Systems Design and Implementation

I.3 – Kernel and Operating System Interfaces

System Architecture Group, SS 2009

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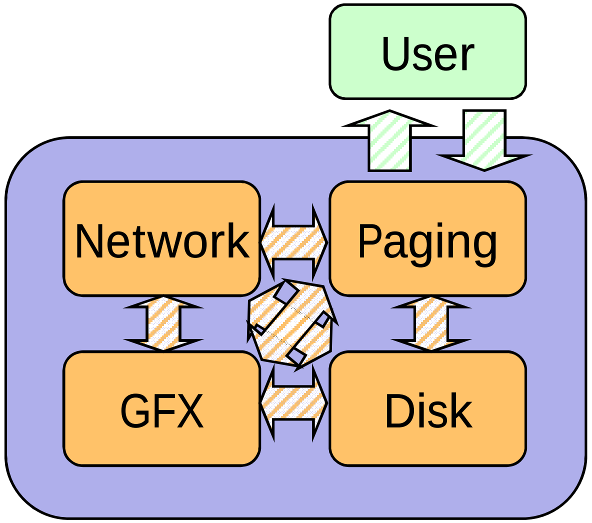
Jan Stoess
University of Karlsruhe

Overview

- Motivation
- User interfaces
- Kernel interfaces in monolithic OSes
  - Case study 1: Linux kernel modules
  - Case study 2: Windows WDM architecture
- Kernel interfaces in multi-server systems
  - Case study 3: The SawMill Multiserver Architecture
  - Case study 4: Virtualization interfaces

Motivation

- Operating systems run user programs
  - May request service
  - May need event notification
- Operating systems have different subsystems
  - e.g., paging call disk subsystem to swap
  - Need an interface



- Kernel Interfaces
  - Sharing/Transferring Data
  - Sharing/Transferring Code
  - Implications on programming model
    - E.g., C-Routines, RPC, ...

User Interfaces

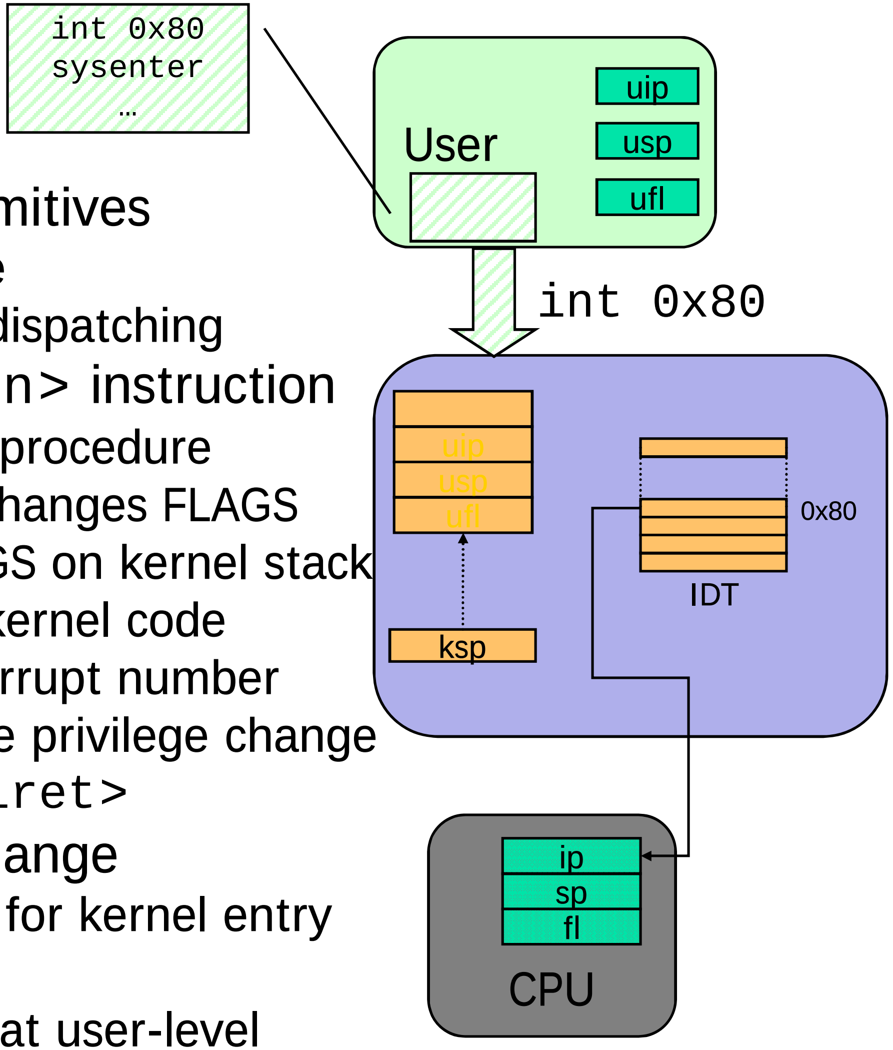
- Required functionality:
  - System Services (system calls)
    - read from disk, send over network, ...
    - Synchronous
    - Enhances privileges
    - Interface data:
      - Kernel service routine identifier
      - Parameters
  - Notifications (signals)
    - Division by 0, Protection fault, completion of asynchronous service, ...
    - May be asynchronous
    - Must switch back to user privileges
    - Interface data
      - User-level callback handler identifier
      - Arguments

User Interfaces

- Required functionality:
  - Kernel-accessible user data
    - Statistics, configuration data (/proc), ...
    - May be accessed asynchronously
- Constraints:
  - Safety:
    - User may not call arbitrary kernel routines
    - User may not arbitrarily switch to kernel privileges
    - User may not change arbitrary kernel data

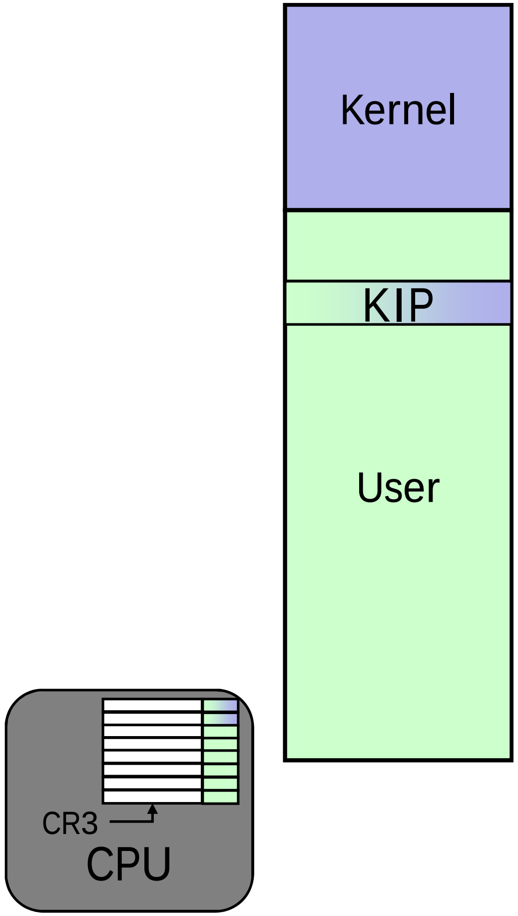
User Interfaces

- Solution:
  - System services:
    - Leverage hardware primitives
      - Safe privilege change
      - Safe system service dispatching
    - Example: IA-32 `<int n>` instruction
      - Safe call to interrupt procedure
      - Loads kernel stack, changes FLAGS
      - Saves EIP, ESP, FLAGS on kernel stack
      - Transfers control to kernel code
        - Specified by interrupt number
        - Implies hardware privilege change
      - Return to user via `<iret>`
    - Hardware subject to change
      - Use trampoline page for kernel entry
      - Versatile interface
      - Can execute syscalls at user-level



