Operating Systems Research at UNSW and NICTA

and
Opportunities for Students

COMP9242 2004/S2 Week 14

OVERVIEW

- What is NICTA?
- Embedded systems research agenda
- Present projects
- Opportunities

NATIONAL ICT AUSTRALIA (NICTA)

- National Centre of Excellence in Information and Communications Technology (ICT)
- Created in October 2002 by Australian Government
- Members:
  - University of New South Wales (UNSW), Sydney
  - Australian National University (ANU), Canberra
  - NSW and ACT governments
- Locations:
  - Sydney (UNSW campus and ATP technology park)
  - Canberra
  - Melbourne (University of Melbourne Campus)
  - Brisbane (in progress)

NICTA'S FOUR PILLARS

- Research
  - ➜ conduct world-class ICT research that makes an impact
  - ➜ "use-inspired fundamental research"
- Education
  - ➜ produce world-class PhD graduates
  - ➜ students enrolled at one of the member/partner universities
- Linkages
  - ➜ collaborate with top research institutions around the world
- Commercialisation
  - ➜ turn research into products
  - ➜ focus on
    - ➜ local small and medium-sized enterprises (SMEs)
    - ➜ multinational corporations (MNCs)

NICTA STRUCTURE

- Presently ≈ 150 researchers, 150 PhD students
- Researchers belong to *Research Programs*
  - ➜ aligned with discipline areas (≈ 5–10 researchers)
  - ➜ lifetime 5–10 years
- *Priority Challenges* drive research
  - ➜ PC1: trusted wireless networks
  - ➜ PC2: from data to knowledge
- *Projects* focused on specific outcomes
  - ➜ collaborative or client-focused
  - ➜ lifetime 1–5 years
- *International Science Advisory Group*
  - ➜ Richard Newton (UCB), Shankar Sastry (UCB), Raj Reddy (CMU), Rodney Brooks (MIT), Jeff Ullman (Stanford), Gunnar Bjurel (SIKS), Gilles Kahn (INRIA), Ya-Qin. Zhang (Microsoft), ...

EMBEDDED, REAL-TIME AND OPERATING SYSTEMS (ERTOS) PROGRAM

- One of presently 16 Research Programs in NICTA
  - ➜ 8 FTE PhD-qualified researchers (1 vacant)
  - ➜ 11 FTE research engineers / research assistants (2 PhDs)
  - ➜ 20 PhD students (10 core OS topics)
- Competencies in
  - ➜ operating systems, microkernels
  - ➜ networking
  - ➜ real-time systems
  - ➜ reconfigurable computing
  - ➜ programming languages and compiler front-ends

EMBEDDED SYSTEMS IN AUSTRALIA

- Australian embedded systems industry landscape
  - little industrial research
  - innovation concentrated in SMEs
  - little confidence in locally-developed technology
  - operating in niche markets
- Implications:
  - no scope for ASICs, use COTS hardware components
  - main focus is on software
  - reconfigurable hardware will be increasingly important
    - ➜ prototyping
    - ➜ small series
    - ➜ flexibility

NICTA PRIORITY CHALLENGE: TRUSTED WIRELESS NETWORKS

To enable greater confidence, freedom, and capability through improved efficiency, reliability, and security of all wireless environments.

- Strongly based on embedded systems technology
- Issues relevant to ERTOS:
  - efficiency
  - reliability
  - security
  - cost

ERTOS Vision

To develop methodologies, tools, components and systems that will deliver reliable, trustworthy and inexpensive embedded systems software

ERTOS research is to be driven by applications

- to identify common challenges
- to provide generic systems software

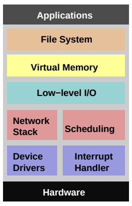
Embedded System

Computer system that is part of a larger system

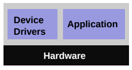
General-Purpose vs. Embedded

Traditional view:

general-purpose system



embedded system



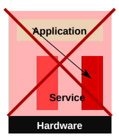
- ➜ minimal
- ➜ no OS at all or small "real-time executive"
- ➜ no protection

Security Challenges

- Growing functionality
  - ➜ increasing software complexity
  - ➜ increased number of faults
  - ➜ increased likelihood of security faults
- Wireless connectivity
  - ➜ subject to attacks from outside (crackers)
- Downloaded contents (entertainment)
  - ➜ subject to attacks from inside (viruses, worms)
- Increasing dependence on embedded systems
  - ➜ increased exposure to embedded-systems security weaknesses

Embedded Systems Software

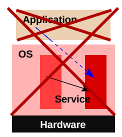
Present approaches 1: Real-time executives



- Small, simple operating system
  - ➜ optimised for fast real-time response
  - ➜ suitable for systems with very limited functionality
- No internal protection
  - ➜ every small bug/failure is fatal
  - ➜ no defence against viruses, limited defence against crackers

Embedded Systems Software

Present approaches 2: Linux, Windows Embedded, ...



