EXOKERNELS

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Ambitious applications must fight OS

- OS abstractions preempt application design decisions since:

  No perfect implementation exists

  No perfect interface exists

  You cannot avoid them

- Result: applications run slowly or can’t be written

Exokernel: maximize application freedom

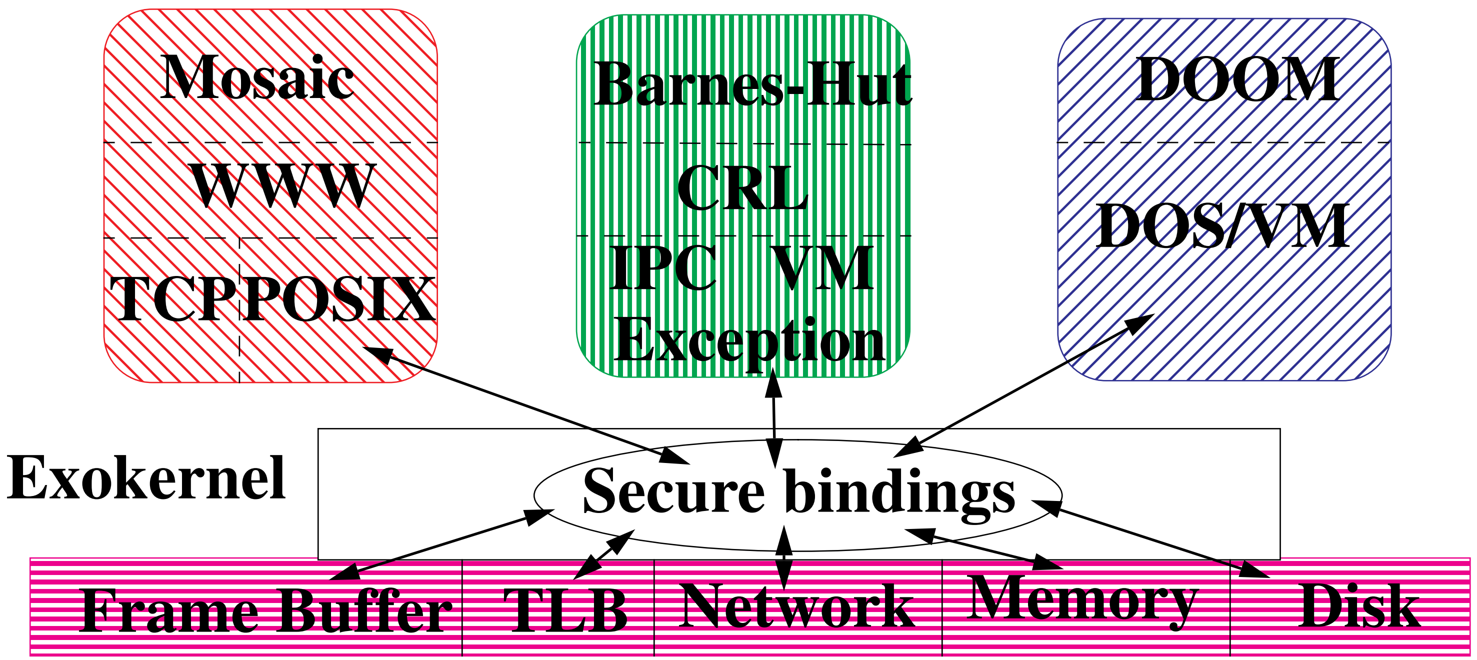
- Insight: implement OS abstractions at application-level
- How: securely multiplex hardware without abstracting it

  Export hardware to applications

  Protection by thin OS veneer, the exokernel

  System objects and policies in untrusted libraries
- Result: Can do operations impossible on traditional systems

Exokernel architecture



- An exokernel safely exports hardware to applications
- Applications build abstractions with library OSs
- Shared libraries to reduce space consumption

Advantages of library operating systems

- Tightly coupled to applications
  - Simple specialized implementations
  - New abstractions
  - Libraries can trust applications
- Fast system evolution
  - Library operating systems can be developed in isolation
  - Anyone can develop, modify library OS
  - Crucial: # of application writers >> kernel hackers