User Interfaces

- Solution:
  - Notifications
    - Leverage MMU hardware
    - Kernel shares user address space
      - Can modify user-state
      - Can transfer control
    - But not vice-versa
  - User-accessible kernel data
    - Dedicated shared pages
      - E.g. kernel interface page
    - Map to system calls
      - e.g., proc file system



Kernel Interfaces in monolithic OSes

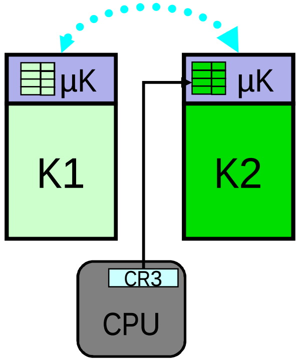
- Monolithic Kernel design
  - Design principle: global, shared kernel
  - Programming language defines interface
    - Data interfacing through shared data
    - Control interfacing through direct control transfer
    - Compiler and linker determine and resolve addresses

Kernel Interfaces in monolithic OSes

- Monolithic Kernel design
  - Design principle: global, shared kernel
  - Programming language defines interface
  - Logical/Semantical separation of concerns
    - C-structs, extern functions, static functions
    - header files, source files
    - classes, members, namespaces, ...
  - *No* boundary protection
    - Software can easily cross semantic boundaries
    - arbitrary control transfers (e.g., using assembler)
    - arbitrary data access and modifications (e.g., using typecasts and pointers)

Kernel Interfaces in monolithic OSes

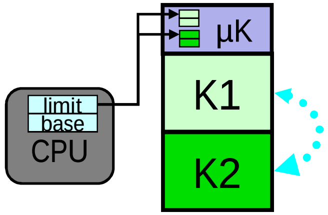
- Monolithic Kernel design
  - *No* privilege separation
    - All kernel subsystems can execute all processor instructions
    - All kernel subsystems can access all I/O hardware
  - Motivation: Performance
    - Crucial factor in OS
    - Protection domain switches are costly
      - Full address space switch (Pentium IV):
        - changes *all* AS translations
        - Implies TLB flush
          (~ 500 cycles)
        - Implies (Virtual) Trace Cache flush
          (up to 4000 cycles)
        - + TLB replacement + Trace cache reloading
          (~ 5000 cycles)

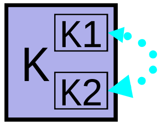


Source: Uhlig et. al. ***Performane of Address-Space Multiplexing on the Pentium.*** Fak. f. Informatik, Univ. Karlsruhe, 2002

Kernel Interfaces in monolithic OSes

- Monolithic Kernel design
  - *No* privilege separation
    - All kernel subsystems can execute all processor instructions
    - All kernel subsystems can access all I/O hardware
  - Motivation: Performance
    - Crucial factor in OS
    - Segmentation (partial AS switch)
      - Changes base offset, accessible limits within AS
      - Changes protection parameters
      - Implies segment register reloading (~300 cycles)
      - No TLB and TC flushing
      - But Restrictions on AS layout and size
    - Monolith lacks protection but retains performance
      - Direct calls, direct data accesses
      - Cross-component accesses and optimizations
      - Ad-hoc extensibility





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Kernel Modules: Extensibility in Linux

- Linux is becoming more and more complex
  - vast amount of device drivers, network protocols, file systems
  - Linux should support crufty hardware
  - Support not always needed
- Need dynamic kernel extensibility
  - Loading (and unloading) kernel components on demand
    - E.g., device detection routine loads appropriate drivers
- Two subproblems:
  - Make component functionality available to kernel
  - Make kernel functionality available to component

Kernel Modules: Extensibility in Linux

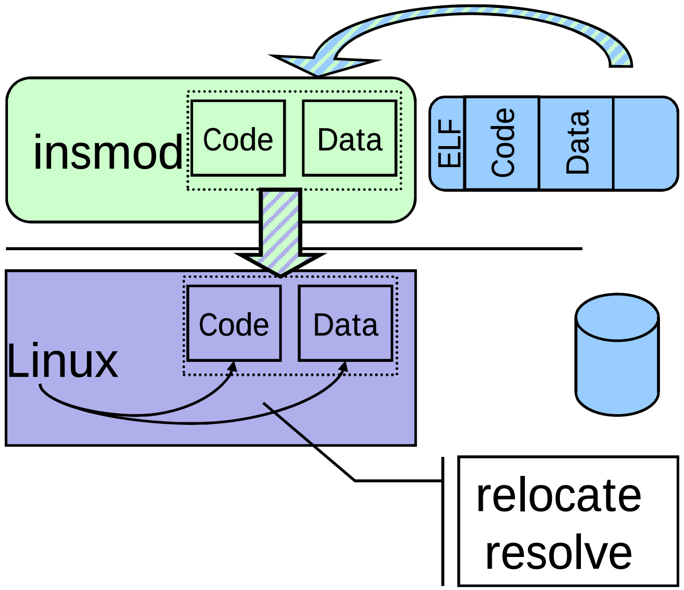
- Linux kernel interface are defined by programming language (“C”)
  - Data layout implicitly defined by compiler
    - structs, enums, arrays, (classes)
  - Global symbol namespace
    - Represents code and data
    - *Compiler* generates code and local symbols from source file (object files)
      - Relative addresses for internal references, placeholders for external references
      - References are stored within the object file itself (ELF format)
    - *Linker* resolves local symbols and computes global addresses to combine multiple object files
      - Resolves address collisions
      - Resolves external references
      - Must contain an ELF format parser

Kernel Modules: Extensibility in Linux

- Linux kernel interface are defined by programming language (“C”)
  - Idea: Perform run-time linking of additional object files
    - Kernel modules are run-time linked kernel libraries
      - Images are relocatable
    - Store linking information within module
      - Special “__ksymtab” and “.modinfo” section in ELF file
      - Contains text names for symbols
    - Store linking information within kernel symbol table

Kernel Modules: Extensibility in Linux

- Loading kernel modules
  - Modules are plain object files (.o)
  - User-space helper programs
    - insmod, modprobe and friends
    - ELF-load and parse modules
    - Pass special structure to kernel
  - Kernel
    - Relocates module image according to its dedicated virtual address space
    - Resolves external references based on kernel symbol table
    - Finds dependencies and loads more modules if required
    - Executes module init routine
      - Can register new driver, or functionality



Kernel Modules: Extensibility in Linux

- Analysis:
  - Modules serve the need:
    - Provide dynamic extensibility
    - Preserve the normal programming language based kernel interface
  - But: Extensibility tied to the source code
    - Floating and volatile interface
    - Loading requires exact module/kernel match

Kernel Modules: Extensibility in Linux

- Analysis:
  - Kernel modules are not a protection mechanism
    - Modules link into the same address space
    - Can be abused (LKM root kits)
    - Raises dependability and reliability issues
  - Implementation
    - Kernel depends on user-space programs (so what?)
    - Module dependencies bear substantial complexity
      - Arbitrary <uses> and <depends> relations
      - circular dependencies
      - Inevitable with modularization?

