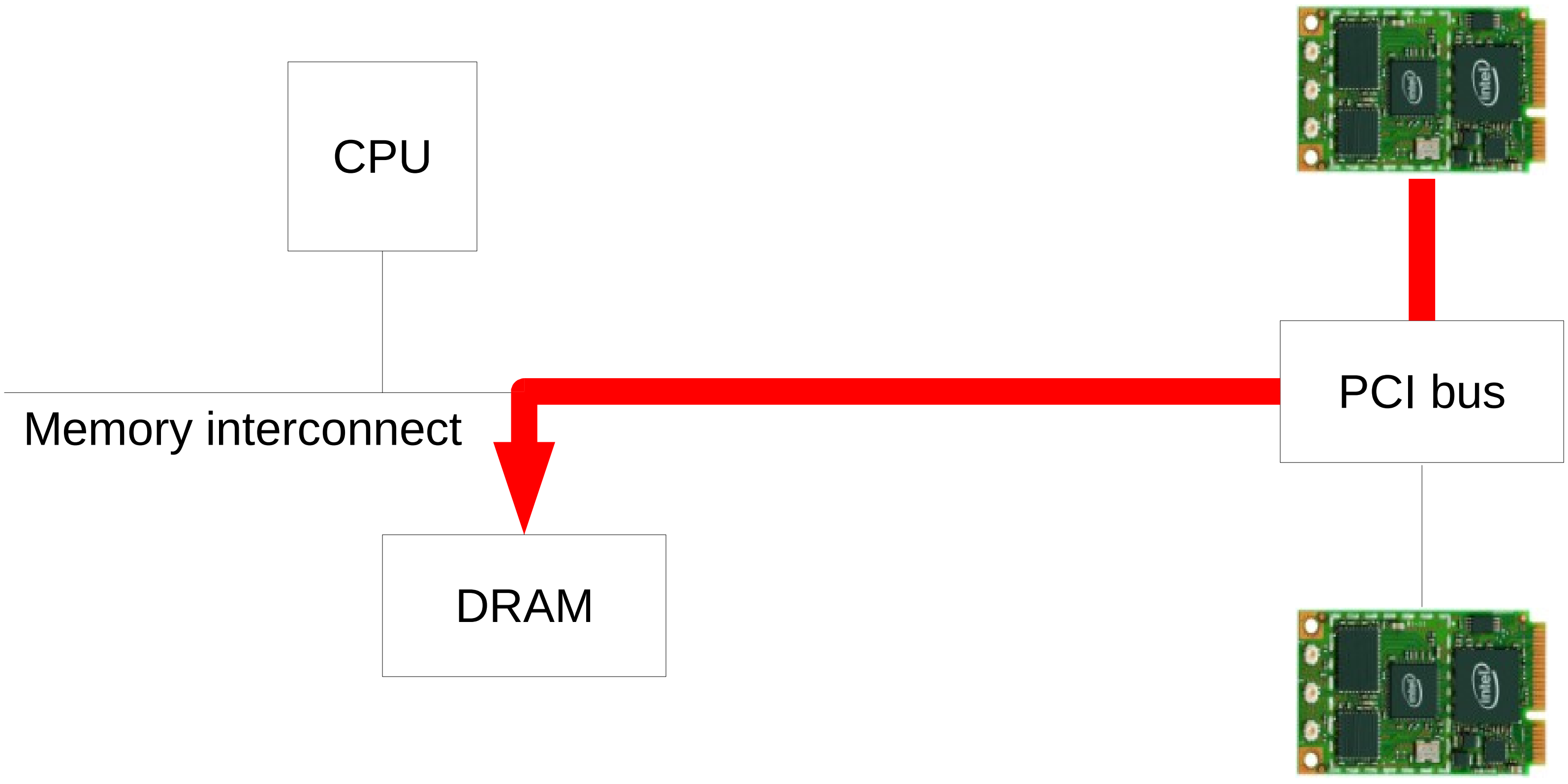
Driver configures the device to execute attacks

- DMA to DRAM



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Driver configures the device to execute attacks

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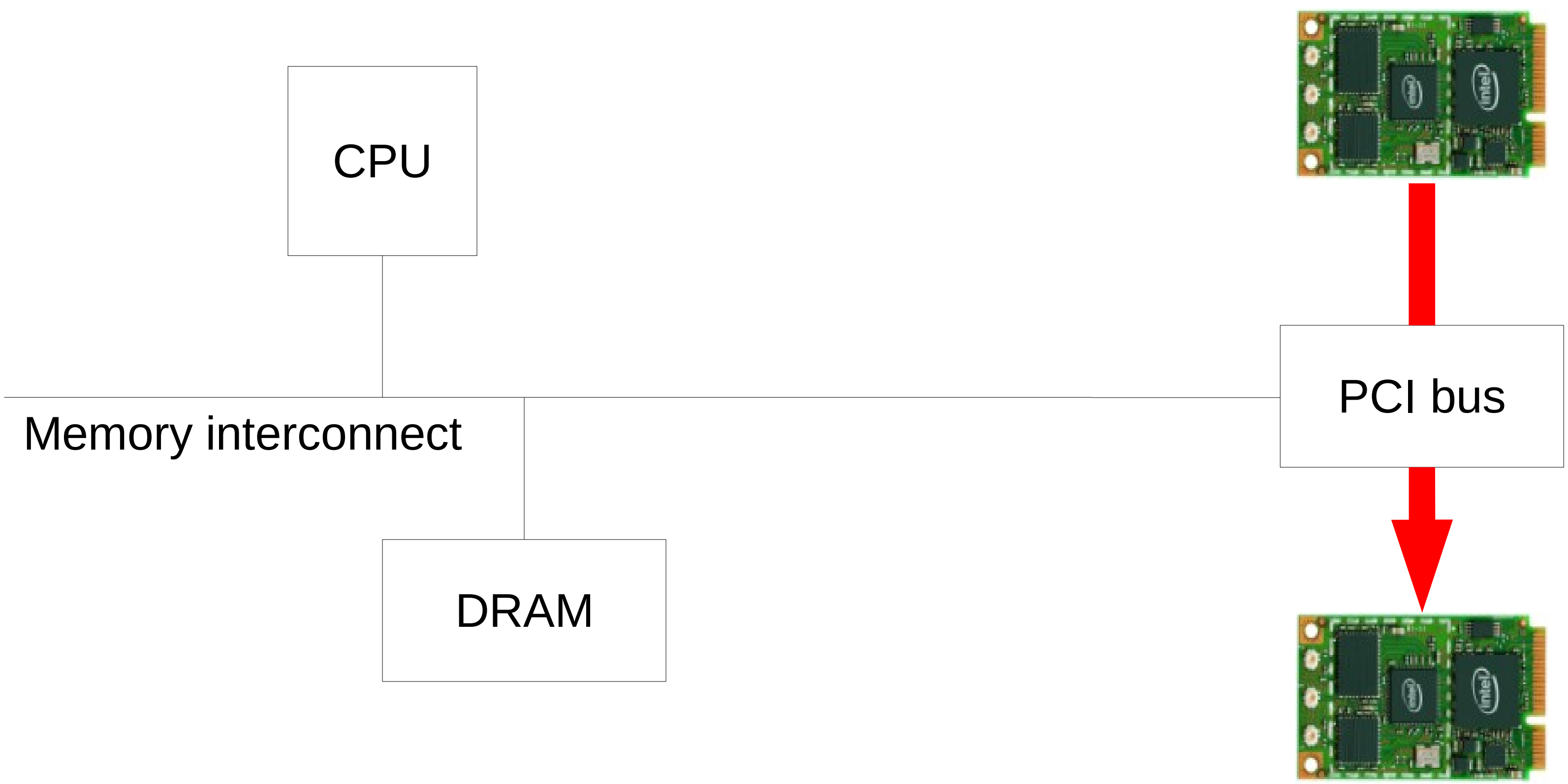

