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 Centre of Excellence in Information and Communications Technology (ICT)

Created in October 2002 by Australian Government
NATIONAL ICT AUSTRALIA (NICTA)

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- Members:
  - University of New South Wales (UNSW), Sydney
  - Australian National University (ANU), Canberra
  - NSW and ACT governments
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- Locations:
  - Sydney (UNSW campus and ATP technology park)
  - Canberra
  - Melbourne (University of Melbourne Campus)
  - Brisbane (in progress)
NICTA’S FOUR PILLARS

- Research
- Education
- Linkages
- Commercialisation
NICTA’s Four Pillars

- Research
  - conduct world-class ICT research that makes an impact
  - “use-inspired fundamental research”

- Education

- Linkages

- Commercialisation
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● Research
  ➤ conduct world-class ICT research that makes an impact
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● Education
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  ➤ students enrolled at one of the member/partner universities

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- **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)
Presently $\approx 150$ researchers, 150 PhD students
NICTA Structure

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• Researchers belong to *Research Programs*

  ➔ aligned with discipline areas (\( \approx \) 5–10 researchers)
  ➔ lifetime 5–10 years
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  - PC1: trusted wireless networks
  - PC2: from data to knowledge
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- 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
Embedded Systems in Australia

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- Implications:
  - no scope for ASICs, use COTS hardware components
  - main focus is on software
**Embedded Systems in Australia**

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  - 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.
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
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
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ERTOS research is to be driven by applications

- to identify common challenges
- to provide generic systems software
Computer system that is part of a larger system
General-Purpose vs. Embedded

Traditional View:

General-purpose system

- Applications
- File System
- Virtual Memory
- Low-level I/O
- Network Stack
- Scheduling
- Device Drivers
- Interrupt Handler
- Hardware
GENERAL-PURPOSE VS. EMBEDDED

TRADITIONAL VIEW:

general-purpose system

embedded system
**GENERAL-PURPOSE vs. EMBEDDED**

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- **embedded system**
  - Device Drivers
  - Application
  - Hardware

→ minimal
→ no OS at all or small “real-time executive”
→ no protection
SECURITY CHALLENGES

- Growing functionality
- Wireless connectivity
- Downloaded contents (entertainment)
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• Growing functionality
  ➔ increasing software complexity
  ➔ increased number of faults
  ➔ increased likelihood of security faults

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Security Challenges

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- Wireless connectivity
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- Downloaded contents (entertainment)
  - Subject to attacks from inside (viruses, worms)

- Increasing dependence on embedded systems
  - Increased exposure to embedded-systems security weaknesses
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
**EMBEDDED SYSTEMS SOFTWARE**

**PRESENT APPROACHES 1: REAL-TIME EXECUTIVES**

- Small, simple operating system
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Present approaches 1: Real-time executives

- Small, simple operating system
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- No internal protection
  - every small bug/failure is fatal
  - no defence against viruses, limited defence against crackers
Present Approaches 2: Linux, Windows Embedded, ...

- Scaled-down version of desktop operating system
  ➔ operating system protected from application misbehaviour
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**Embedded Systems Software**

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  - operating system protected from application misbehaviour
  - excessive code base for small embedded system
  - too much code on which security of system is dependent
Embedded Systems Software

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- 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
EMBEDDED SYSTEMS REQUIREMENTS:

RELIABILITY, TRUSTWORTHINESS, SECURITY

- Achieved by:
  - exhaustive testing?
  - systematic code inspection?
  - formal methods?
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  TCB: The part of system that must be relied on for the correct operation of the system
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- Why minimal TCB?
  - minimise exposure to bugs/faults
  - minimise exposure to attacks (internal and external)
  - support poorly-scaling verification methods
WHAT DOES THE TCB CONTAIN?
TRUSTED COMPUTING BASE

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- Kernel \(\overset{\text{def}}{=} \text{part of system that executes in privileged mode}\)

  ➔ everything running in privileged mode can bypass security
TRUSTED COMPUTING BASE