Windows WDM driver architecture

- Windows is a proprietary, closed-source OS
- Still it…
  - Needs to support various (crufty) hardware devices
  - Needs to enable device manufacturers to develop their own driver software
  - Needs a standardized interface to let drivers interact with
    - I/O hardware
    - Other windows kernel subsystems
    - Applications

Source: M. Tsegaye and R. Foss ***A comparison of the Linux and Windows device driver architectures***
Operating Systems Review 2004 2:38 p.8-33

Windows WDM driver architecture

- Basic Idea:
  - Provide a special driver interface
  - Use an abstract driver model as foundation
    - I/O request packets
    - WDM driver stack
    - Hardware abstraction layer
  - Specify interaction as programming interface
    - WDM API defines standard methods, data structures, ...
    - Windows uses .inf files to install drivers

Source: M. Tsegaye and R. Foss ***A comparison of the Linux and Windows device driver architectures***
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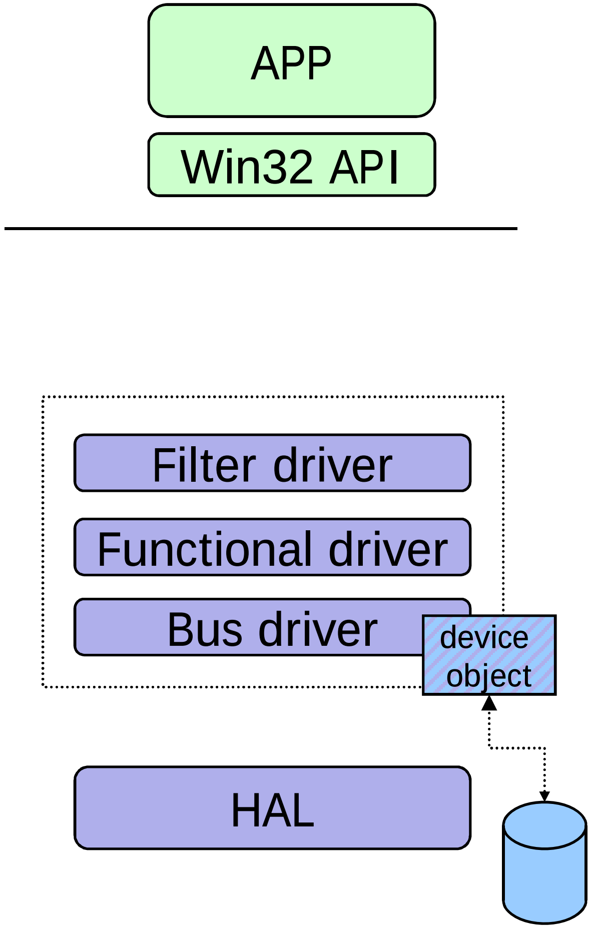
Windows WDM driver architecture

- Some details
  - Driver objects
    - Filter, functional, bus drivers
    - Stackable
    - Specified functionality
      - init, addDevice, dispatch, unload
  - Device objects
    - Represent a real HW device
    - Managed by a (set of) drivers
    - Can have a name
      - 128-bit device name space
    - Specify how I/O is transferred from user to kernel
      - Direct, buffered, pinned DMA



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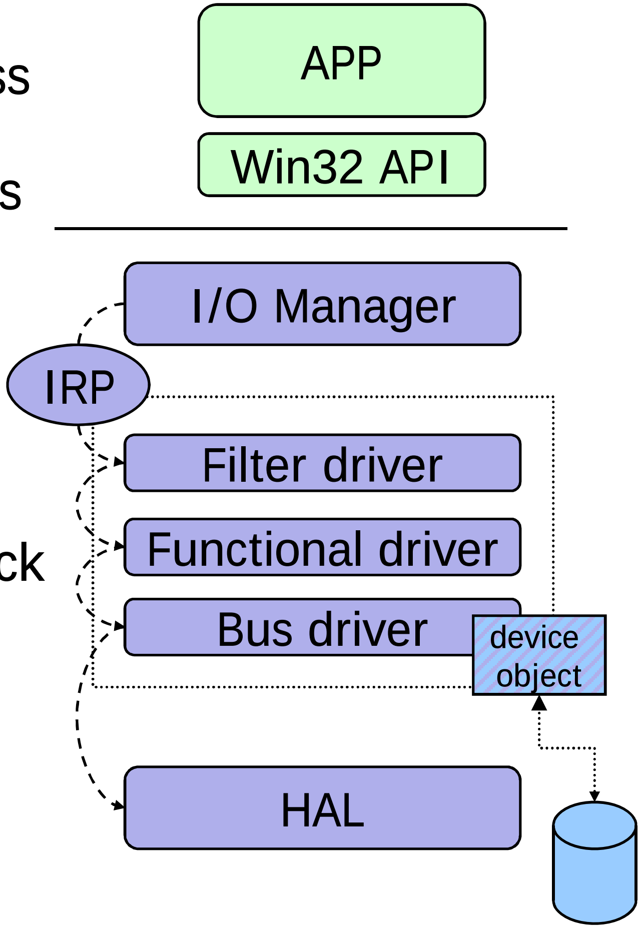
Windows WDM driver architecture

- Some details
  - I/O request packet (IRP)
    - represents an abstract I/O process data unit
    - Passed to driver stack by windows kernel subsystem
    - Percolates through the specified dispatch routines
  - Driver programmer
    - implements driver components
    - links them together to form a stack
    - provides device names
  - Application programmers
    - Can perform I/O based on device name.