Attacks from hardware

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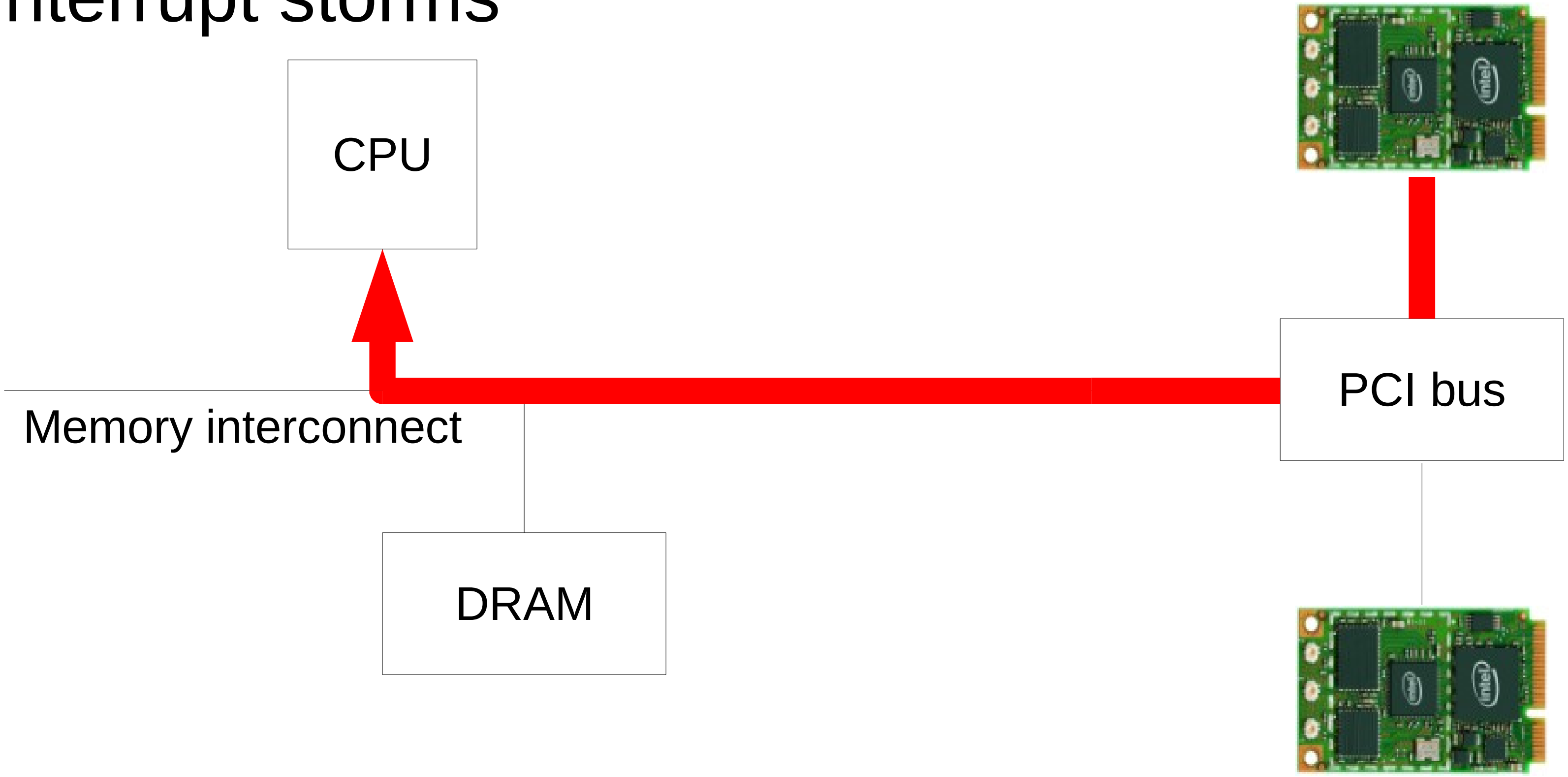
- DMA to DRAM
- Peer-to-peer messages
- Interrupt storms



Attacks from hardware

Driver configures the device to execute attacks

- DMA to DRAM
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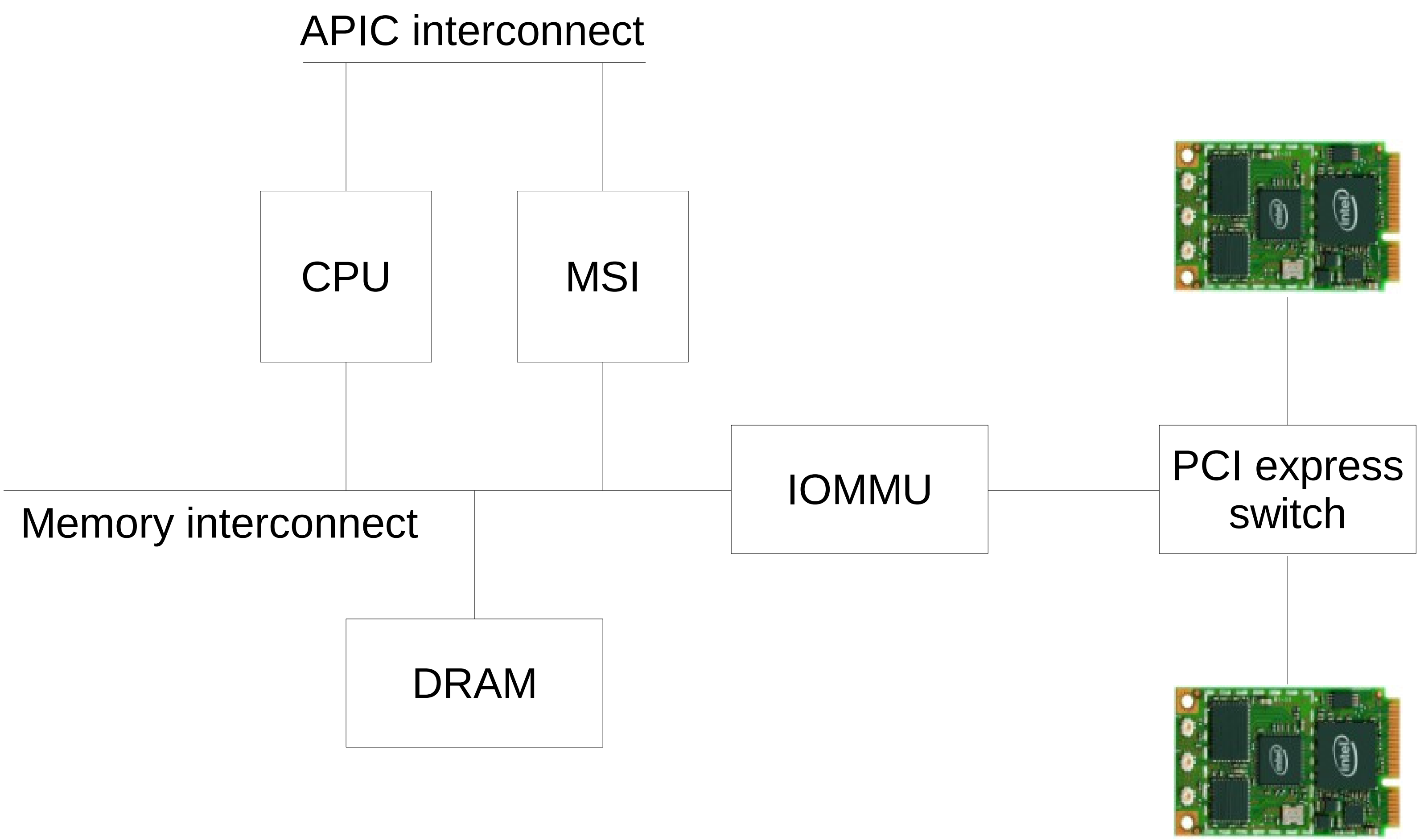
- Interrupt storms