Challenges of application control

- Preventing system chaos

  Use standards and good programming methodology

- Portability

  Standard solution: hardware abstraction layer

- Decentralizing services

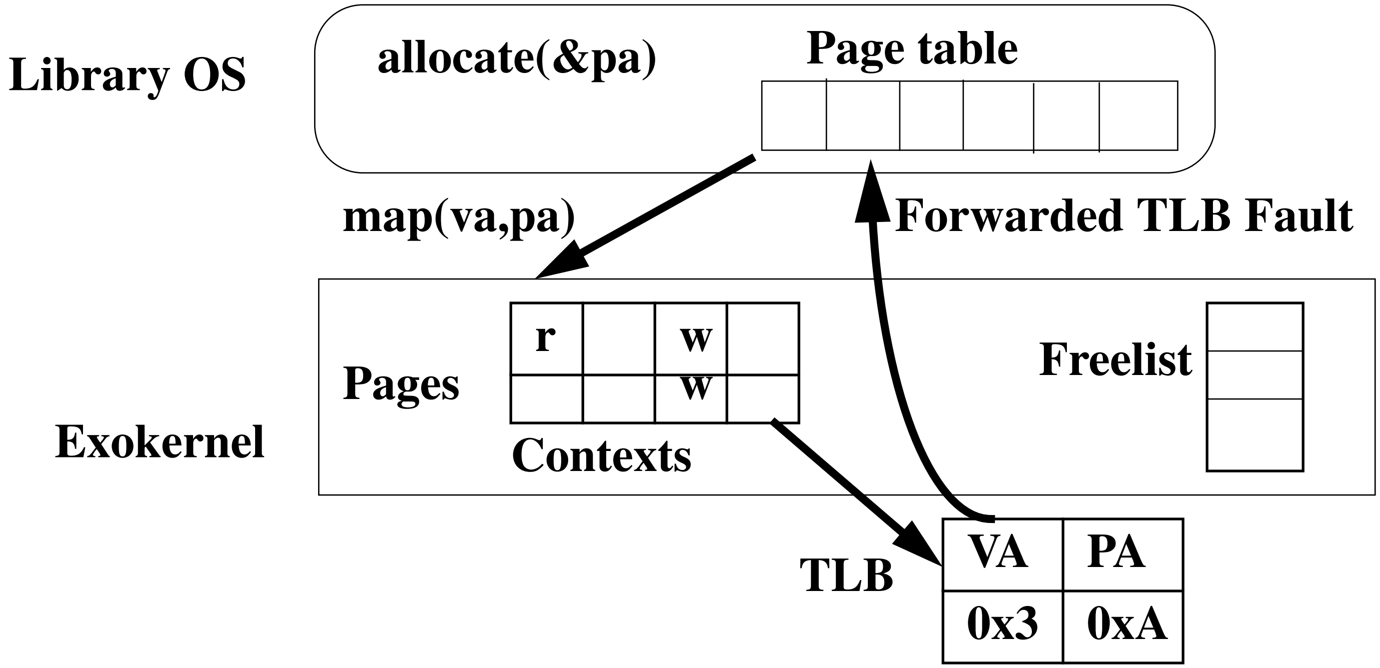
  Use kernel protection mechanism to replace servers

- Reconcile global performance with local optimization

Maximize application control

- **Fine-grain multiplexing of hardware**
- **Low-level interface**
- **Limit kernel resource management to protection**
- **Revoke resources visibly**
- **Expose kernel data structures, hardware, and names**