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- **Kernel** (def part of system that executes in privileged mode)
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- **Device drivers**
  - DMA-capable devices can bypass protection
  - drivers can mount DoS attacks
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  - resource owner can deny resource
  - resource owner can leak/corrupt data
**TRUSTED COMPUTING BASE**

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- **Everything** on MPU-less processors
  - no memory-protection hardware ⇒ no memory protection
MINIMISING THE SIZE OF THE TCB

... MEANS FIRST OF ALL:

- Use an MPU — microcontrollers are out!
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Minimising the Size of the TCB

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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
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MINIMISING KERNEL SIZE:

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- Minimal TCB required \( \Rightarrow \) microkernel required!
NICTA Approach: Microkernel

- Extremely small kernel
  - microkernel only contains code that must run in privileged mode
  - all other “systems” code runs as unprivileged servers
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  - microkernel provides protection of all components from each other
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- What’s the difference?
Hardware
Application
Service

Hardware
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Service

Hardware
Application
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Microkernel

System: traditional embedded
TCB: all code

Linux/ Windows
100,000’s loc

Microkernel-based
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TRUSTED COMPUTING BASE

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    • embedded

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Small is beautiful:

- Small kernel ⇒ potentially small TCB
- Small TCB ⇒ more trustworthy TCB!
**TRUSTED COMPUTING BASE**

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OS
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Microkernel-based
Microkernel
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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

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- Standard API supported by de-privileged Linux server
  - full binary compatibility with native Linux
- Sensitive part of system has small TCB

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- 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 $\approx 100$kB)
  - should fit on smartcard
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  - remove long IPC!
  - reduce number of virtual registers (16–64)
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  - remove local thread IDs
  - remove remaining drivers from kernel
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  ➔ physically-addressed TCBs \( \Leftarrow \) honours thesis
  ➔ single kernel stack per CPU \( \Leftarrow \) 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
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  ➜ process management
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  ➜ security management

... based on some system-wide policies
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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
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  ➔ allocation, deallocation, sharing, ...
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★ Protection-domain (process) management

★ Thread management
SAMPLE IGUANA SYSTEM
Iguana: Basic Approach

- Basic idea: single address space (SAS)
**IGUANA: BASIC APPROACH**

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    - Minimises copying
    - No problems with pointers
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  - enforce security policy
    - any access is subject to access control
  - do not interfere with sharing
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  - Works with MMU-less microprocessors
  - Cheap context switches on ARM7/ARM9
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- Based on UNSW Mungi system
Iguana Concepts

- Memory section
  - unit of VM allocation and protection
  - can be an encapsulated object with methods and data
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- 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
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- External Space
  ➔ address space extern to Iguana’s SAS
  ➔ for legacy support and large processes
Iguana Philosophy

- Small and lightweight
- Strong yet unintrusive protection
- Support for resource management
- Legacy support
- Code and concept re-use
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  ➔ in principle, although it isn’t implemented yet!

- Legacy support

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**IGUANA PHILOSOPHY**

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  - in principle, although it isn’t implemented yet!

- **Legacy support**
  - designed to run Linux server

- **Code and concept re-use**
**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

Thread

Memory section
IGUANA CONCEPTS

Protection Domain

Thread

Memory section
Iguana Concepts

Protection Domain

Thread

Server Thread

Memory section
Iguana Concepts

Protection Domain

Thread

Server Thread

Method

Memory section
IGUANA CONCEPTS

Protection Domain

Thread

Server Thread

Interface

Method

Memory section
Iguana Concepts

- Protection Domain
- Thread
- Invocation Rights
- Session
- Server Thread
- Interface
- Method
- Memory section
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
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- 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: COMMONALITIES

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  - `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
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  - more familiar to potential users
  - avoids some (as yet) unresolved resource management issues
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• 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
A capability is a token that confers some access right(s)
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
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  ★ 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:
    
    \[
    \text{mem\_cap} = \text{pd}\rightarrow\text{new\_mem}(\text{size});
    \]
**MEMORY SECTIONS**