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Windows WDM driver architecture

- Driver interface details
  - API approach
  - Programmer relies on specified C-functions and data structures

```
#include <ntddk.h>

NTSTATUS DriverEntry(PDRIVER_OBJECT DriverObject, PUNICODE_STRING RegistryPath)
{
        ...
        return STATUS_SUCCESS;
}
```

  - Windows provides a build utility (DDK)

```
TARGETNAME = mydriver
TARGETPATH = obj
TARGETTYPE = DRIVER
INCLUDES = %BUILD%\inc
LIBS = %BUILD%\lib
SOURCES = mydriver.c
```

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Windows WDM driver architecture

- Analysis:
  - WDM
    - provides dynamic extensibility for device drivers
    - API based kernel interface
  - Extensibility *not* tied to the source code
    - Fixed interface
    - Build process can produce drivers for different Windows versions
  - Interface specialized to device drivers
    - Does not provide generic module/subsystem extensibility

Windows WDM driver architecture

- Analysis:
  - WDM does not provide protection
    - Drivers link into the same address space
    - Raises dependability and reliability issues
    - Drivers are known to be highly error-prone*
  - Implementation
    - Data-centric model
      - I/O Request packets and dispatchers
    - Simple component dependencies
      - Stack of dispatchers

*Source: A. Chou et al. ***An Empirical Study of Operating System Errors.*** Proceedings of the 18th ACM Symposium on Operating Systems Principles (SOSP) p.73-88

Kernel Interfaces in Multi-server Systems

- Multi-server kernel (system) design
  - Privilege separation through address-space protection
    - µ-Kernel is privileged but limited in functionality
    - Other kernel subsystems are “user programs”
      - Can not execute privileged instructions
      - Can not access arbitrary memory locations
      - Can not access arbitrary I/O hardware
  - Motivation: Protection
    - Premise for security, reliability, dependability, …
    - Crucial factor in OS
    - But protection domain switches are costly
    - Multi-server system trades off protection against performance
    - Key problem: Keep good performance

Kernel Interfaces in Multi-server Systems

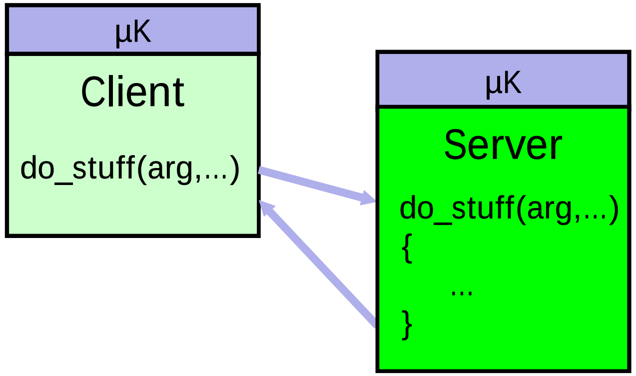
- Multi-server interfaces
  - Kernel subsystems are “user programs”
    - Normal user interface for µ-Kernel services
    - Direct addressing and data sharing between other subsystems unfeasible
  - µ-kernel must cater for subsystem interaction
  - Should be generic and versatile
    - Support different subsystems
      - resource managers, schedulers, pagers, drivers, UI, ...
    - Support different programming models
      - Different manufacturers, compilers, languages, black-box binaries,...
    - Support different interaction scenarios
      - Service requests and returns
      - Data sharing
      - Notifications, callbacks, exceptions, ...

Kernel Interfaces in Multi-server Systems

- Multi-server interfaces
  - (L4) Idea: provide simple and generic IPC
    - Used by kernel subsystems
    - Used by user programs
  - Develop specializations on top
    - Subsystem-specific interaction
    - Programming models (APIs, C-like function calls, ...)
    - Data sharing (shared memory, request buffers, ...)
    - Naming and addressing schemes

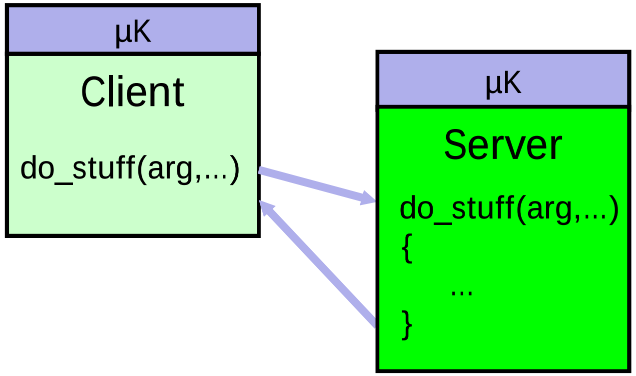
Kernel Interfaces in Multi-server Systems

- But how to define interfaces?
  - Subsystem-specific interfaces
  - Programming models (APIs, C-like function calls, ...)
  - Data sharing (shared memory, request buffers, ...)
  - Naming and addressing schemes
- Idea: Leverage work from distributed systems
  - Same scenario: distributed components + interaction
  - E.g., Remote procedure call model
    - Client/Server model
    - Need transparent, procedure-call like semantics
      - Client calls server for service
      - Server returns after processing
    - Provide remote procedure call (RPC)
      - Synchronous communication
      - Can pass and return arguments



Kernel Interfaces in Multi-server Systems

- But how to define interfaces?
  - Subsystem-specific interfaces
  - Programming models (APIs, C-like function calls, ...)
  - Data sharing (shared memory, request buffers, ...)
  - Naming and addressing schemes
- Idea: Leverage work from distributed systems
  - Same scenario: distributed components + interaction
  - E.g., Remote procedure call model
    - Problems:
      - Calling convention
        - No shared data
        - Pointers? References?
      - Transparency
        - Should “feel” like normal call/ret
        - Latency? IPC Errors?



Kernel Interfaces in Multi-server Systems

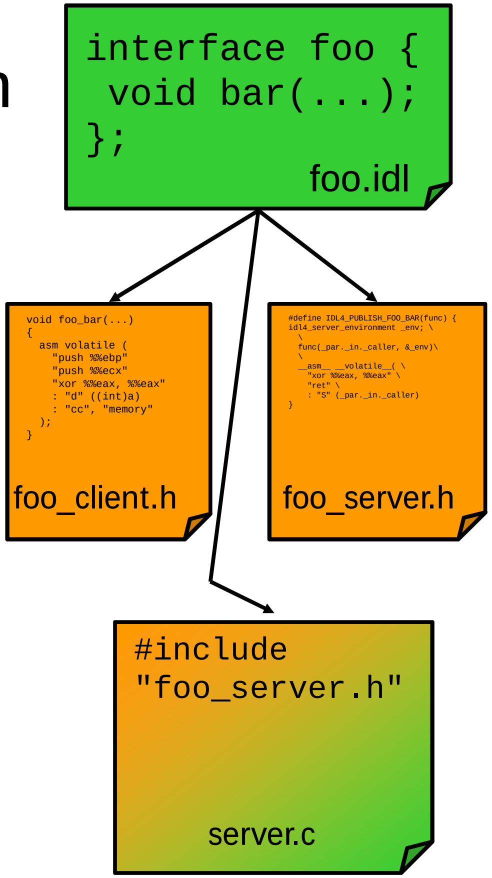
- Remote procedure call approaches
  - Client and server stubs
    - Transform call/ret semantics into communication
      - Parameter marshaling/unmarshaling
      - Procedure multiplexing/demultiplexing
      - Message and data layout definition
      - Leverages system communication primitives
  - Steps:
    - Client procedure-calls client stub
    - Client stub
      - marshals parameters
      - builds message
      - calls kernel to send message to server
    - Server stub decodes message
      - dispatches the correct procedure (if needed)
      - unmarshals parameters
      - calls corresponding server-side procedure
    - Server processes the request and returns to the server stub