Example: virtual memory

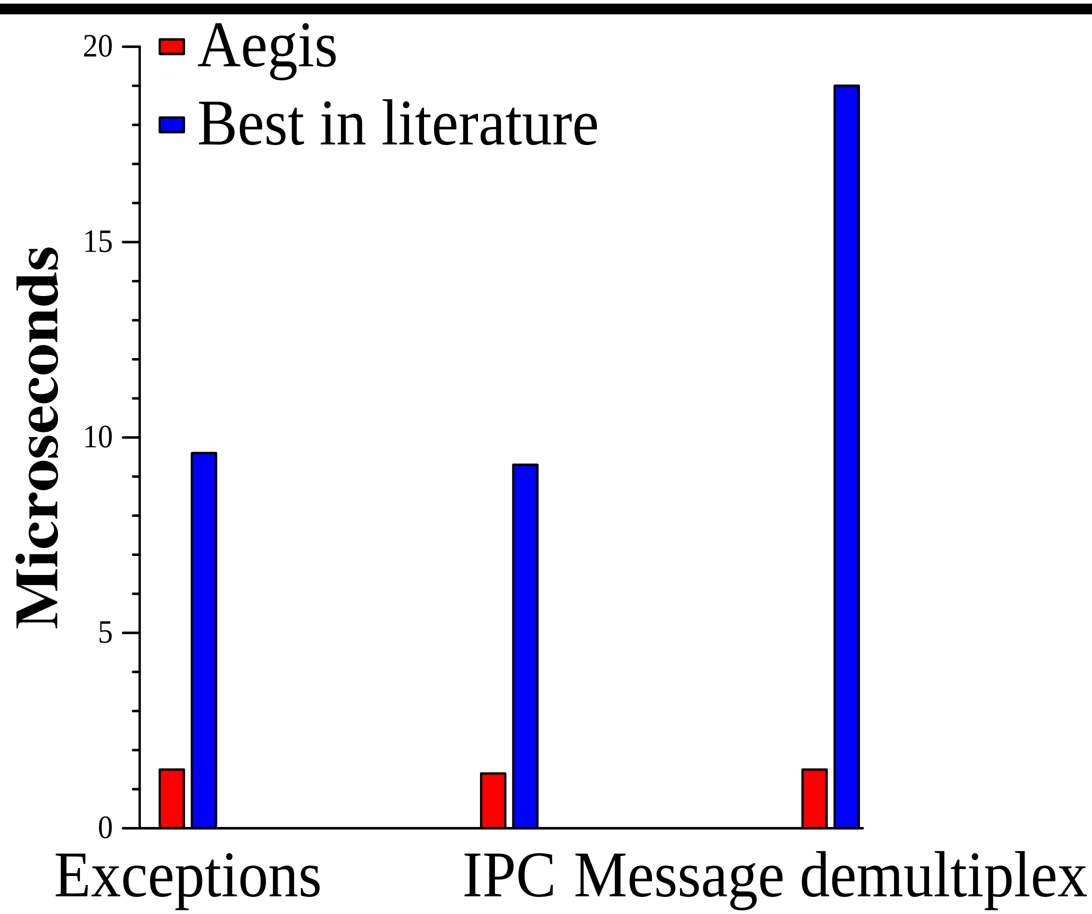


- Revocation: ask application for physical page
- If application is uncooperative, take pages by force

Aegis: A prototype MIPS exokernel

- Physical memory
- TLB entries
- Time slices
- Network
- Environments (process as defined by hardware):
  1. Interrupt/exception forwarding vector
  2. Pinned virtual mappings
  3. Control transfer entry points

Aegis performance on DEC5000/25Mhz



- **Easy to make simple operations fast**

ExOS: an application-library OS

- Rudimentary UNIX-like library
- Completely implemented in application space

1. Processes (fork, exec)
2. IPC (signals, LRPC, shared memory, and pipes)
3. Virtual memory (sbrk, mmap, shared memory)
4. Exception handling (fast user-level traps)
5. Networking (IP protocols, NFS, Sun RPC)

Application-level VM (AVM)

- Flexibility examples with AVM:
  1. Fine-grained monitoring (hardware is visible)
  2. Tighter integration with other abstractions

- Performance (times in μsec):

OS	Dirty	Appel1	Appel2
Ultrix	n.a.	262	232
ExOS	9.8	34	22

Extending AVM

- Linear versus clustered page-tables [SOSP 95]
- Performance (times in μsec):

Structure	(un)Prot1	Prot100	Appel1	Appel2
Cluster	13	238	25	15
Linear	16.9	109	34	22

- Easy to modify library OS:

  Implemented in library in few weeks by undergrad

  Difficult to do even as trusted user on traditional OS

Extensibility example: Trusted LRPC

- Trusted LRPC: trust server to save and restore registers

LRPC system	Performance (µsec)
Traditional LRPC	6.9
Trusted LRPC	2.9

- Pay for what you need

Summary of paper results

- Simple kernel primitives are fast
- OS abstractions can be efficiently implemented as libraries
- Extensibility gives substantial performance benefits

Summary

- Problem: OS abstractions hurt applications
- Insight: Securely export hardware without abstracting it
- How: Exokernel architecture

  Kernel interface at hardware level

  OS abstractions in untrusted libraries
- Advantages:

  Can do operations not possible on traditional systems

  Large implementor base = fast system evolution