HW access module prevents attacks

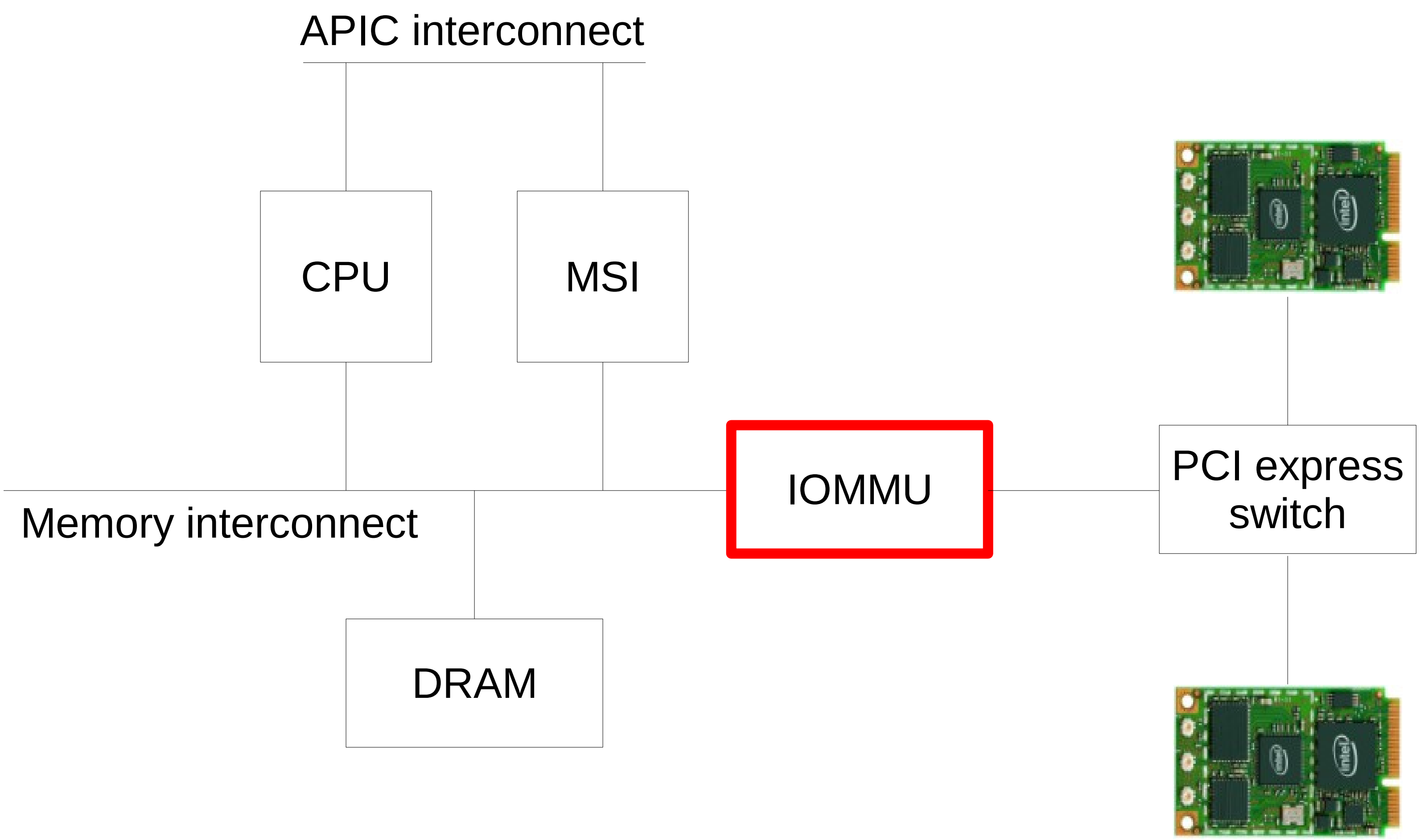
- Interposes on driver-device communication
- Uses IO virtualization to provide direct device access

IO virtualization hardware



IO virtualization hardware

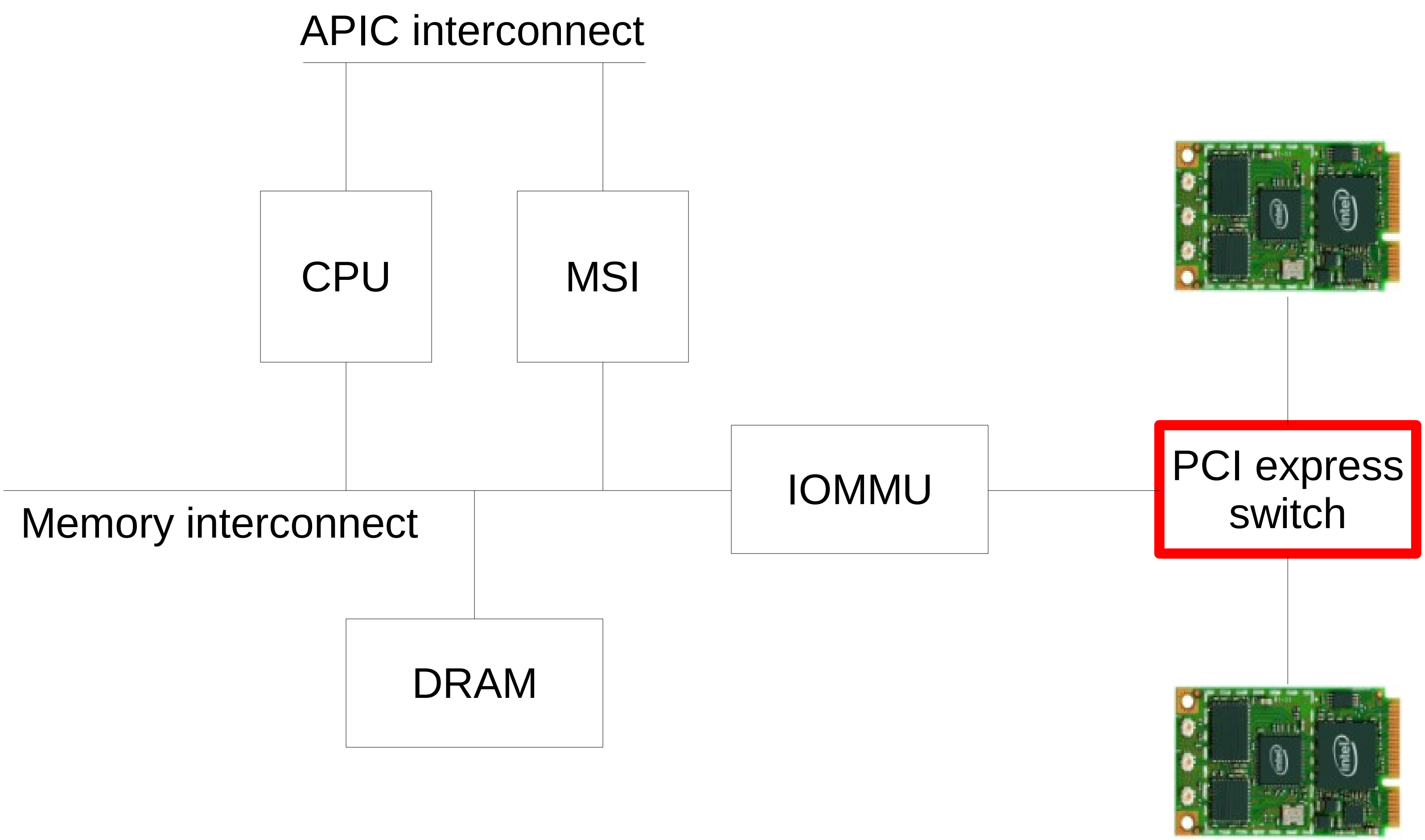
- Use IOMMU to map DMA buffer pools
  - Prevents DMA to DRAM attacks