- Scaled-down version of desktop operating system
  - ➜ operating system protected from application misbehaviour
  - ➜ excessive code base for small embedded system
  - ➜ too much code on which security of system is dependent
- Dubious or non-existent real-time capabilities
  - ➜ unsuitable for hard real-time systems

Embedded Systems Requirements:

Reliability, trustworthiness, security

- Achieved by:
  - ➜ exhaustive testing?
  - ➜ systematic code inspection?
  - ➜ formal methods?
  - ✗ scale poorly (few 1000 loc)
- Requires minimal *trusted computing base* (TCB):

  TCB: The part of system that must be relied on for the correct operation of the system
- Why minimal TCB?
  - ☑ minimise exposure to bugs/faults
  - ☑ minimise exposure to attacks (internal and external)
  - ☑ support poorly-scaling verification methods

Trusted Computing Base

What does the TCB contain?

- Kernel $\left(\stackrel{\text{def}}{=}\right.$ part of system that executes in privileged mode$\left.\right)$
  - ➜ everything running in privileged mode can bypass security
- Device drivers
  - ➜ DMA-capable devices can bypass protection
  - ➜ drivers can mount DoS attacks
- Services that control resources
  - ➜ resource owner can deny resource
  - ➜ resource owner can leak/corrupt data
- *Everything* on MPU-less processors
  - ✗ no memory-protection hardware $\Rightarrow$ no memory protection

MINIMISING THE SIZE OF THE TCB

... MEANS FIRST OF ALL:

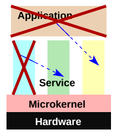
- Use an MPU — microcontrollers are out!
- Minimise the size of the kernel!

MINIMISING KERNEL SIZE:

- Reduce kernel to what is *essential for supporting secure systems*
- What does not *require* privileged mode *must not* be in the kernel
- This is the definition of a *microkernel*
- *Minimal TCB required ⇒ microkernel required!*

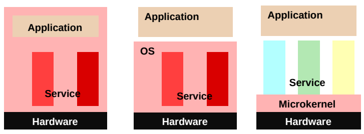
EMBEDDED SYSTEMS SOFTWARE

NICTA APPROACH: MICROKERNEL



- Extremely small kernel
  - ➜ microkernel only contains code that *must* run in privileged mode
  - ➜ all other "systems" code runs as unprivileged servers
  - ➜ microkernel protected from application *and* other systems code
  - ➜ microkernel provides protection of all components from each other
- What's the difference?

TRUSTED COMPUTING BASE



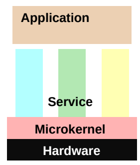
System:	traditional embedded	Linux/ Windows	Microkernel-based
TCB:	**all** code	100,000's loc	10,000's loc

Small is beautiful:

- Small kernel ⇒ potentially small TCB
- Small TCB ⇒ more trustworthy TCB!

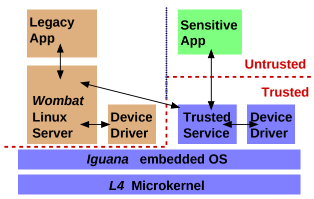
Challenge: Can we *guarantee* the trustworthiness of the TCB?

MICROKERNEL BENEFITS



- Fault isolation
  - ☑ other components protected from fault
- Hot swapping / hot upgrade
  - ☑ can replace servers on running system
- Software engineering techniques
  - ☑ componentised system
- Enforcement of security policies
  - ☑ kernel controls communication even between system services
- Resource management for system services
  - ☑ OS servers are like normal user code
- Formal verification
  - ☑ hardware-enforced isolation reduces complexity

A SAMPLE SYSTEM



- Sensitive part of system has small TCB
- Standard API supported by de-privileged Linux server
  - ➜ full binary compatibility with native Linux
- Compromised legacy system cannot interfere with trusted part

L4: NICTA L4-EMBEDDED API

SIMPLER/SMALLER IMPLEMENTATION

- L4Ka::Pistachio issues
  - optimised for supporting high-end systems (servers)
  - large memory footprint (presently ≈ 100kB)
    - ➜ should fit on smartcard
  - complexity (in-kernel page faults, preemption, code bloat)
    - ➜ makes it hard to validate implementation (formally or informally)
    - ➜ makes it hard to establish hard worst-case latencies
    - ➜ harder to optimise for high performance
- NICTA::Pistachio
  - ➜ remove long IPC!
  - ➜ reduce number of virtual registers (16–64)
  - ➜ remove timeouts
  - ➜ remove local thread IDs
  - ➜ add asynchronous notification
  - ➜ remove remaining drivers from kernel
  - ➜ physically-addressed TCBs ⇐ *honours thesis*
  - ➜ single kernel stack per CPU ⇐ *honours project*

IGUANA: OS PERSONALITY FOR EMBEDDED SYSTEMS

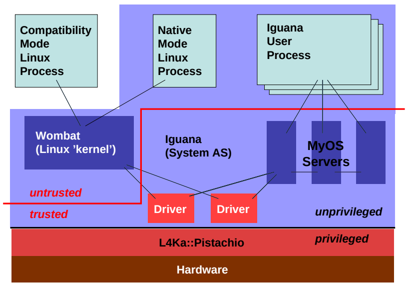
- Remember, L4 is (almost) a "strict" microkernel:
  - ➜ does not provide any services
  - ➜ does not provide policies (or only very few)
  - ➜ provides mechanisms
- L4 aspires to be generic kernel, suitable for all kinds of systems
- Almost any system requires a set of core services:
  - ➜ process management
  - ➜ memory management
  - ➜ security management

  ... based on some system-wide policies
- Iguana provides these (or at least more tools for providing them)
  - ➜ designed for use in embedded systems
  - ➜ designed to minimise trusted computing base

WHAT DOES IGUANA PROVIDE?