Kernel Interfaces in Multi-server Systems

- Special considerations for node-local (multi-server) RPC
  - Communication is more efficient,
    thus stub code efficiency has more impact
  - Same hardware: same endianess, bit width, float precision, ...
  - Same µ-kernel, can rely on its data types, interfaces etc.
  - Simplifies/speeds up stub code

Kernel Interfaces in Multi-server Systems

- Remote procedure call
  - Writing stubs is tedious
  - Idea: Automate stub code generation
  - Interface definition languages
    - Language that *specifies* interfaces
      - Remote method definition
      - Special data types for argument passing
    - Compiler generates interface stubs
      - Client stub
      - Server stub
      - Server skeleton (basic dispatcher)
    - Examples: Flick, Corba IDL, DCOM
    - See lab lecture: using IDL^4



```
interface foo {
 void bar(...);
};
```

foo.idl

```
void foo_bar(...)
{
  asm volatile (
    "push %%ebp"
    "push %%ecx"
    "xor %%eax, %%eax"
    : "d" ((int)a)
    : "cc", "memory"
  );
}
```

foo_client.h

```
#define IDL4_PUBLISH_FOO_BAR(func) {
idl4_server_environment _env; \
  \
  func(_par._in._caller, &_env)\
  \
  __asm__ __volatile__( \
    "xor %%eax, %%eax" \
    "ret" \
    : "S" (_par._in._caller)
}
```

foo_server.h

```
#include
"foo_server.h"
```

server.c

The SawMill Multiserver Architecture

- The SawMill Approach
  - Complexity of OS increases
  - Need specialized OS personalities for different scenarios
  - Need a development path to build such specialized operating systems

Source: A. Gefflaut et al. ***The SawMill Multiserver Approach*** ACM SIGOPS European Workshop 2000

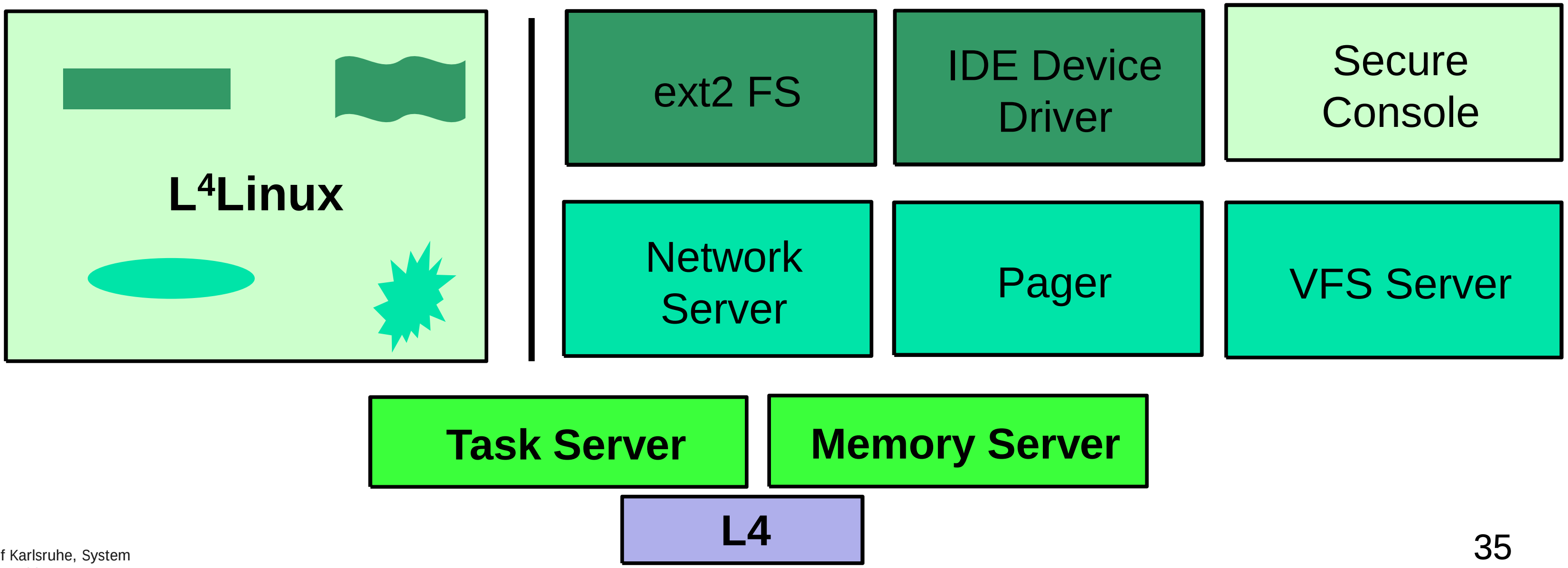
The SawMill Multiserver Architecture

- The SawMill Approach
  - Idea: *Decompose* existing operating systems for flexibly reusable components
    - Extend existing OS with functionality
    - Customize existing OS: strip them down for application requirements
  - The SawMill approach consists of
    - An architecture to build systems
    - A set of protocol design guidelines to solve multi-server problems

Source: A. Gefflaut et al. ***The SawMill Multiserver Approach*** ACM SIGOPS European Workshop 2000

The SawMill Multiserver Architecture

- *Example "SawMill" Multi-Server Linux:*
  - (1) isolate Linux services from each other;
  - (2) improve them one by one:
    - *VM, scheduling, security (denial of service), reliability, SMP, large memory, mmap, async io, select, large files*
  - Extend Linux, add value:
    - *New security policies, …*
  - Customize Linux for special devices.

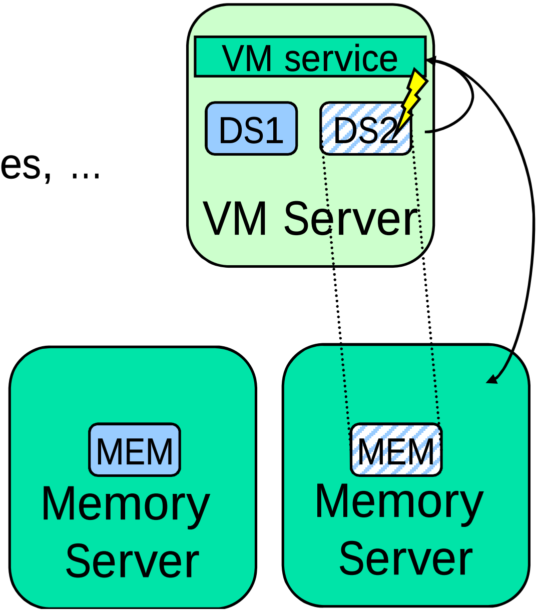


The SawMill Multiserver Architecture

- SawMill design considerations
  - The multiserver OS must provide
    - Protection
      - Protect execution integrity of servers
      - Protect data integrity/confidentiality of user data
    - Coherent semantics
      - Obtain and enforce system policies
      - Obey atomicity requirements
    - Performance (efficient services)
      - Protection implies more frequent IPC
        - IPC replaces procedure calls
        - Additional IPCs required for consistency, synchronization, resource management, security policies, ...
      - Protection implies more complex IPC
        - Parameter transfer
        - Parameter marshaling
        - See previous slides

