AND WE WISH TO THANK EVOLUTION FOR SLOWLY TURNING SOME SPECIES OF DINOSAUR INTO A WALKING BALL OF MEAT WITH A TINY HEAD.
EECS 370 Discussion

Exam 2

• Solutions posted online

• Will be returned in next discussion (12/9)
  – Grades hopefully up on CTools earlier
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Roadmap to end of semester

• Homework 7 – Thursday 12/5

• Project 4 – Friday 12/6

• Final Exam – Monday 12/16 10:30 am – 12:30 pm
  make sure you don’t have a conflict...
EECS 370 Discussion

• Project 4
  – Overview
  – Tips
  – Example

• Virtual Memory
  – Motivation
  – Page Tables
  – Translation Lookaside Buffer
  – Hierarchical Page Table
EECS 370 Discussion

Project 4

Start from correct P1 code
- remove printstate()
- add printaction()

What are the three times you access memory?
EECS 370 Discussion

Project 4

Start from correct P1 code
- remove printstate()
- add printaction()

What are the three times you access memory?
LW, SW, and Fetch
Implement an arbitrary cache
   - 2D array of structs, perhaps

Possible Function Prototypes:
• int load(int address)
• void store(int address, int data)
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Project 4

sw 0 1 6
lw 0 1 23
lw 0 1 30
halt

[0-3] from the memory to the cache ➞ Cache Miss
[0-0] from the cache to the processor ➞ Fetch
[4-7] from the memory to the cache ➞ Cache Miss
[6-6] from the processor to the cache ➞ SW
[1-1] from the cache to the processor ➞ Fetch
[4-7] from the cache to the memory ➞ Eviction (dirty)
[20-23] from the memory to the cache ➞ Cache Miss
[23-23] from the cache to the processor ➞ LW
[2-2] from the cache to the processor ➞ Fetch
[20-23] from the cache to nowhere ➞ Eviction (clean)
[28-31] from the memory to the cache ➞ Cache Miss
[30-30] from the cache to the processor ➞ LW
[3-3] from the cache to the processor ➞ Fetch
Virtual Memory

Virtual Addresses map to Physical Addresses

Software sees:

Hardware sees:
Virtual Memory

Virtual Addresses map to Physical Addresses

Software sees:
Virtual Addresses

Hardware sees:
Physical Addresses
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Motivation - Efficiency

Virtual Memory

Address Space

Program 1

Program 2

Program 3

0x0

0xFF
EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

Program 1

Program 2

Program 3

Address Space

0x0

0xFF
EECS 370 Discussion

Motivation - Efficiency

Virtual Memory

Program 1
Program 2
Program 3

Address Space

Program 1
Program 2
EECS 370 Discussion

Motivation - Efficiency

Program 1

Program 2

Program 3
Motivation - Efficiency

Program 1

Program 2

Program 3

Virtual Memory

Address Space

Program 3

Program 2

0x0

0xFF
EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

Program 1
Program 2
Program 3

Address Space

Program 3
Wasted Space
Program 2
Wasted Space

0x0
0xFF
Virtual Memory

Motivation - Efficiency

This wouldn’t happen if we could split up programs into smaller chunks
Virtual Memory

Motivation - Size

Program 1

Address Space

0x0

0xFF
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Virtual Memory

Motivation - Size

Programs bigger than main memory simply can’t be run?

How do I play Civ 5 then? (6.98 GB)
Motivation - Security

Program 1
(Operating System)

Program 2
(Written by you)

Virtual Memory

Address Space

Program 1

Program 2
Motivation - Security

Program 1
(Operating System)

Program 2
(Written by you)

Virtual Memory

Address Space

Program 1

Program 2

Writes to memory...
Motivation - Security

Program 1
(Operating System)

Program 2
(Written by you)

Virtual Memory

Address Space

0x0

0xFF

Program 1
Crashes

Program 2

Writes to memory...
Virtual Memory

Solution:

Program is split into smaller chunks (pages)
Virtual Addresses map to where page is actually stored
Could be Main Memory or Disk

Memory acts like a cache for the disk
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Virtual Memory

Motivation - Efficiency

Program 1

Program 2

Program 3

Address Space

Program 3

Part of Program 1

Program 2

Part of Program 1

Program 2

Part of Program 1
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Virtual Memory

Motivation - Size

Program 1 (1/4)
Program 1 (2/4)
Program 1 (3/4)
Program 1 (4/4)

Address Space

Program 1 (1/4)
Program 1 (2/4)
Program 1 (3/4)
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Virtual Memory

Motivation - Size

Program 1 (1/4)
Program 1 (2/4)
Program 1 (3/4)
Program 1 (4/4)

Address Space

Program 1 (1/4)
Program 1 (4/4)
Program 1 (3/4)
Virtual Memory

We can also protect memory

Check addresses during translation
only allow writes from the correct programs

Mark entire pages as read-only
Virtual Memory

Page Table

Data Structure for address translation
Indexed by Virtual Page Number

Each entry has
Physical Page Number
Valid Bit
Dirty Bit

LRU Policy for evictions
Virtual Memory

Page Table is usually stored in Main Memory

What’s the problem here?
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Virtual Memory

Page Table is usually stored in Main Memory

What’s the problem here?
  Two memory accesses per memory access

SUPER SLOW!
Virtual Memory

Solution:

Translation Lookaside Buffer (TLB)
special cache for Page Table entries only
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Virtual Memory

TLB Hit

Virtual Page Number

Translation Lookaside Buffer

Physical Page Number

Main Memory

Page Table

Physical Page Number

Data

Processor

Data
Hierarchical Page Tables:

- Page Table points to locations of other Page Tables
- Bottom level points to actual Physical Address

Uses much less space on average
Uses much more space at worst
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Virtual Memory

Diagram:
- Superpage Table
- Subpage Table
- Physical Address
  - Physical Address
  - Physical Address
  - Physical Address
  - Physical Address
  - Physical Address
  - Physical Address
  - Physical Address
  - Physical Address