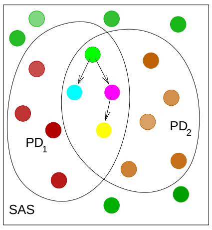
- Convenient way of using L4 primitives
  - ➜ OO-style method invocations instead of explicit IPC calls
  - ➜ IDL compiler for automatic generation of stubs
- Protection framework for access rights management
  - ➜ capability based, flexible
  - ➜ able to model most standard security models
- Virtual memory management
  - ➜ allocation, deallocation, sharing, ...
  - ➜ single-address-space view, supporting FASS on ARM
- Protection-domain (process) management
- Thread management

Sample Iguana System



Iguana: Basic Approach

- Basic idea: single address space (SAS)
  - eases sharing of data
    - ➜ minimises copying
    - ➜ no problems with pointers
- Per-process *protection domains*
  - enforce security policy
    - ➜ any access is subject to access control
  - do not interfere with sharing
- Advantages
  - works with MMU-less microprocessors
  - cheap context switches on ARM7/ARM9
- Based on UNSW Mungi system



Iguana Concepts

- Memory section
  - ➜ unit of VM allocation and protection
  - ➜ can be an encapsulated object with methods and data
- Thread
  - ➜ execution abstraction, as in L4
- Server
  - ➜ thread associated with memory section
  - ➜ invoked through methods with well-defined interfaces
- Protection domain
  - ➜ defines access and resource rights of a thread
  - ➜ corresponds to a process in traditional OS

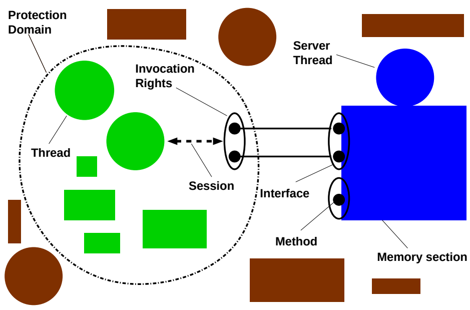
Iguana Concepts

- Session
  - ➜ client-server (or peer-to-peer) communication channel
  - ➜ amortises authentication cost over many invocations
- Capability
  - ➜ represents access rights
  - ➜ basis of protection
- Resource token
  - ➜ represents resource usage right
  - ➜ basis of resource management
- External Space
  - ➜ address space extern to Iguana's SAS
  - ➜ for legacy support and large processes

Iguana Philosophy

- Small and lightweight
  - ➜ geared towards embedded systems
  - ➜ allow optimal utilisation of hardware
- Strong yet unintrusive protection
  - ➜ hide protection machinery from most apps
  - ➜ able to emulate most standard protection models
- Support for resource management
  - ➜ in principle, although it isn't implemented yet!
- Legacy support
  - ➜ designed to run Linux server
- Code and concept re-use
  - ➜ utilise what we've leaned in and developed for Mungi project

Iguana Concepts



Iguana Objects

- Six kinds of *objects*
  1. memory sections
  2. threads
  3. protection domains (PDs)
  4. sessions
  5. resource tokens (restoks)
     - ➜ not yet implemented, not covered here
  6. external spaces
     - ➜ not full Iguana objects
     - ➜ serve as proxies for non-Iguana objects
- Access controlled by *capabilities*

Objects: Commonalities

- Objects have a unique name — *object ID* (OID)
  - ➜ OIDs are addresses in Iguana's SAS
  - ➜ only for memory sections does this address correspond to actual memory
- Objects have *methods* that can be invoked
  - one method that exists for all objects: *destroy*
  - each kind of object has a set of pre-defined methods
- Objects are created by invoking constructor on a PD:
  - ➜ `kind_cap = pd->new_kind(args);`
- Methods are grouped into *interfaces*
  - interfaces also have unique IDs (IIDs) that are OID + interface number
  - interfaces have capabilities
    - ➜ grant rights to invoke an interface's methods
  - all pre-defined methods belong to separate interfaces
    - ➜ i.e., access is individually protected

Differences to Mungi

- SAS name space extended to *all* objects
  - ➜ not just memory
  - ➜ supports unified access control and resource management
- Secondary storage not part of SAS
  - ➜ meant to run on 32-bit hardware
  - ➜ meant to run on embedded systems without disk
- Provision for management of all resources (i.e. objects
  - ➜ only half worked out yet
  - ➜ one honours student working on details
- Client-server model instead of migrating-threads model
  - ➜ more familiar to potential users
  - ➜ avoids some (as yet) unresolved resource management issues
- Aimed at commercial deployment ⇒ more conventional
  - ➜ Mungi is a pure research system
  - ➜ useful for trying out things