The SawMill Multiserver Architecture

- SawMill architecture
  - Three types of components
    - System servers
      - Main OS functionality
      - File server, network server, …
    - Resource servers
      - Manage core resources
      - Distributed among system servers
      - Memory, IRQs, security abstractions, …
    - Ubiquitous services
      - “Libraries” that augment servers
      - Multiserver-aware management
      - Synchronization, ACL, Naming, IPC primitives, …
  - Example: Virtual memory
    - VM system server exports a *dataspace*
    - Memory server provides core memory
    - Ubiquitous VM service handles indirection between dataspace and core memory

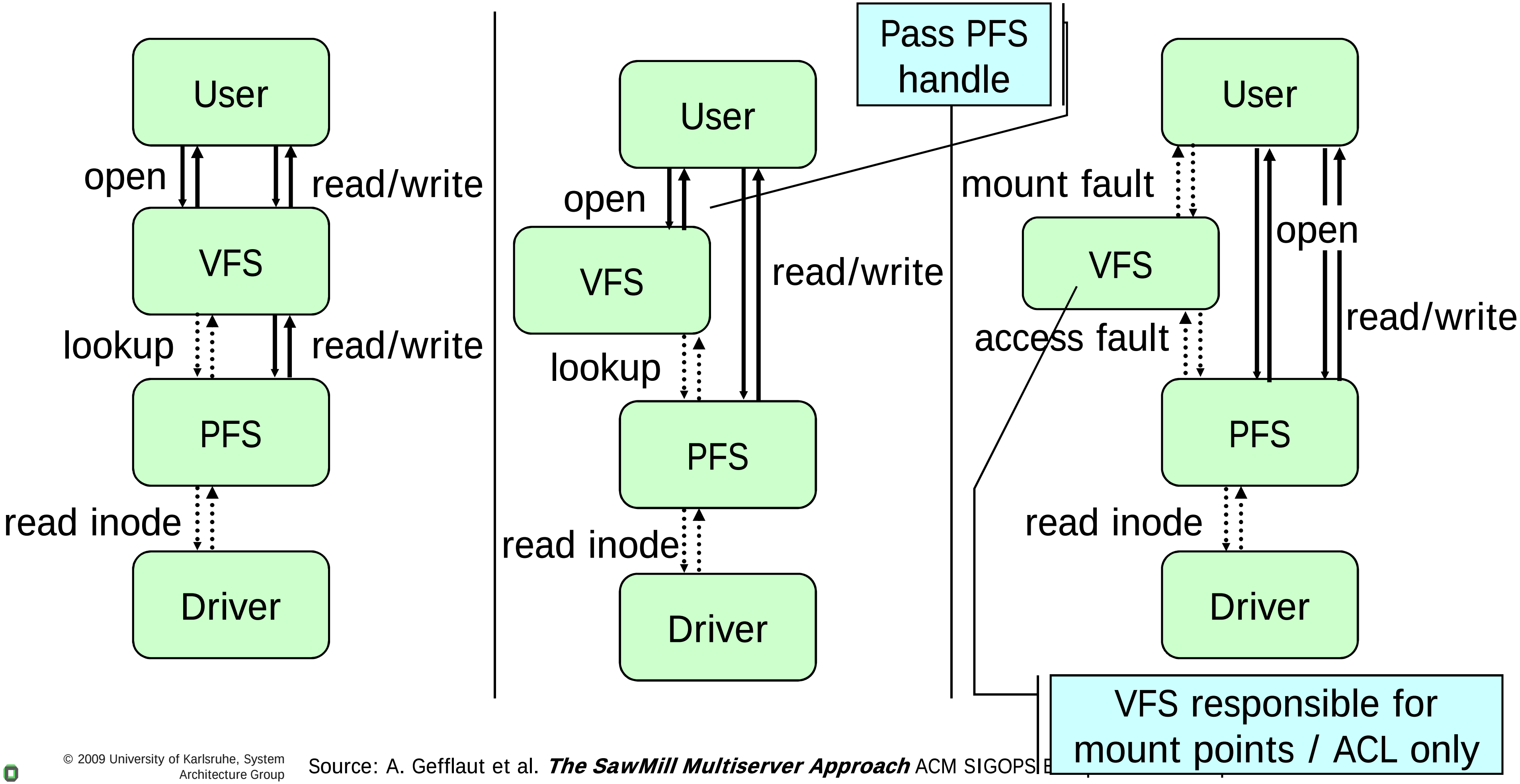


The SawMill Multiserver Architecture

- SawMill protocols
  - Goal: minimize IPC frequency and overhead
  - Design principles:
    - Make direct calls to processing servers
      - Let clients communicate directly with subsequent servers
    - Partition control data
      - Distribute control data among involved servers
      - Use caching in servers if possible
      - Minimize synchronization
        - Minimize writes
        - Weaken consistency models
        - Use “Master copy” schemes
    - Heavily use data sharing