- Memory sections represent virtual memory
  - allocation of a certain amount of virtual memory:
    
    $\text{mem\_cap} = \text{pd->new\_mem}(\text{size})$

- 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
To create a service:

- register a server thread on memory section

\[
\text{base} \rightarrow \text{new_server} (\text{thread}_\text{id}) ;
\]

⇒ base is the base address (OID) of the memory section

- register interfaces (user-defined methods)

\[
\text{base} = \text{iid} \rightarrow \text{new_cap} () ;
\]

⇒ iid refers to number of new interface
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

- IID's 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
Remember 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
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
THREADS

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  - 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)
**THREADS**

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    - 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:

  \[ \text{thread\_cap} = \text{pd}\rightarrow\text{new\_thread}(&\text{l4\_tid}); \]

  ✴ returns two kinds of thread IDs

  ✴ Iguana thread ID (\text{tid}), part of the \text{thread\_cap}
    → used for protection and other Iguana-specific purposes

  ✴ L4 thread ID (\text{l4\_tid})
    → used for L4 syscalls
Thread Operations

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\text{thread\_cap} = \text{pd->new\_thread}(&l4\_tid);
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★ 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 \textit{inactive}

★ can be activated by:

➔ L4 syscall \texttt{ExchangeRegisters}() (local threads only)
➔ Iguana method \texttt{tid->start(ip,sp)}
THREAD OPERATIONS...

• Obtain L4 thread ID
  ➔ 14tid = tid->14_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 reduce authentication overheads of repeated calls
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
SESSIONS

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  \[\text{session} = \text{pd}\rightarrow\text{new}\_\text{session}(\text{server});\]

  ★ establishes session between target PD and server

  ★ \textit{server} is a PD ID

  ➔ \textbf{Note:} This is likely to change
Sessions

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

```c
    session = pd->new_session(server);
```
- Establishes session between target PD and server
- `server` is a PD ID
  
  \[\text{Note: This is likely to change}\]
- Iguana informs the server by invoking its notification method

```c
    server->session_created(pd);
```
- Iguana notifies remaining partners if the session is destroyed

```c
    pd_or_server->session_destroyed(session);
```
Iguana capabilities are user-level objects

- *password capabilities*, consisting of OID and password

<table>
<thead>
<tr>
<th>object ID</th>
<th>password</th>
</tr>
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- Length of password is configurable (normally $\geq 64$ bits)
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
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• 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:
    ```c
    hardware->back_mem(adr, p_adr, caching);
    ```
    maps the memory section (adr) to the specified physical address with specified caching attributes
  - interrupt association:
    ```c
    hardware->register_interrupt(tid, irq);
    ```
    registers the specified thread as the handler of the specified interrupt
• 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
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
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- Attributed to poor Mach IPC performance, large cache footprint
PORTING MONOLITHIC KERNELS: PROS

• Code reuse: Existing services

• Code reuse: Legacy support

• Coder reuse

• Buzzword reuse
Porting Monolithic Kernels: Pros

• Code reuse: Existing services
  ➔ can use existing code unchanged (file systems, network stacks, drivers, ...)
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- 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!
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  - Question is: *How much slower??*

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• 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
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• How about performance?
  ➜ L4 primitives much faster than Mach and others
  ➜ fast enough?
L4 on Linux: History

L4 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 L4 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
  - L4 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
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- Much reduced dependence on Linux internals

- Binary compatibility via syscall redirection

- Proper Linux scheduling of Linux apps

- Potential to achieve good performance on ARM
WOMBAT IMPLEMENTATION

- Dresden L⁴Linux approach:
  - applied modifications to architecture-dependent part of kernel
    - very x86-specific
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  - introduced new arch/l4/ in Linux source
    ➔ kept as architecture-neutral as possible
    ➔ architecture-dependent code in arch/l4/sys-arm etc
**Wombat Implementation**