Iguana Capabilities

- A capability is a token that confers some access right(s)
- Two kinds of capabilities in Iguana:
  - *master capability*
    - ➜ created when an object is created
    - ➜ confers rights on all methods of object
    - ➜ allows creation of further capabilities
  - *invocation capability*
    - ➜ created when an interface is created
    - ➜ confers right to invoke methods of a single interface
- Capabilities are only active if stored in PD's *capability lists*
  - ➜ as in Mungi

Memory Sections

- Memory sections represent virtual memory
  - allocation of a certain amount of virtual memory:

    mem_cap = *pd*`->new_mem(`*size*`);`
- Memory sections are the only objects that support user-defined methods
  - ➜ others have pre-defined (standard) methods only
- Used to provide encapsulated services:
  - service = memory (data) + server (thread) + methods

Memory Sections...

- To create a service:
  - register a server thread on memory section

    base`->new_server(`*thread_id*`);`
    - ➜ *base* is the base address (OID) of the memory section
  - register interfaces (user-defined methods)

    base = *iid*`->new_cap();`
    - ➜ *iid* refers to number of new interface
- Registering interfaces supports user-defined methods
  - remember: each interface can have one or more methods
    - ➜ interface number only interpreted by server
    - ➜ similarly, the method number is an opcode delivered to the interface
  - IIDs and method numbers allocated by system implementor
    - ➜ part of the service's interface protocol

Memory Sections: Pseudo Methods

- Read (R), write (W), execute (X) are logically considered methods
  - subjects them to same protection mechanisms as other methods
  - no actual methods exist corresponding to those operations
- Further pseudo-method is *clist* (C)
  - allows holder to add an object to the Clist array

Threads

- Iguana threads are essentially L4 threads:
  - threads within same PD operated on by plain L4 syscalls
    - ➜ correspond to local L4 threads (i.e., same L4 AS)
    - ➜ `ExchangeRegisters`, `IPC`
  - direct IPC to non-local threads is not allowed
    - ➜ use method invocations (corresponding to server thread)
    - ➜ presently not enforced by Iguana
    - ➜ requires enhancements to L4 (forthcoming API) to do efficiently
    - ➜ will provide attribute to ensure enforcement (at a cost)
- Certain operations require privileges
  - e.g. thread creation and deletion done by privileged L4 `ThreadControl()` call
- Done by Iguana on invocation of appropriate methods

Thread Operations

- Thread creation:

  thread_cap = *pd*`->new_thread(&`*l4_tid*`);`
  - returns two kinds of thread IDs
    - ∗ Iguana thread ID (*tid*), part of the *thread_cap*
      - ➜ used for protection and other Iguana-specific purposes
    - ∗ L4 thread ID (*l4_tid*)
      - ➜ used for L4 syscalls
- New thread created *inactive*
  - can be activated by:
    - ➜ L4 syscall `ExchangeRegisters()` (local threads only)
    - ➜ Iguana method `tid->start(ip,sp)`

Thread Operations...

- Obtain L4 thread ID
  - ➜ `l4tid = tid->l4_tid();`
- Obtain own thread ID
  - ➜ `tid = myself();`
- Obtain protection domain of thread
  - ➜ `pd = tid->domain();`
- Obtain and modify scheduling parameters
  - ➜ `tid->schedule_info(&info);`

SESSIONS

- Sessions reduce authentication overheads of repeated calls
- Prior to invoking methods on a service, must establish session

```
session = pd->new_session(server);
```

  - establishes session between target PD and server
  - `server` is a PD ID
    - ➜ **Note:** This is likely to change
  - Iguana informs the server by invoking its notification method

```
server->session_created(pd);
```

  - Iguana notifies remaining partners if the session is destroyed

```
pd_or_server->session_destroyed(session);
```


IGUANA CAPABILITIES

- Iguana capabilities are user-level objects
  - ➜ *password capabilities*, consisting of OID and password

object ID	password

  - ➜ Length of password is configurable (normally $\geq$ 64 bits)
- Same model as in Mungi
  - ➜ implicit presentation
  - ➜ two-level structure (Clists caps array, Clists)
  - ➜ same confinement approach

EXTERNAL SPACES

- External spaces are “raw” L4 address spaces
  - ➜ not part of Iguana SAS
- Provided to deal with restrictions of Iguana model
  - ➜ 32-bit address space may not be large enough to share between all protection domains
  - ➜ legacy support (e.g. strict `fork()` semantics) may require separate address spaces
- External spaces come at a cost
  - unable to make full use of fast address-space switching on ARM
  - not well integrated with Iguana world
    - ➜ no fine-grained access control provided by Iguana capabilities
    - ➜ not allowed to communicate with any PD other than creator
      - ➜ not even with Iguana —cannot invoke methods
      - ➜ enforced via L4 redirectors

EXTERNAL SPACES — OPERATIONS

- Creation requires explicit specification of KIP and UTCB address

```
es = pd->new_es (kip, utcb_area);
```

- Thread creation also requires arguments similar to L4

```
l4tid = es->new_thread(pager,scheduler,starter,utcb);
```