The SawMill Multiserver Architecture

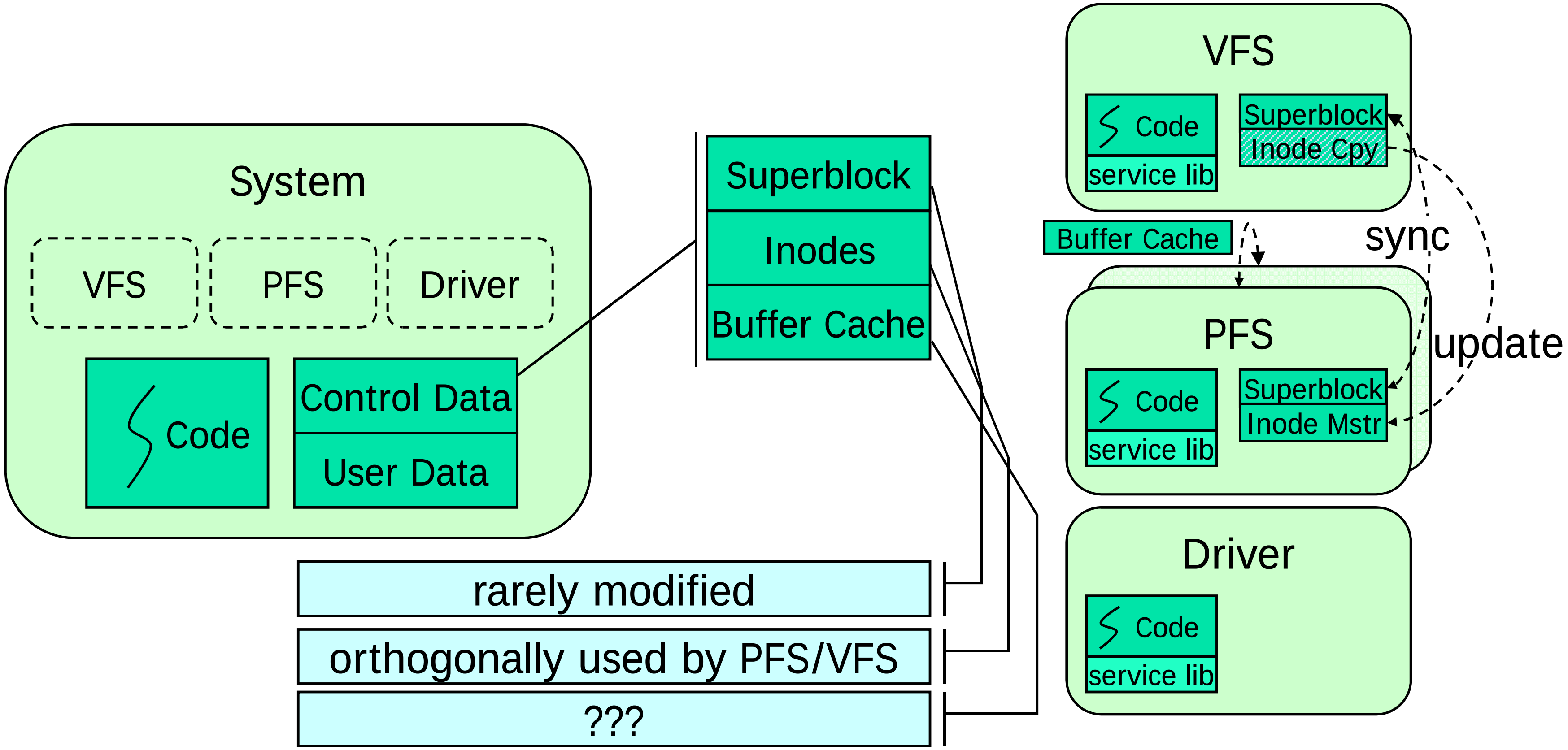
- Envisage direct calls



Source: A. Gefflaut et al. ***The SawMill Multiserver Approach*** ACM SIGOPS E

The SawMill Multiserver Architecture

- Partition control data



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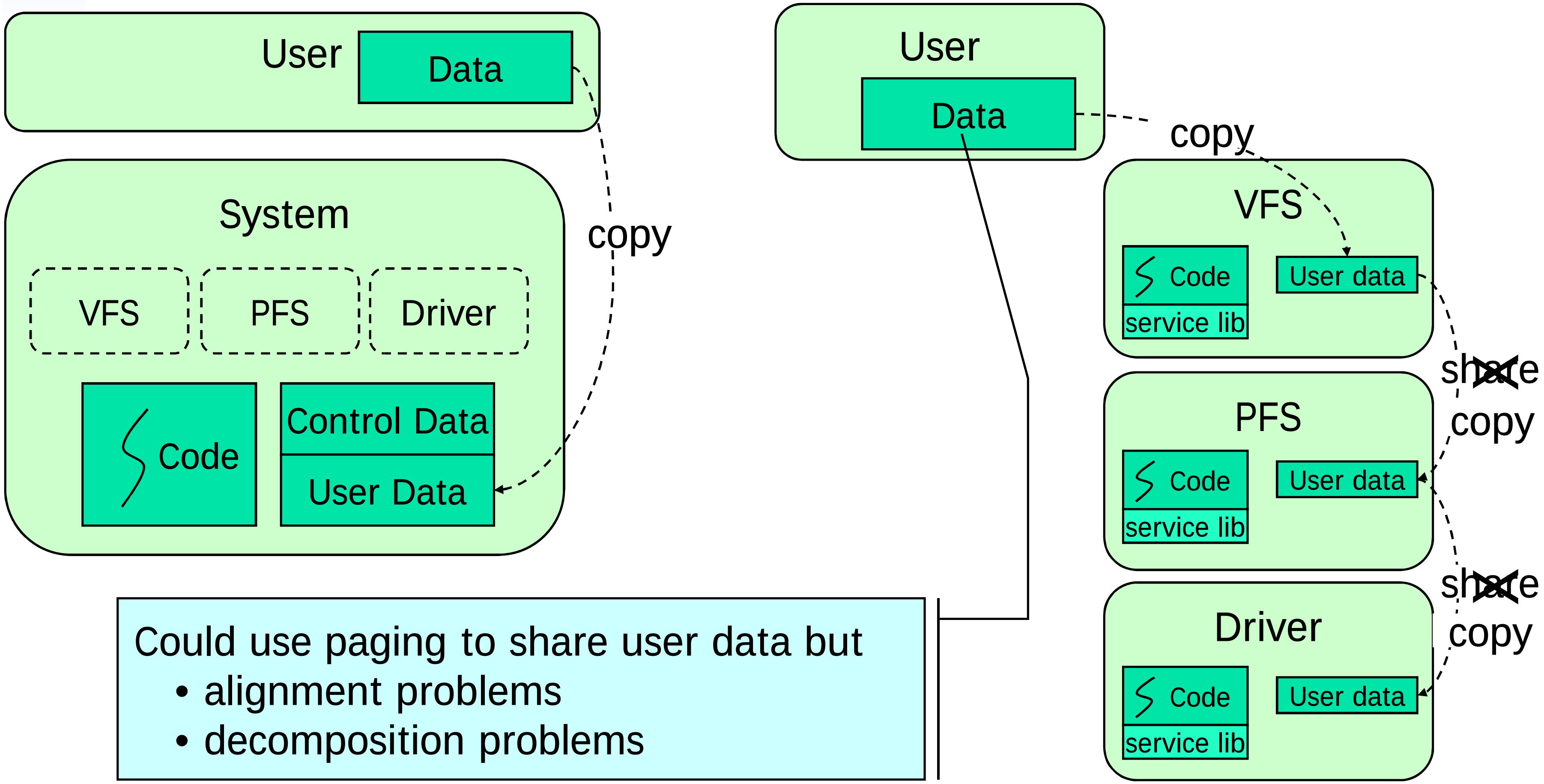
The SawMill Multiserver Architecture

- Share user data



Could use paging to share user data but

- alignment problems
- decomposition problems

Sources: A. Gefflaut et al. ***The SawMill Multiserver Approach*** ACM SIGOPS European Workshop 2000
P.Druschel et al. ***Fbufs: A High-Bandwidth Cross-Domain Transfer Facility*** Proceedings of the 14th Symposium on Operating Systems Principles 1993 p189-202

The SawMill Multiserver Architecture

- Analysis
  - SawMill
    - Envisages customized, modular OS personalities
    - Uses a *decomposition* approach for reuse
  - Presents a basic architecture
    - µ-kernel based client/server architecture
    - Servers, ubiquitous services, core resource managers
  - And a set of protocol guidelines
    - Make direct calls to processing servers
    - Partition control data
    - Share user data
    - Used to design and implement components and interfaces

The SawMill Multiserver Architecture

- Analysis
  - Problems
    - Decomposition is hard
    - Stripping down is hard
      - SawMill Linux has a huge code base
      - SawMill must maintain/fight against legacy Linux semantics
      - Linux was never designed to deal with multi-server problems
    - Partitioning control data is complicated
    - Sharing user data is complicated
      - Especially together with legacy semantics
      - E.g., how to partition entangled control/user data (skbuffs)?
      - How to share unaligned data?