IO virtualization hardware

Use PCI ACS to prevent peer-to-peer messaging

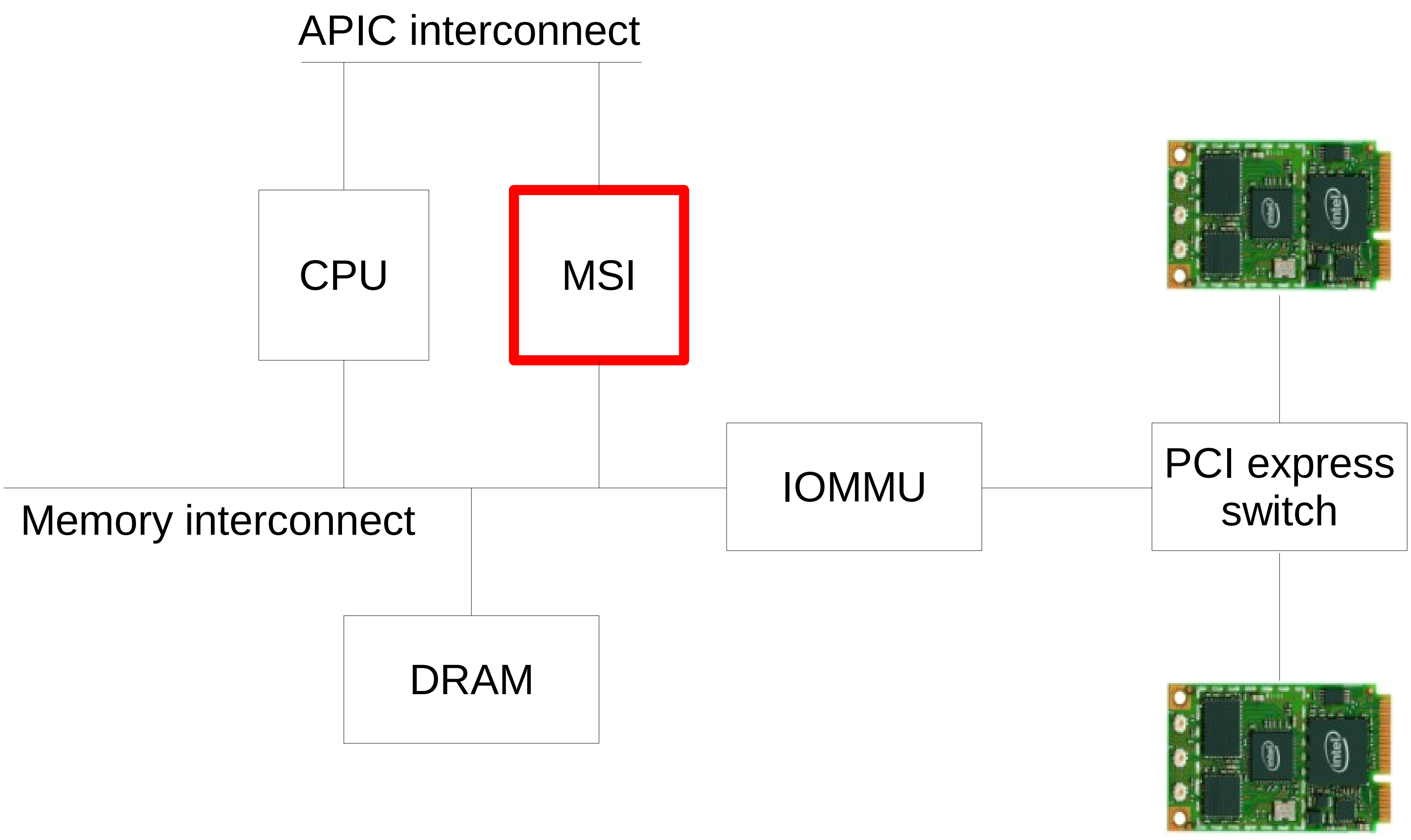
- Prevents peer-to-peer attacks



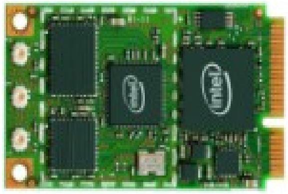
IO virtualization hardware

Use MSI to mask interrupts

- Prevents interrupt storms



Interrupt handlers in Linux



MSI

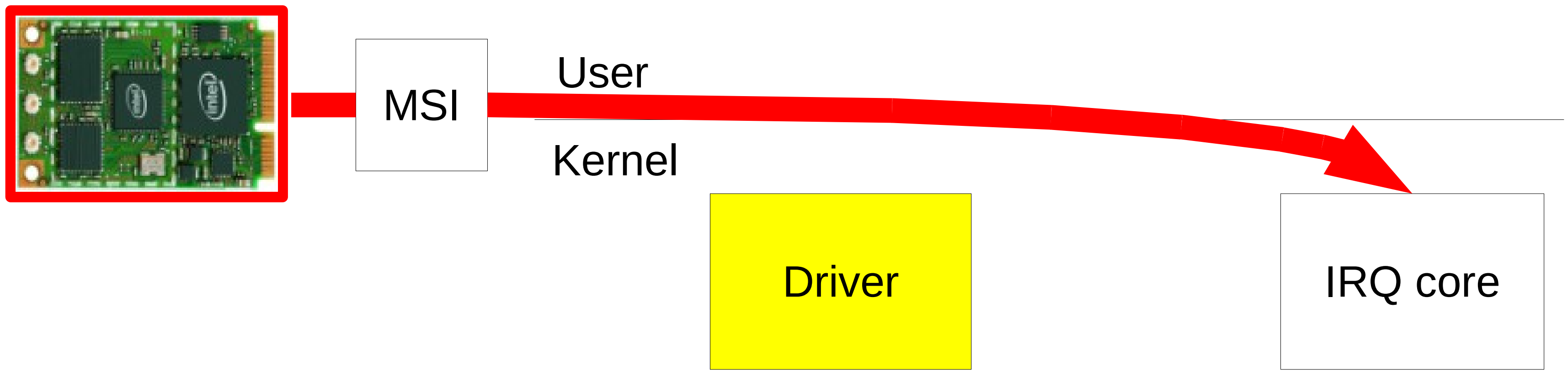
User

Kernel

Driver

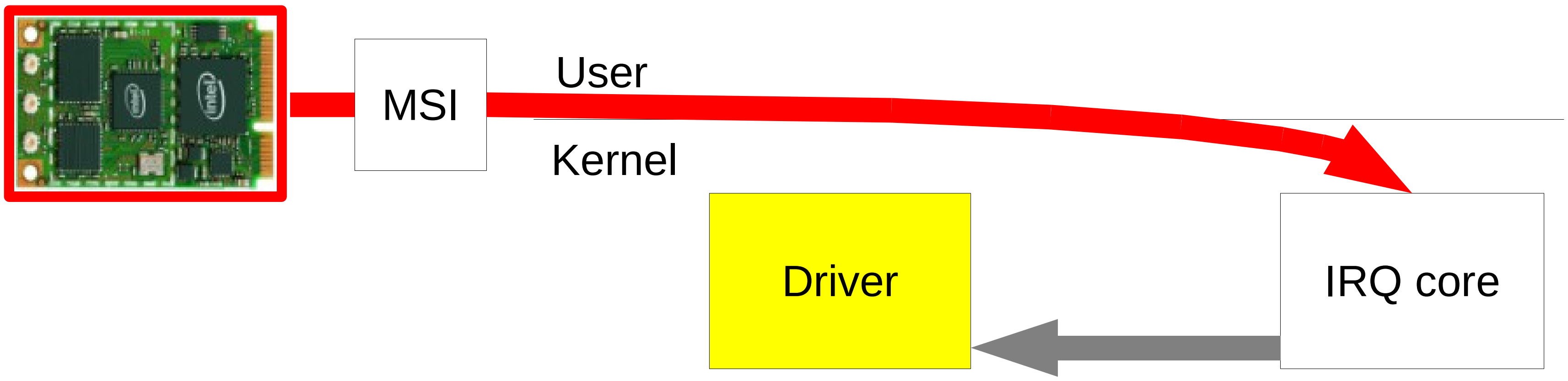
IRQ core

Interrupt handlers in Linux



Interrupt handlers in Linux

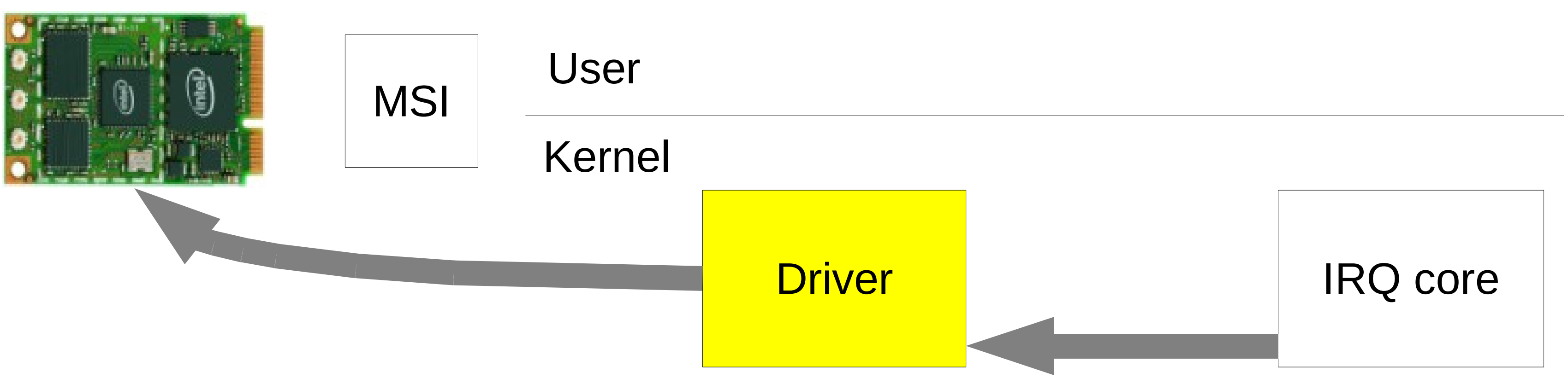
Driver called with IRQs disabled (non-preemptable)