HARDWARE ACCESS

- Device drivers need to access raw hardware features
- Iguana provides a (static) `hardware` object for this
  - physical memory access:

```
hardware->back_mem(adr, p_adr, caching);
```

    - ➜ maps the memory section (`adr`) to the specified physical address with specified caching attributes
  - interrupt association:

```
hardware->register_interrupt(tid,irq);
```

    - ➜ registers the specified thread as the handler of the specified interrupt

RESOURCE TOKENS

- Iguana’s resource management mechanism
- Note: presently this only exists conceptually
  - ➜ details of the model still need to be worked out
  - ➜ however, model is based on our experience with a similar model in Mungi
- Basic idea: all resources have a price that must be paid by the user
- Model provides great flexibility for defining charging details
- Generalisation of Mungi bank accounts

WOMBAT: A PORTABLE LINUX SERVER ON L4

MOTIVATION

- Provide Linux API
- Support architectures other than x86
- Be easily maintainable
- Integrate with Iguana

LEGACY APIS ON L4

- Microkernel, like L4, provides mechanisms, not services
  - ➜ services implemented by user-level server
  - ➜ microkernel is OS agnostic
  - ➜ can, in principle, provide any OS API (OS “personality”)
  - ➜ can provide multiple OS APIs
- Multiple OS APIs are a classical *motivation* for microkernels
- Simplest approach is to port an existing monolithic kernel
  - ➜ e.g., Unix, Linux
  - ➜ even several running concurrently
- Past experience poor:
  - ➜ Mach Unix server
  - ➜ IBM Workplace OS (Mach-based)
- Attributed to poor Mach IPC performance, large cache footprint

Porting Monolithic Kernels: Pros

- Code reuse: Existing services
  - ➜ can use existing code unchanged (file systems, network stacks, drivers, ...)
  - ➜ dramatic reduction of cost of building new system
  - ➜ potential reduction in maintenance cost (but...)
- Code reuse: Legacy support
  - ➜ can support huge number of existing apps (if sufficiently compatible)
  - ➜ dramatic reduction of cost of deploying new system
- Coder reuse
  - ➜ can provide a familiar target for programmers
  - ➜ reduction of cost of maintaining system and new app development
- Buzzword reuse
  - ➜ can jump on Linux bandwagon while really doing something more sensible...
  - ➜ good PR value ;-)

Porting Monolithic Kernels: Cons

- Performance
  - – Microkernel inherently adds overhead
    - ➜ microkernel-mediated rather than direct access to hardware
    - ➜ IPC to server (4 mode switches) rather than syscall (2 mode switches)
  - ⇒ Legacy system on L4 will **always** be slower than native!
  - – Question is: *How much slower???*

Porting Monolithic Kernels: Cons

- Miss out on most advantages of microkernels
  - – software-engineering advantages
    - ➜ microkernels can provide strongly encapsulated components with small interfaces
    - ➜ Linux approach is unmaintainable in the long run [Schach *et al*, Maintainability of the Linux Kernel, IEE Proceedings Software, **149** 18–23 (2002)]
  - – reduction of *trusted computing base*
    - ➜ trusting 2–3Mloc vs 10kloc kernel plus core services and drivers
  - – potential for formal verification of TCB?
    - ➜ might be feasible if it's small
    - ➜ definitely infeasible with something the size of Linux
- Main-stream systems have notoriously poor real-time support
  - ➜ typically unsuitable for hard real time

Hybrid Systems: Best of Two Worlds?

- Legacy server and native apps running side-by-side
  - ➜ code/coder/buzzword reuse
  - ➜ software-engineering advantages for critical/new parts
  - ➜ hard real-time apps not affected by legacy system
- How about performance?
  - ➜ L4 primitives much faster than Mach and others
  - ➜ fast enough?

L4 on Linux: History

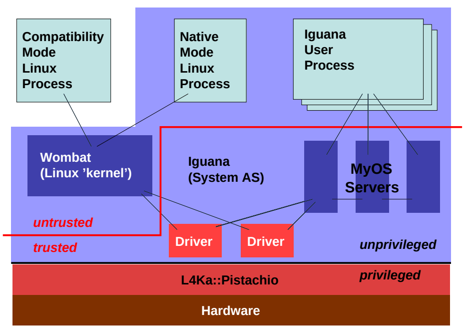
L^{4}Linux

- First port of Linux kernel to L4
- Done for ix86 at Dresden [SOSP 97]
  - – modified architecture-specific part of Linux to use L4 syscalls
  - – binary compatibility: syscall redirection to Linux server
    - ➜ syscall exception delivered to L^{4}Linux via exception IPC
  - – better performance using modified libc
    - ➜ syscall trap replaced by L4 IPC to Linux server
  - – re-done for 2.2, 2.4, 2.6
    - ➜ L^{4}Linux implementation highly dependent on Linux internals
    - ➜ significant effort for forward porting (start from scratch each time)

Wombat Linux Server

- Done at NICTA 03–04
  - ➜ done from scratch, independent of Dresden work
- Portable between architectures
  - ➜ based on Iguana
  - ➜ presently runs on x86, ARM, MIPS64
  - ➜ MIPS64 supports 32-bit and 64-bit executables
- Much reduced dependence on Linux internals
- Binary compatibility via syscall redirection
- Proper Linux scheduling of Linux apps
- Potential to achieve good performance on ARM