Virtualization interfaces

- Background
  - Complexity of OS increases
  - Want to improve or introduce new OS functionality
    - Effective time sharing (aka server consolidation)
    - Simultaneous support of multiple OS APIs
    - Transparent migration
    - Security services
  - Monolithic OS design has serious limits
    - Complex, entangled, unreliable, insecure, ...
    - Hard to customize, hard to extend, hard to decompose

Virtualization interfaces

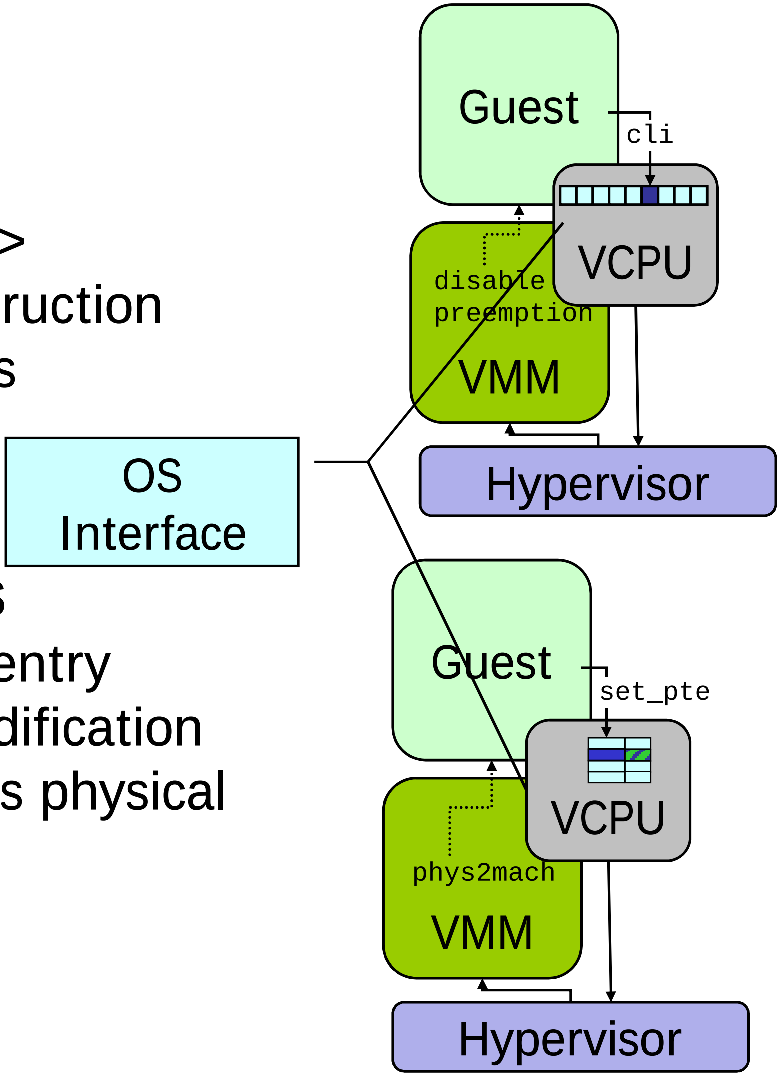
- Problem: Legacy support
  - New OS must support old programs
  - API support not sufficient
    - Want to support old OS functionality as well
    - Many applications are tailored to specific OS versions
    - Need a development path to incorporate new and keep old functionality *at the same time*

Virtualization interfaces

- Idea: Virtualization
  - Provide hardware interface
  - But transparently change semantics
- Interface constituted by hardware specification
  - Fixed and well-designed interface
  - Already used by guest OS, no porting effort needed
- Virtualization only changes semantics
  - Restrict side effects to virtual machine and dedicated hardware
  - Keeps illusion of real hardware

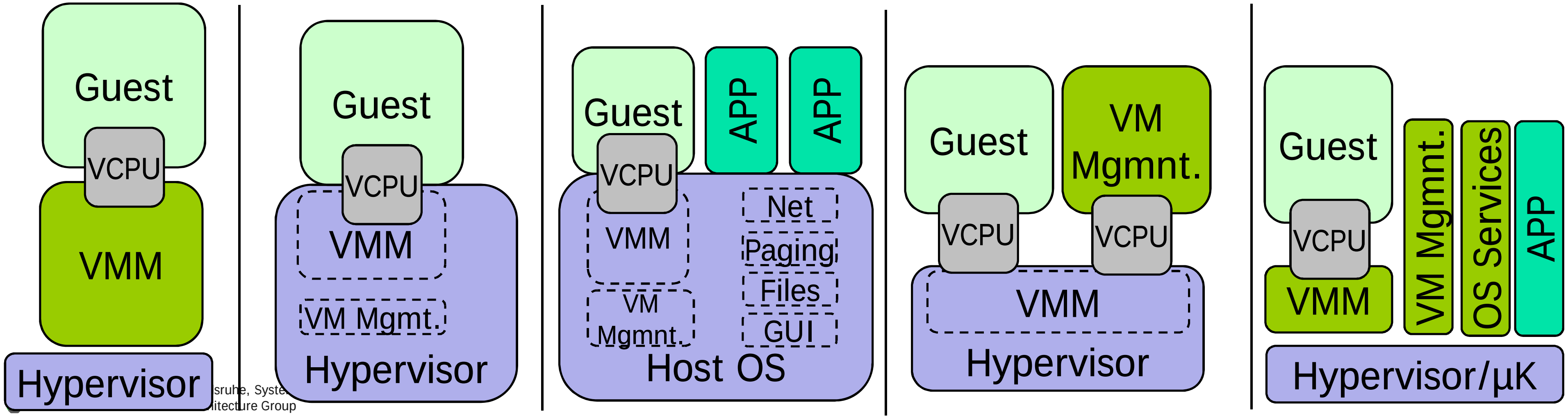
Virtualization interfaces

- Examples:
  - Interrupts
    - Guest executes <clear IF>
    - Hypervisor intercepts instruction
    - Monitor/Emulator disables preemption of Guest OS
  - Page table modifications
    - Guest inserts page table entry
    - Hypervisor intercepts modification
    - Monitor/emulator modifies physical mapping if necessary



Virtualization interfaces

- Virtualization provides stacked OS model
  - Guest OS contains applications and (unprivileged) OS services
  - Hypervisor/host OS contains privileged OS services and emulation
- Additional OS services can be designed freely
  - No interface requirements
  - Multi-server components
  - Leverage host OS
  - Use specialized virtual machines



Virtualization interfaces

- Analysis
  - Interface defined by hardware
    - Fixed and well-designed interface
    - Already used, no porting effort needed
  - Virtualization changes semantics
    - Semantics are not specified
    - Transparency introduces overhead
  - Hardware Interface may be inappropriate
    - Example: Disk I/O
    - Guest performs write to device
    - File access? Swapping?
  - Example: Network I/O
    - Guest calls virtual NIC to send buffer
    - Virtual NIC must decode packets again
  - Virtualization *only* provides legacy
    - It does not address the design of new OS functionality
    - It does not address the design of new or improved interfaces

Thursday

- Maifeiertag