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    - third is `printk` (additional early debug output)
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    ➜ third is printk (additional early debug output)
  ★ tracked head revision of Linux from 2.5.x to 2.6.4
    ➜ now at 2.9, will go forward soon
PAGE FAULTS AND EXCEPTIONS

- Wombat has a single server thread per CPU, like L^4Linux
  - is L4 pager and exception handler for Linux processes
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  - is L4 pager and exception handler for Linux processes
  - Linux “syscalls” are L4 exceptions
  - 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
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
**System-Call Processing**

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- Signal processing is architecture dependent
  - emulates Linux signal handling
Linux Processes

- Linux process
- Linux process
- 'kernel' process
- Syscall redirection
- Timer
- Wombat
WOMBAT SCHEDULING

- Wombat has second thread: timer
  - high-priority thread normally in timed wait
  - maintains Linux time slice
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  - 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
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- 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
WOMBAT SCHEDULING

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  ★ no changes required to (architecture-independent) scheduler
  ★ Linux scheduling policy maintained (sort-of)
  ★ no locking required other than what is already in Linux
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    ➔ 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
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    ➔ Should be able to get exact Linux scheduling (but at a cost!)
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)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Server</th>
<th>Linux</th>
<th>Trampoline L4</th>
<th>IPC L4</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>getpid()</td>
<td>L⁴Linux</td>
<td>1.68</td>
<td>9.66</td>
<td>3.7</td>
<td>3.95</td>
</tr>
<tr>
<td></td>
<td>Wombat</td>
<td>0.41</td>
<td>1.94</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>2-proc ctxsw</td>
<td>L⁴Linux</td>
<td>7.0</td>
<td>18.2</td>
<td>2.6</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>Wombat</td>
<td>4.03</td>
<td>9.66</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>pipe</td>
<td>L⁴Linux</td>
<td>29.0</td>
<td>69.4</td>
<td>2.4</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>Wombat</td>
<td>6.3</td>
<td>16.5</td>
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<td></td>
</tr>
</tbody>
</table>

- L⁴Linux 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)
Iguana Device Drivers

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- 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
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- Provides methods as per Iguana driver protocol
Wombat has stub driver module

- invokes Iguana driver
- sample exists for console
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
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- 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
HIGH-PERFORMANCE USER-LEVEL DRIVERS

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• L4 IPC performance is very high
  ✤ with well-designed driver interfaces can achieve good performance
USER-LEVEL DEVICE DRIVERS ON LINUX

Client

BSD Sockets

IRQ/ACK

Linux Kernel

TCP/IP Stack

Network Driver

TX and RX
Shared buffers

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)
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- Collaboration between NICTA and UNSW Gelato project
  - 1 PhD student
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- **Goal**
  - satisfy high security requirements
  - support *certifiably secure systems*
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• 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*!
Formal Verification of Microkernel

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  1. develop a formal specification of the kernel API
     ➔ seL4

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  3. prove that implementation is correct
     ➔ never before been done for any protected kernel!
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- 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
L4 Verification Pilot Project

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• 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
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    ➔ 1 PhD student
    ➔ 1 honours

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- **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
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  - unfeasible for non-trivial kernel
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  - 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
COMPONENT-BASED SOFTWARE ARCHITECTURE

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- 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
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  ⭐ 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
Aim: Mac OS done right

- remove Mach
- substitute L4
- de-privilege Darwin
- de-privilege IOKit
- kick-ass performance
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
OTHER PROJECTS

• Pre-virtualisation
  ➔ semi-automated high-performance virtualisation
  ➔ covered in Week 6

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• Distributed embedded systems
  ➔ e.g. cars
  ➔ pilot project SUNswift
OTHER PROJECTS...

- Secure GUI
  - window system that ensures isolation of clients
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  - Blackfin, Hitachi, SPARC, Motorola
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- 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
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• Leverage relevant competencies available within NICTA

• Ample opportunities to participate in cutting-edge research
  ➔ summer projects
  ➔ honours theses
  ➔ PhD theses
  ➔ employment