A System Running Wombat



Wombat Implementation

- Dresden L^{4}Linux approach:
  - – applied modifications to architecture-dependent part of kernel
    - ➜ very x86-specific
- Wombat approach:
  - – introduced new `arch/l4/` in Linux source
    - ➜ kept as architecture-neutral as possible
    - ➜ architecture-dependent code in `arch/l4/sys-arm` etc
  - – otherwise only modified 3 Linux source files
    - ➜ two are one-line bug fixes (patches submitted)
    - ➜ third is `printk` (additional early debug output)
  - – tracked head revision of Linux from 2.5.x to 2.6.4
    - ➜ now at 2.6.6, will do 2.9 within a week

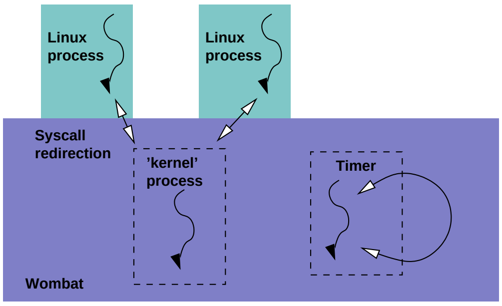
Page Faults and Exceptions

- Wombat has a single server thread per CPU, like L[4]Linux
  - is L4 pager and exception handler for Linux processes
  - Linux "syscalls" are L4 exceptions
    - ➜ use `swi` instruction
    - ➜ Pistachio uses an invalid jump causing a *prefetch abort* for its system calls
    - ➜ easy to distinguish L4 and Linux syscalls
  - other exceptions are reflected back as Linux signals
- Have single runnable Linux user process per CPU, unlike L[4]Linux
  - differs from Dresden/Karlsruhe L[4]Linux approaches
  - helps to maintain Linux scheduling behaviour

System-Call Processing

- Access to application memory by Wombat:
  - provide `copy_to`/`copy_from` functions
  - look up page table and find page(s) in server's memory pool
  - on MIPS could instead run Wombat in supervisor mode
    - ➜ would give direct access to user's address space
- Context switching:
  - Wombat maintains pointer to state of current Linux process
  - On a process switch, switches state and updates pointer
    - ➜ on ARM, state is banked user registers
- Signal processing is architecture dependent
  - ➜ emulates Linux signal handling

Linux Processes



Wombat Scheduling

- Wombat has second thread: timer
  - high-priority thread normally in timed wait
  - maintains Linux time slice
  - when woken:
    - ➜ checks whether same Linux process is still running
    - ➜ if so, sets *reschedule* flag
    - ➜ if flag already set then sets Linux process' *total quantum* to zero
    - ➜ forces preemption, and an IPC to the scheduler (the "kernel" thread)
- Scheduling happens when Linux process enters kernel
  - checks reschedule flag, if set:
    - ➜ invokes Linux scheduler
    - ➜ perform context switch, reset reschedule flag

Wombat Scheduling

- Actual scheduling decision made by *unmodified* Linux scheduler
  - ➜ unlike L[4]Linux
- Advantages of this approach:
  - no changes required to (architecture-independent) scheduler
  - Linux scheduling policy maintained (sort-of)
  - no locking required other than what is already in Linux
- Disadvantages:
  - Linux scheduling only approximately maintained
    - ➜ actual scheduling happens next time process enters kernel *after* time slice expired
    - ➜ processes run normally slightly longer than Linux time slice
    - ➜ CPU-bound process runs up to twice as long
    - ➜ Should be able to get exact Linux scheduling (but at a cost!)

Linux Idle Task

- Linux's idle task executes `cpu_idle()`
  - architecture-specific function
  - in Wombat this IPCs to the "kernel" thread
  - that one just sleeps until the next time tick or interrupt
  - could just as well be made to go into a low-power mode

Wombat Performance (Preliminary)

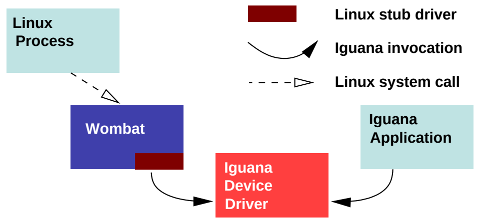
			trampoline		IPC	
Benchmark	**Server**	**Linux**	**L4**	**ratio**	**L4**	**ratio**
`getpid()`	L[4]Linux	1.68	9.66	3.7	3.95	2.4
	Wombat	0.41	1.94	4.7		
2-proc ctxsw	L[4]Linux	7.0	18.2	2.6	16.2	2.3
	Wombat	4.03	9.66	2.4		
pipe	L[4]Linux	29.0	69.4	2.4	22.2	1.8
	Wombat	6.3	16.5	2.6		

- ➜ L[4]Linux 2.0 on 133MHz Pentium [SOSP 97], some improvements since
- ➜ Wombat 2.6 on Pentium-4 Xeon 2.66Ghz, *unoptimised*
  - ➜ overhead should be smaller on RISC processors