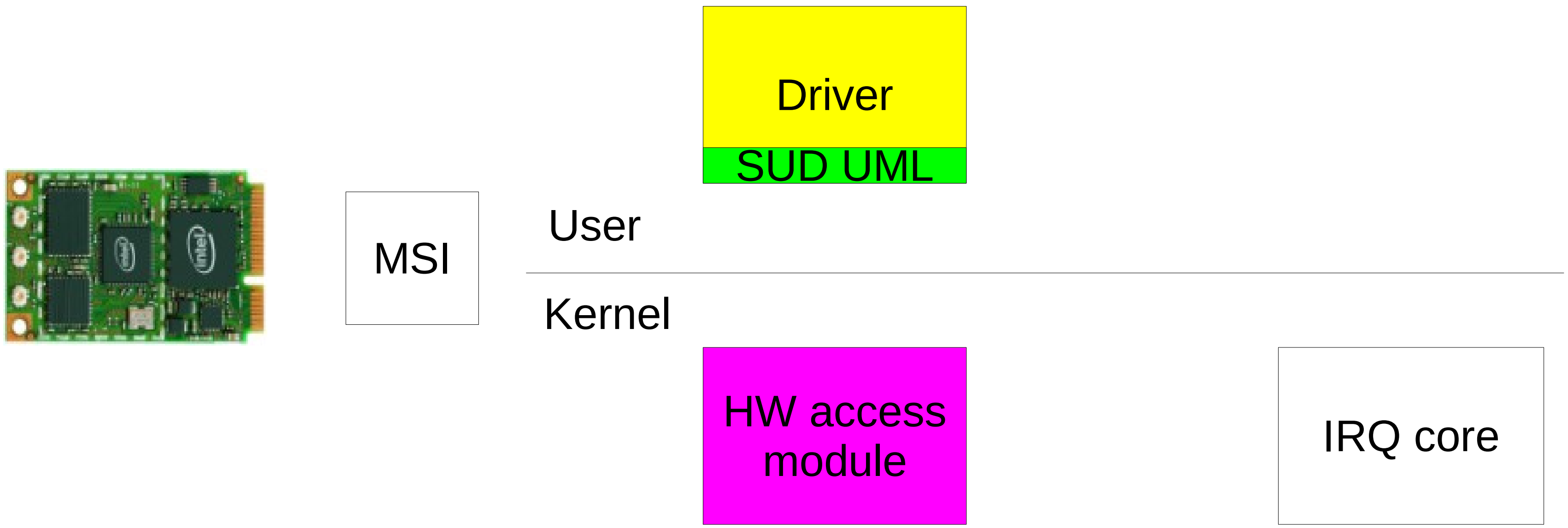
Interrupt handlers in Linux

Kernel calls driver interrupt handler

Driver clears interrupt flag



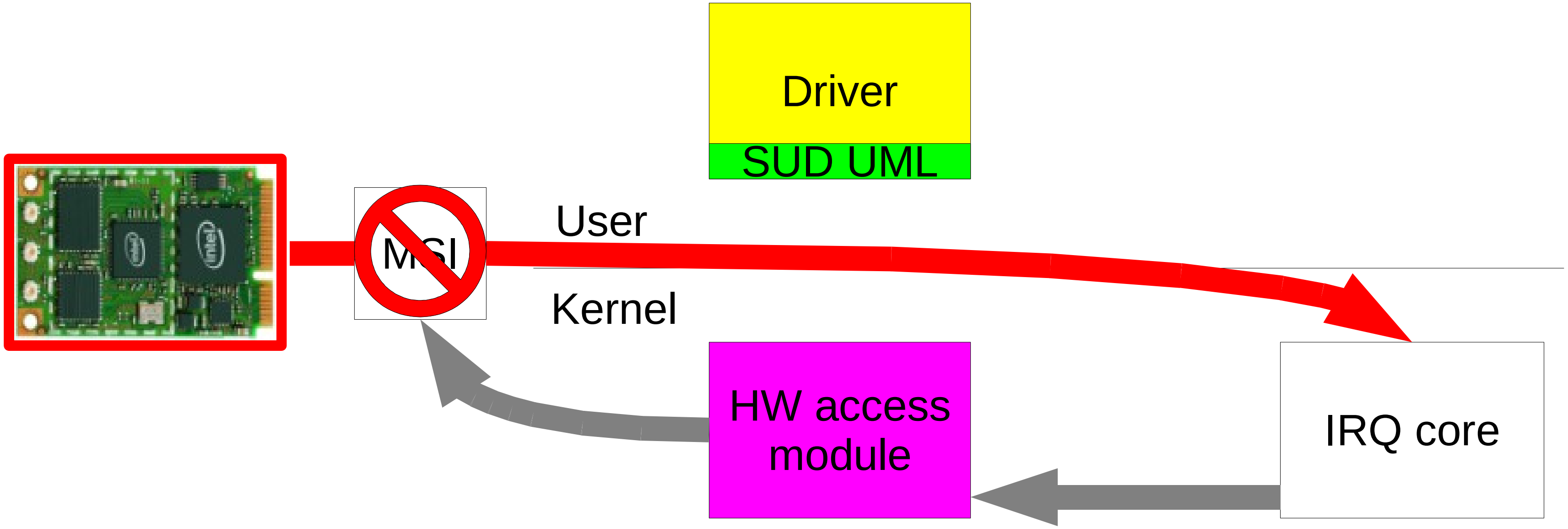
Interrupt handlers with SUD



Interrupt handlers with SUD

Kernel calls HW access module interrupt handler

HW access module masks interrupt with MSI



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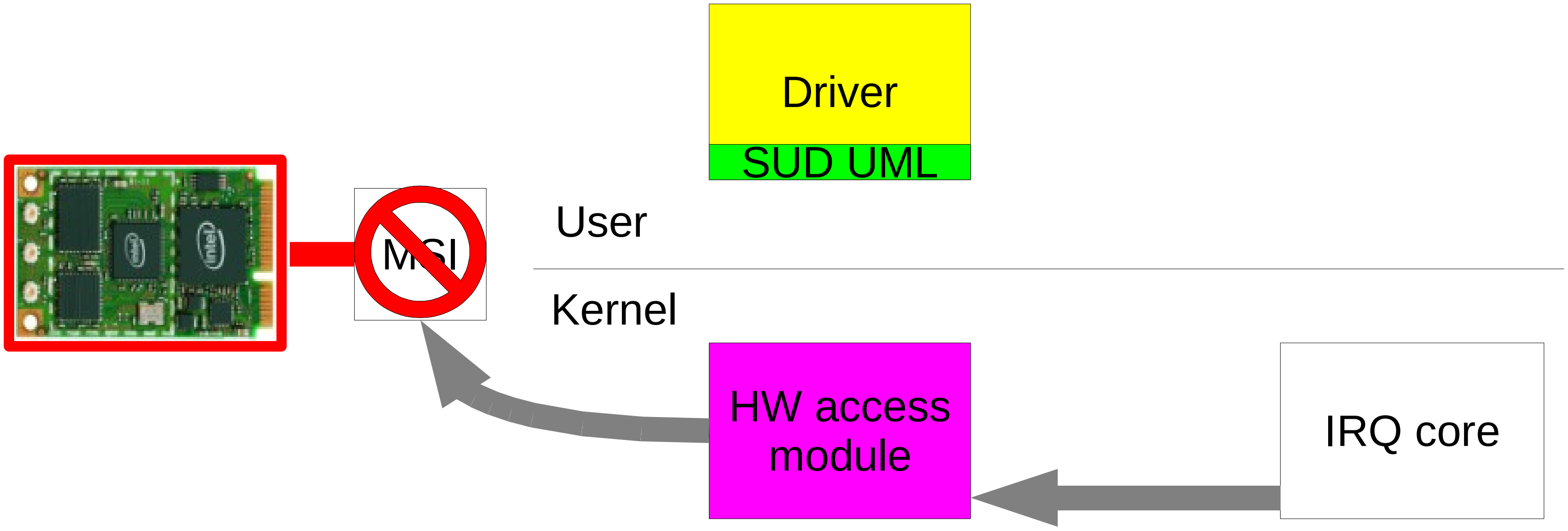