Iguana Device Drivers

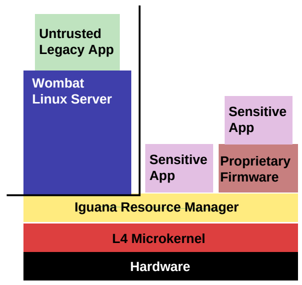
- Drivers are Iguana services (data + server thread + methods)
- At startup obtain access to hardware resources
  - can be done first-come, first-served
  - better: restrict allocation to privileged service
    - ➜ ... by restricting capabilities to the `hardware` object
    - ➜ privileged service can allocate device memory (using `hardware->back_mem`
    - ➜ can then hand capability for device-backed memory section to driver
- Driver is then able to operate the hardware
- Provides methods as per Iguana driver protocol

Sharing Iguana Device Drivers with Wombat



- Wombat has stub driver module
  - ➜ invokes Iguana driver
  - ➜ sample exists for console

Target System Architecture



Similar to Dresden DROPS system

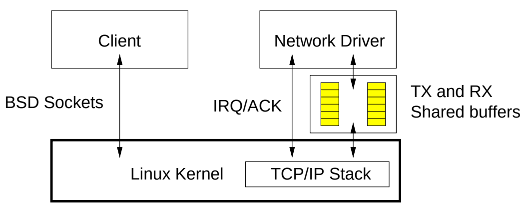
Status: Iguana, Wombat and Driver Framework

- In use at (at least) two multinational companies
- Beta release Feb 05
- Proper release planned Nov 05
- Deployment in products planned for early next year
- Future work:
  - ➜ proper SMP implementation
  - ➜ support for heterogeneous multiprocessors (rSoC)
  - ➜ design and implementation of proper resource management

High-Performance User-Level Drivers

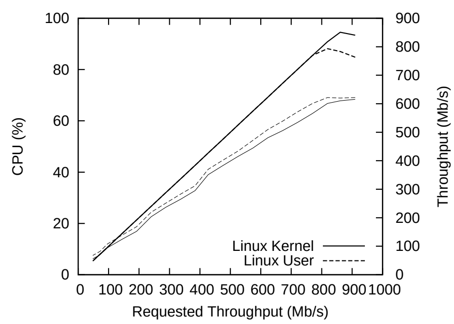
- L4 device drivers are *always* outside the kernel (at user level)
  - Interrupts delivered to driver as IPC from kernel
- Potentially higher communication overhead
  - past experience with user-level drivers: $\geq$50% performance degradation
- L4 IPC performance is very high
  - with well-designed driver interfaces can achieve good performance

User-Level Device Drivers on Linux



Benchmarking setup

User-Level Device Driver Performance



Gigabit Ethernet echo on 900MHz Itanium-2 with 66MHz 64-bit PCI

User-Level Drivers: Ongoing Work

- Complete driver framework and methodology
  - ➜ ease development of high-performance drivers
  - ➜ reduce driver complexity
  - ➜ drivers portable between systems (L4 and Linux)
- Integration with I/O system
  - ➜ Linux VFS layer integration
  - ➜ user-level network protocol stacks
  - ➜ componentised protocol stacks
- Driver encapsulation
  - ➜ use hardware mechanisms to limit DMA
  - ➜ use software mechanisms to limit trust in drivers
  - ➜ goal: untrusted device drivers
- Collaboration between NICTA and UNSW Gelato project
  - ➜ 1 PhD student

seL4: Secure Embedded L4

- Goal
  - satisfy high security requirements
  - support *certifi ably secure systems*
    - ➜ requires *proof of security properties*
    - ➜ present API is known not to support this
- Issues:
  - information flow control
    - ➜ V2: clans & chiefs: clumsy, inflexible, inefficient
    - ➜ V4: redirectors: still clumsy, often inefficient
  - IPC addressing via thread IDs reveals *global* names
    - ➜ violates *need to know*
  - Primitive kernel memory management
    - ➜ allows denial-of-service attacks
    - ➜ reveals internal state
- Collaboration with Dresden, Johns Hopkins (Jonathan Shapiro)
  - ➜ Kevin Elphinstone, 1 staff, students

Formal Verification of Microkernel

- First (and most significant) step to making the TCB *trustworthy*!
- Involves three aspects:
  1. develop a formal specification of the kernel API
     - ➜ seL4
  2. prove safety properties about the API
  3. prove that implementation is correct
     - ➜ never before been done for any protected kernel!
     - ➜ L4 (≈10,000 loc) is at limit of tractability
     - ➜ expect seL4 kernel to be 5000–7000 loc
- Ultimate goal: Verify a *real* kernel (L4) that is used in production
  - ➜ collaboration with NICTA Formal Methods Program
- Reduce risk: pilot project

L4 Verification Pilot Project

- Purpose:
  - test tools and get experience with them
  - feasibility study
  - bridge cultural gap between theorists and kernel hackers
  - develop project plan for full-scale verification project
- Operates on a "slice" of the API (address-space management)
  - done formal model of (simplified) API slice
  - proved some properties (absence of loops in mappings)
  - refined specification down to source code
    - ➜ page table operations and simplified mapping database