Interrupt handlers with SUD

Kernel calls HW access module interrupt handler

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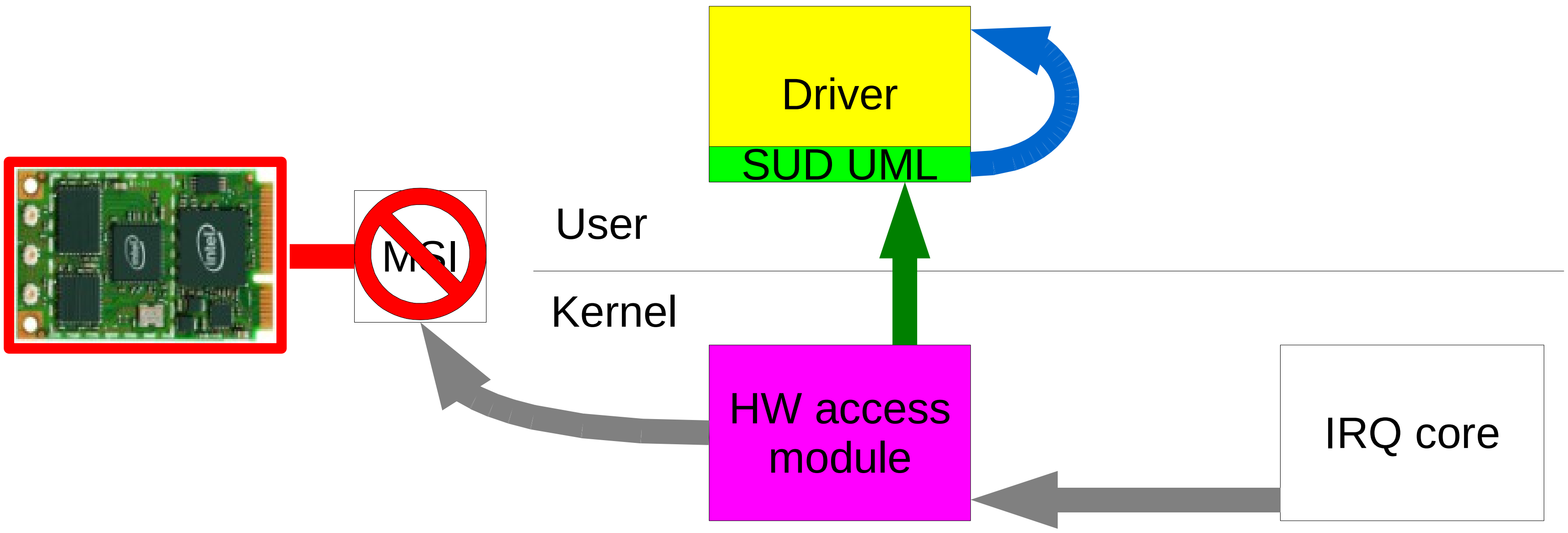
Asynchronous RPC to driver



Interrupt handlers with SUD

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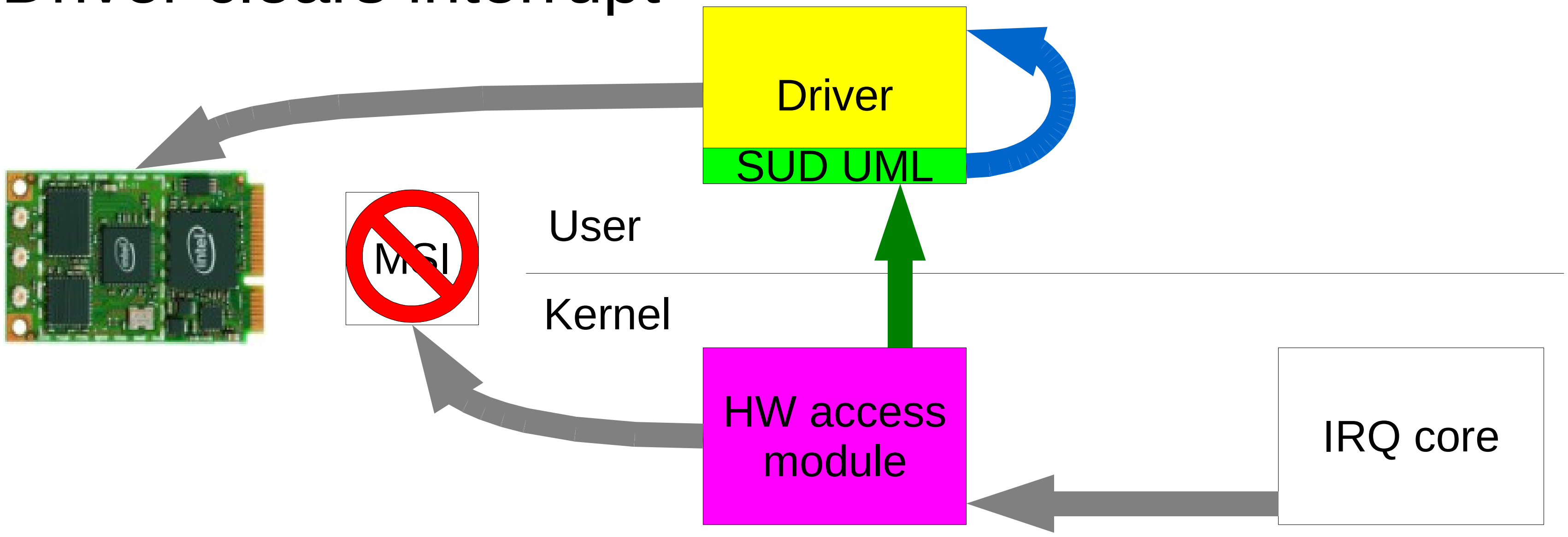
Asynchronous RPC to driver