L4 Verification Project

- Timeline:
  - commenced April 2005
  - 3 years
- Resources: ≈ 20 person years
  - presently:
    - ➜ 2 FTE researchers
    - ➜ 1 PhD student
    - ➜ 1 honours
  - definitely looking for students!
  - desired background:
    - ➜ good systems background and aptitude for maths, or
    - ➜ maths background and aptitude for systems

Project: L4 WCET Analysis

- Hard real-time systems need guarantees of worst-case latencies
  - Need *worst-case execution time* (WCET) of kernel operations
- Usually done:
  - by code inspection
    - ➜ unfeasible for non-trivial kernel
  - experimentally
    - ➜ unreliable: cannot guarantee 100% coverage!
  - by educated guess
    - ➜ highly unreliable (RTLinux got it wrong!)
    - ➜ typically leads to vastly pessimistic latencies
- Need systematic execution-time analysis of complete kernel
  - ➜ never been done for non-trivial kernel!
  - ➜ project leader Stefan Petters done similar (non-kernel) work
  - ➜ looking for students!

Component-Based Software Architecture

- Goal: component architecture that is appropriate for microkernel
  - ➜ based on Iguana
- To support:
  - effective software-engineering techniques
  - robustness by encapsulation without destroying performance
  - hot-swapping / hot upgrading of components
  - real-time (WCET) analysis of system
  - ultimately, formal verification of whole system
- Collaboration with NICTA Empirical Software Engineering Program
  - ➜ 3 staff, several PhD and U/G students, visitors

Secure Mobile Code

- Combines language and OS techniques for secure execution
- Code may be:
  - ➜ accompanied by a proof certificate establishing its trustworthiness
  - ➜ otherwise sandboxed execution
- Lead by Manuel Chakravarty
  - presently working on theoretical foundations
  - later to be integrated with Iguana
  - requires *configurable protection domains*

Goanna: Static Analysis of Systems Software

- Model-checking-based tools looking for bugs in kernel & libs
- Collaboration with NICTA Formal Methods Program
- Pilot Project April 05 – March 06
  - ➜ examine state of the art
  - ➜ evaluate existing tools
  - ➜ analysis framework
  - ➜ get experience with model-checking of systems code
  - ➜ develop plan for follow-on project

Project: OS-Friendliness of Architectures

- Evaluate hardware-dictated OS overheads and trends
- Critical operations
  - ➜ kernel entry and exit
  - ➜ TLB refill
  - ➜ context switch
  - ➜ synchronization primitives
- Hardware characteristics
  - ➜ instruction-set architecture
  - ➜ clock speed
  - ➜ pipeline depth
  - ➜ issue width
- Aim: paper in architecture conference

PROJECT: KERNEL IMPLEMENTATION TRADE OFFS

- Idea: revisit some of Jochen's tricks
  - ➜ virtually- vs physically-addressed TCBs
  - ➜ per-thread vs per-CPU kernel stack
  - ➜ exception IPC vs exception callback
- Question: how much influence of architecture?
- Aim: Conference paper

PROJECT: L4DARWIN

- Aim: Mac OS done right
  - ➜ remove Mach
  - ➜ substitute L4
  - ➜ de-privilege Darwin
  - ➜ de-privilege IOkit
  - ➜ kick-ass performance
- Aim: exercise for the reader

GELATO: LINUX PERFORMANCE AND SCALABILITY

- VM system performance and scalability
  - ➜ superpage support (particularly Itanium)
  - ➜ NUMA support
  - ➜ guarded page tables for large address spaces
- TCP/IP and NFS throughput and scalability
- NUMA-aware scheduling
- Aims: support
  - 1000's of CPUs in a NUMA system
  - 1000's of nodes in a cluster
  - terabytes of RAM
  - support commercial workloads
- Funded by HP and ARC, supported by SGI

OTHER PROJECTS

- Pre-virtualisation
  - ➜ semi-automated high-performance virtualisation
  - ➜ covered in Week 6
- Hot swapping/upgrading of system components
  - ➜ collaboration with IBM research
- Distributed embedded systems
  - ➜ e.g. cars
  - ➜ pilot project SUNswift

OTHER PROJECTS...

- Secure GUI
  - ➜ window system that ensures isolation of clients
- JVM on L4
- API emulation
  - ➜ support Symbian OS, QNX, ...
- Kernel ports
  - ➜ Blackfin, Hitachi, SPARC, Motorola
- Simulators
  - ➜ tools for OS development and architecture research
  - ➜ ARM, PowerPC, ...

SUMMARY: OS RESEARCH AT UNSW/NICTA

- Improve reliability and trustworthiness of embedded systems
  - make a *real* impact on the practice of embedded systems R&D
- Comprehensive approach used on using microkernel technology
- Combination of formal and practical approaches
- Leverage relevant competencies available within NICTA
- Ample opportunities to participate in cutting-edge research
  - ➜ summer projects
  - ➜ honours theses
  - ➜ PhD theses
  - ➜ employment