Driver clears interrupt



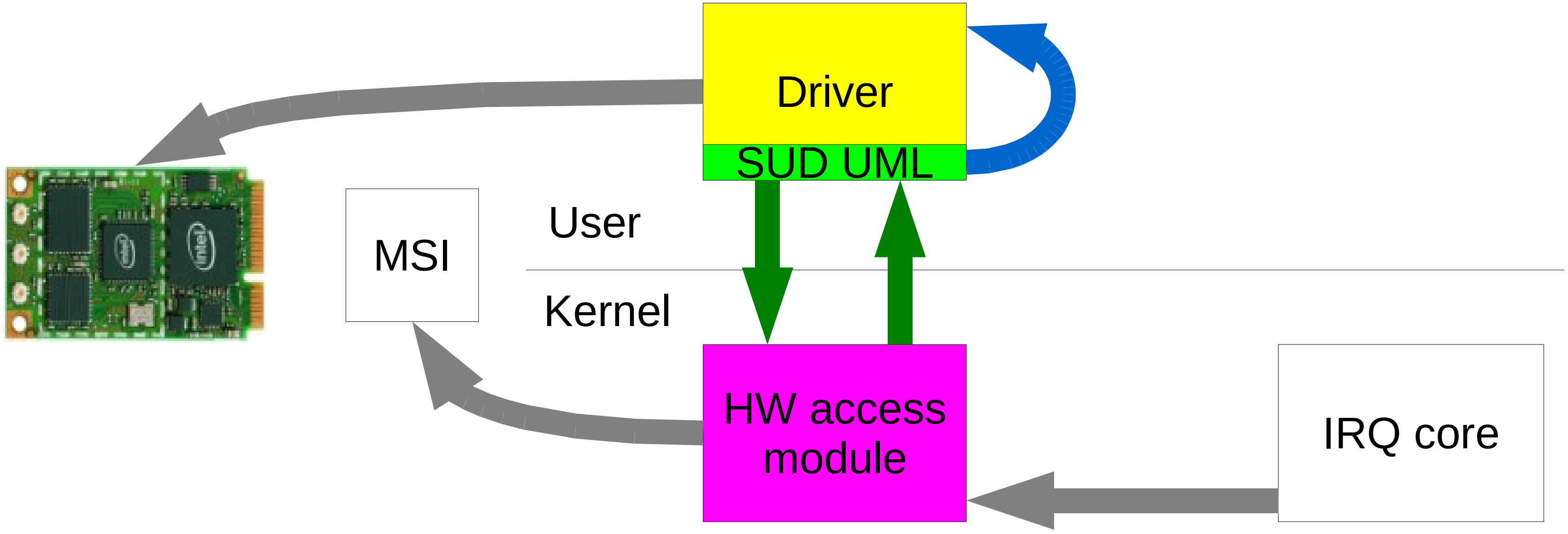
Interrupt handlers with SUD

HW access module masks interrupt with MSI

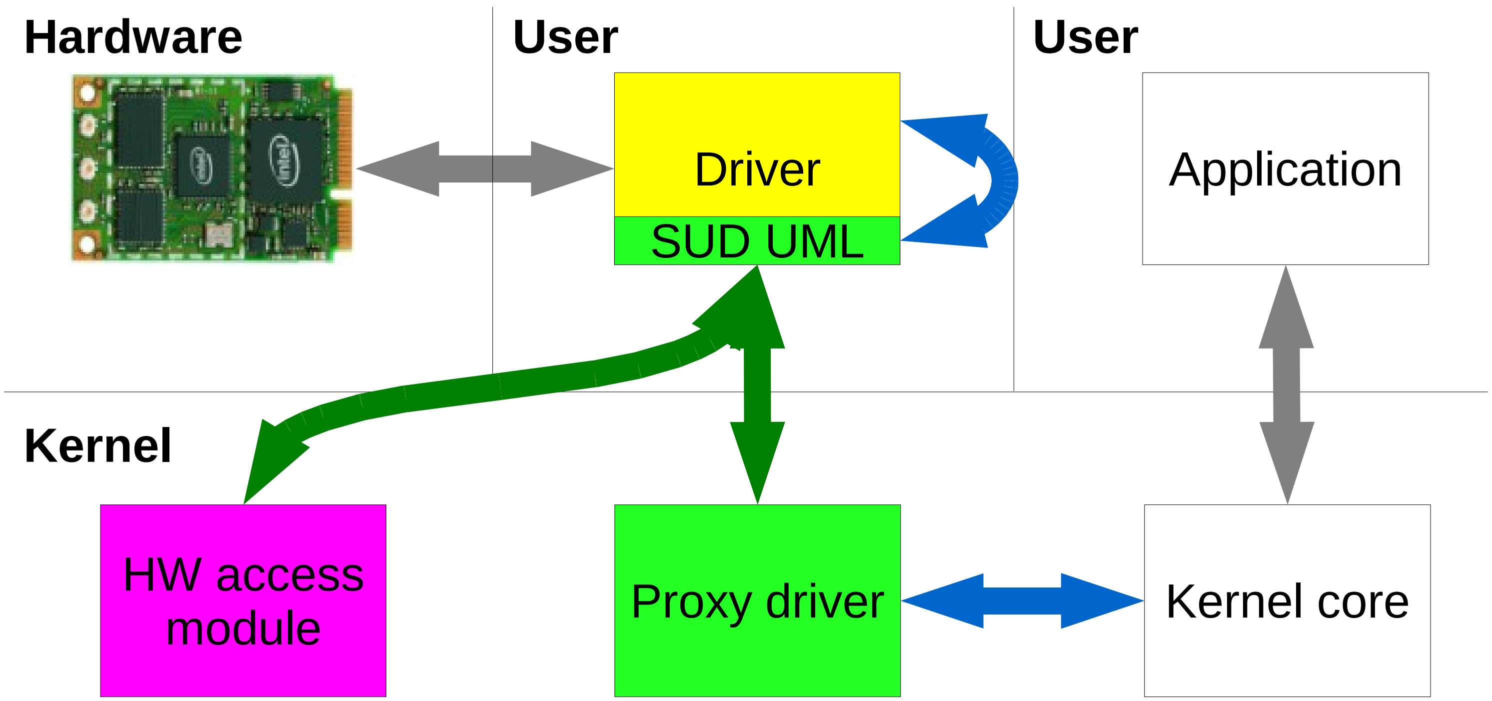
Asynchronous RPC to driver

Driver clears interrupt

HW access module unmasks MSI



SUD overview



Prototype of SUD

Trusted code	Lines of code
PCI access module	2800
Ethernet proxy driver	300
Wireless proxy driver	600
Audio proxy driver	550

Untrusted code	Lines of code
User-mode runtime	5000
Drivers	5000 – 50,000 (each)

Supports all Ethernet, wireless, USB, audio drivers

Tested: e1000e, ne2k-pci, iwlagn, snd_hda_intel, ehci_hcd, uhci_hcd, ...

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Performance

For most devices, does not matter

- Printers, cameras, …

Stress-test: e1000e gigabit network card

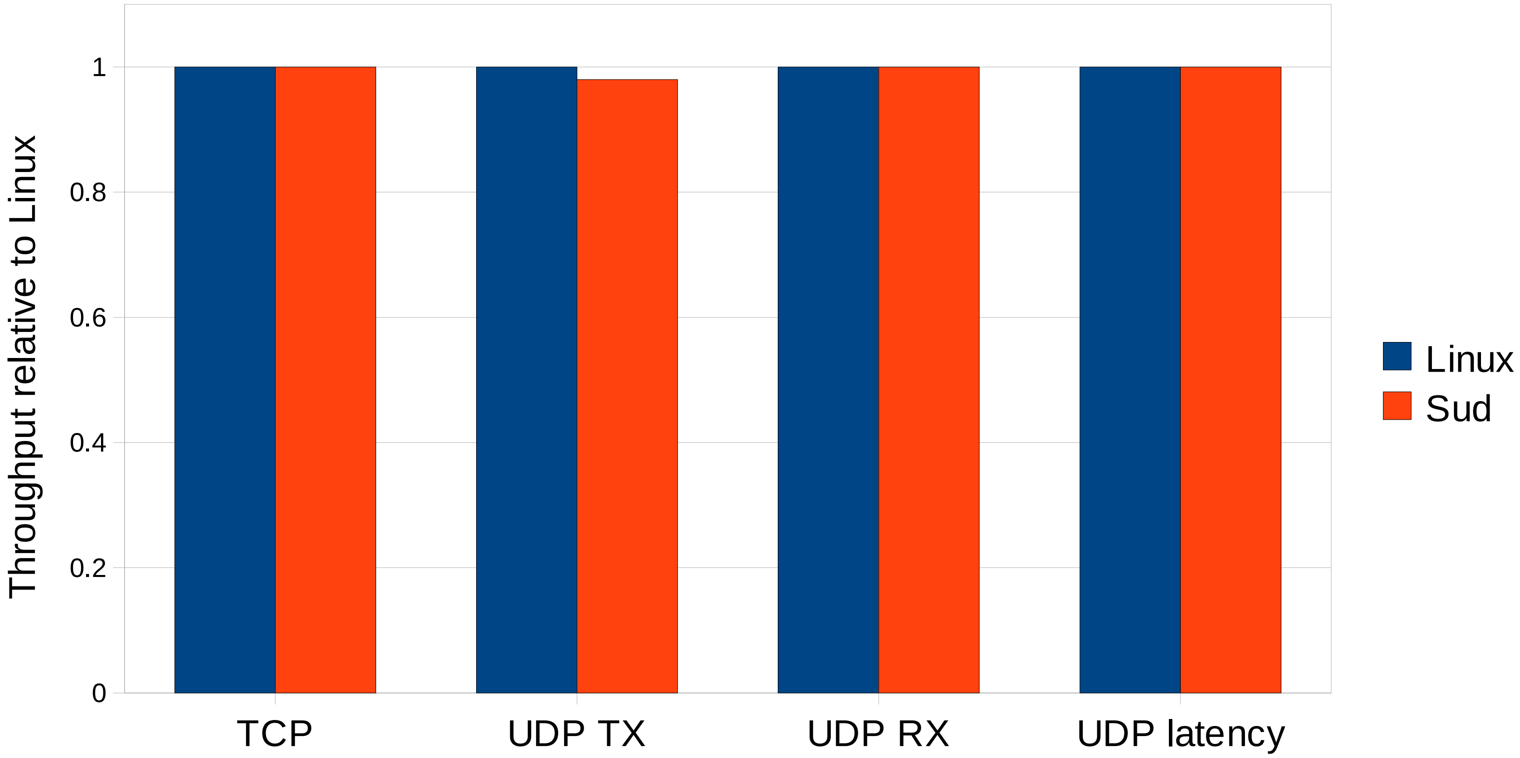
- Requires high throughput
- Requires low latency
- Many device driver interactions

Test machine: 1.4GHz dual core Thinkpad

Performance questions?

- What performance does SUD get?
  - Network throughput, latency
- How much does it cost?
  - CPU cycles

SUD achieves same device performance

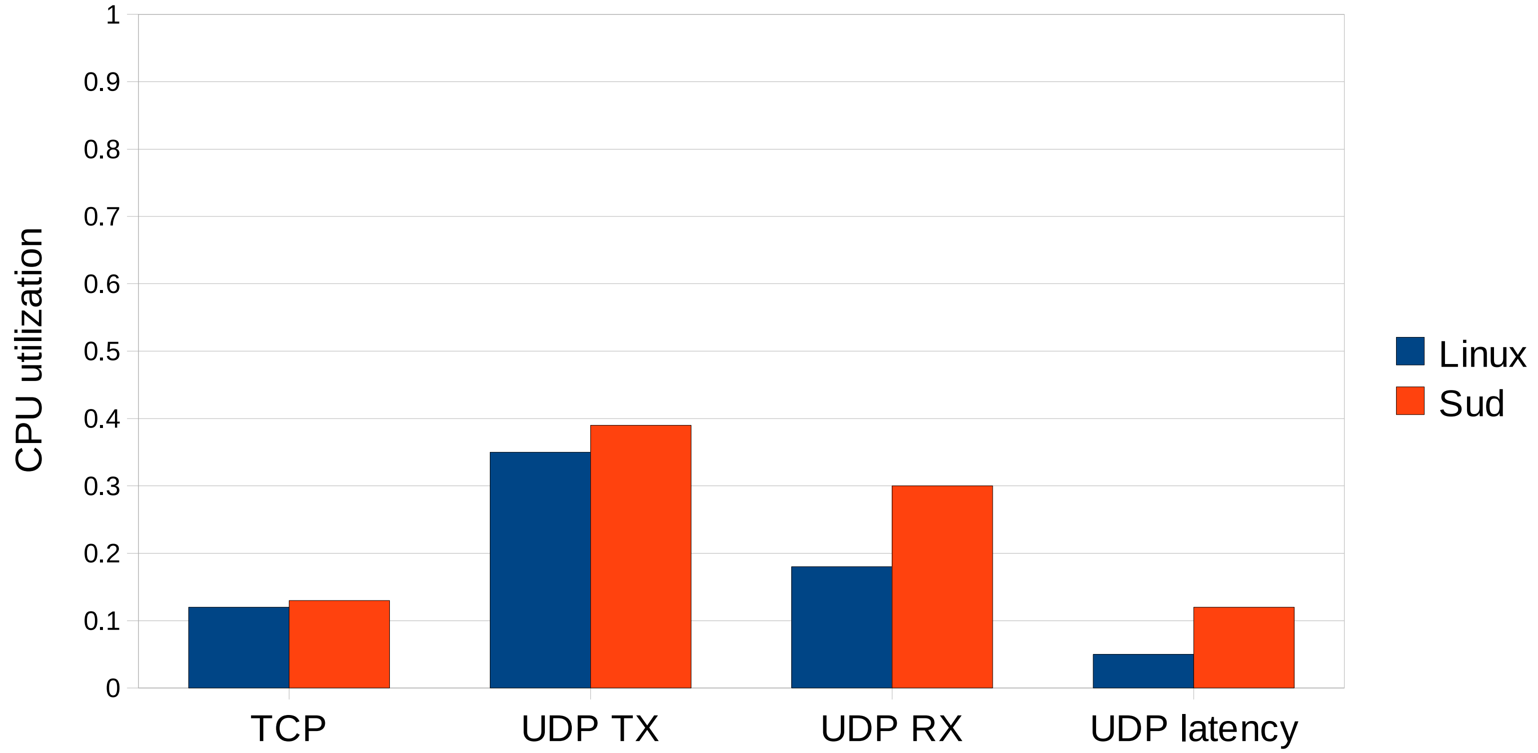


Normalized throughput relative to Linux

TCP: streaming (950 Mbps in both cases)

UDP: one-byte-data packets

CPU cost is low



SUD overhead: user-kernel switch, TLB misses

Overheads not significant for many workloads (packets larger than min. packet size)

Future directions

Explore hierarchical untrusted device drivers

PCI bus → SATA controller → SATA disk → …

Explore giving apps direct hardware access

Safe HW access for network analyzer, X server, …

Performance analysis and optimizations

SUD specific device drivers, super pages, ...

Related work

Mircokernels (Minix, L4, ...)

- Simple drivers, driver API designed for user-space

Nooks, microdrivers

- Handles common bugs, many changes to kernel

Languages (e.g. Termite), source code analysis

- Complimentary to user-space drivers

No need for new OS or language

Summary

Driver bugs lead to system crashes or exploits

SUD protects Linux from malicious drivers using proxy drivers and IO virtualization HW

- Runs unmodified Linux device drivers
- High performance, low overheads
- Few modifications to Linux kernel

Security evaluation

Manually constructed potential attacks

- Memory corruption, arbitrary upcall responses, not responding at all, arbitrary DMA, ...

Relied on security heavily during development

- SUD caught all bugs in user-mode driver framework
- No crashes / reboots required to develop drivers

Ideal, but not done: red-team evaluation?