EECS 370 Discussion

SMBC

EECS 370 Discussion

Exam 2

- Solutions posted online

- Will be returned in next discussion (12/9)
  - Grades hopefully up on CTools earlier

EECS 370 Discussion

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

EECS 370 Discussion

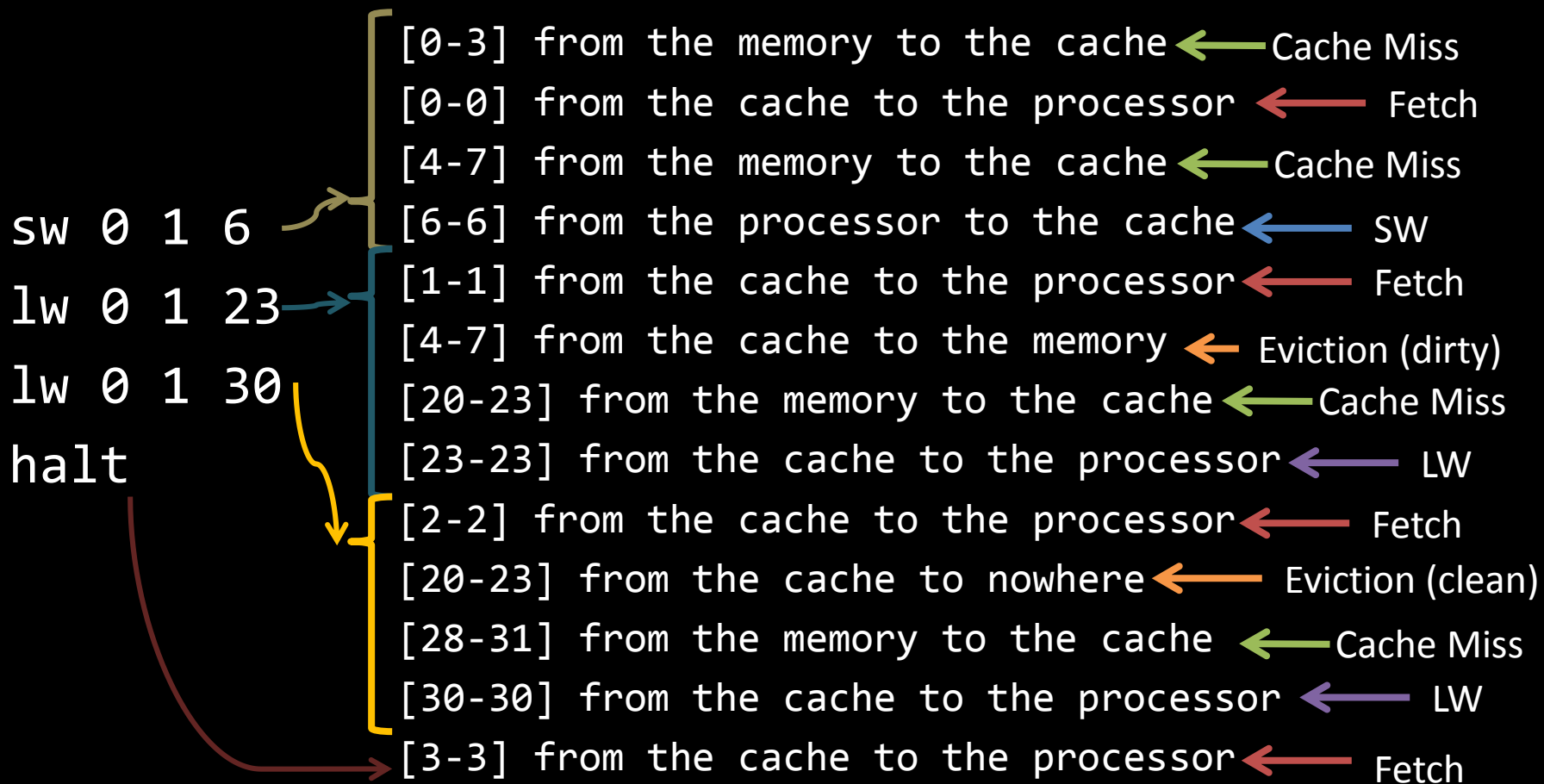## Project 4

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

EECS 370 Discussion

Virtual Memory

Virtual Addresses map to Physical Addresses

Software sees:

Hardware sees:

EECS 370 Discussion

Virtual Memory

Virtual Addresses map to Physical Addresses
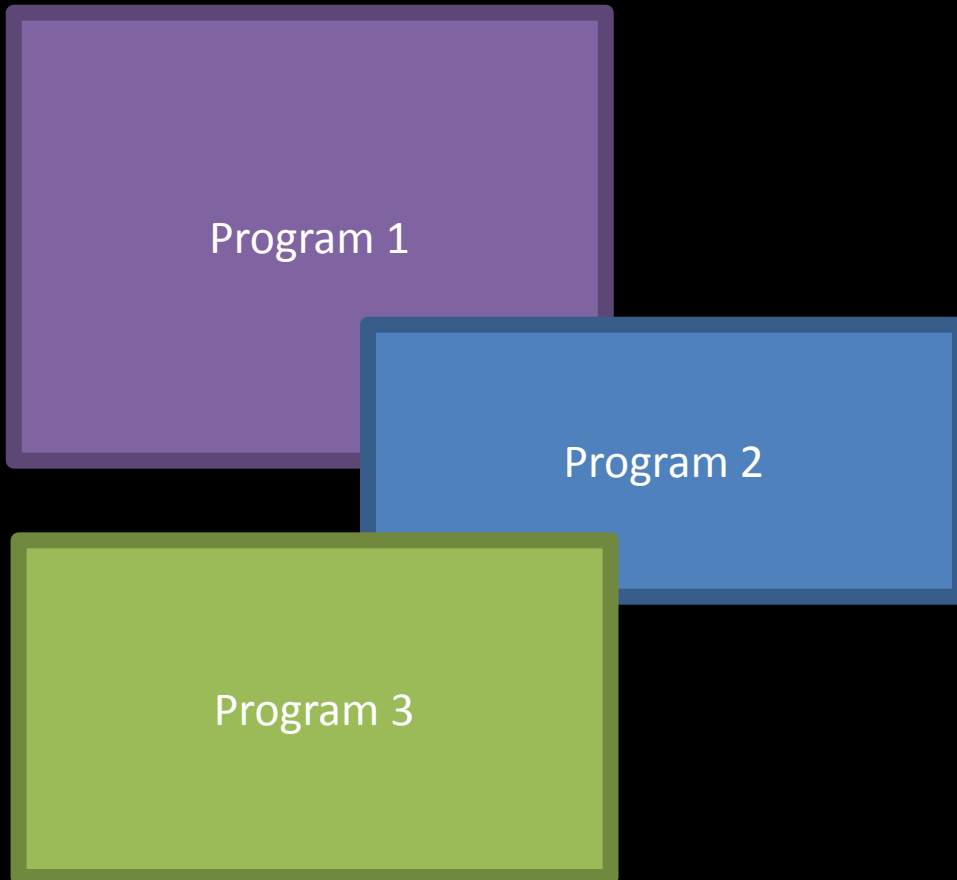
Software sees:

Virtual Addresses

Hardware sees:

Physical Addresses

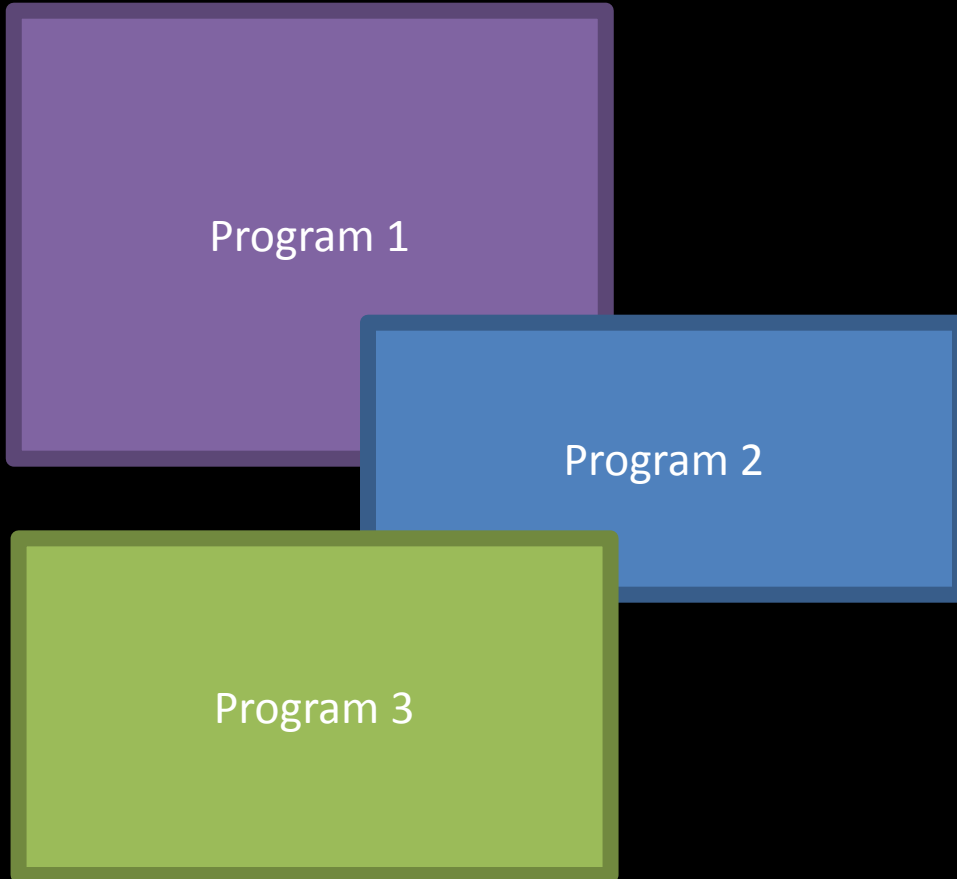# EECS 370 Discussion
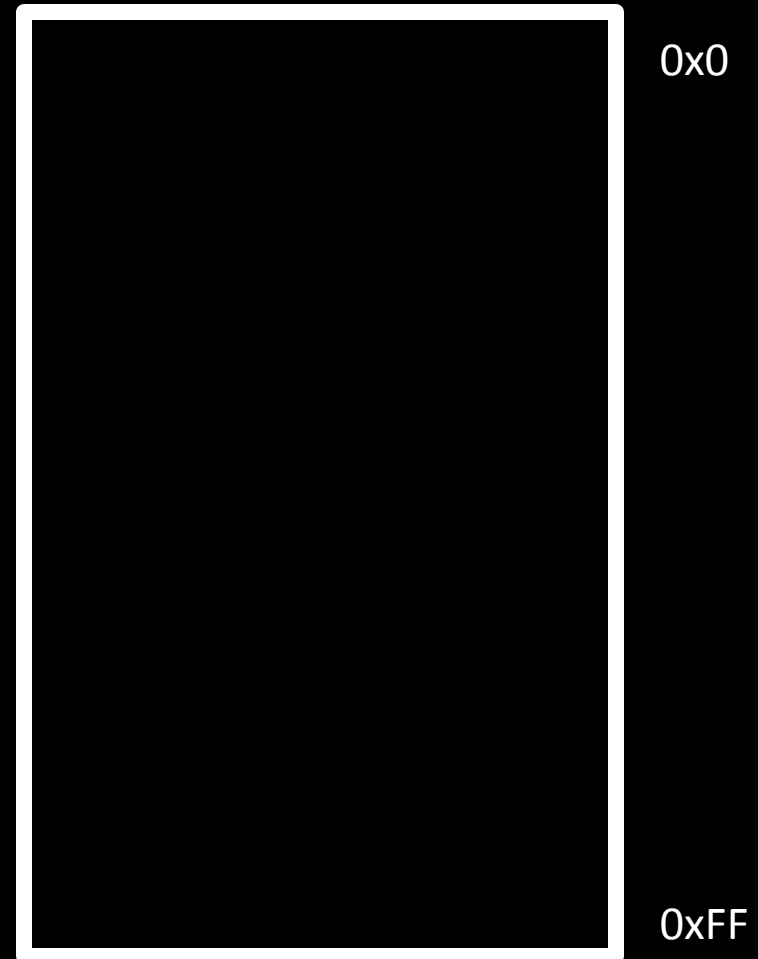
Virtual Memory

Address Space

Motivation - Efficiency

Program 1

Program 2

Program 3

0x0

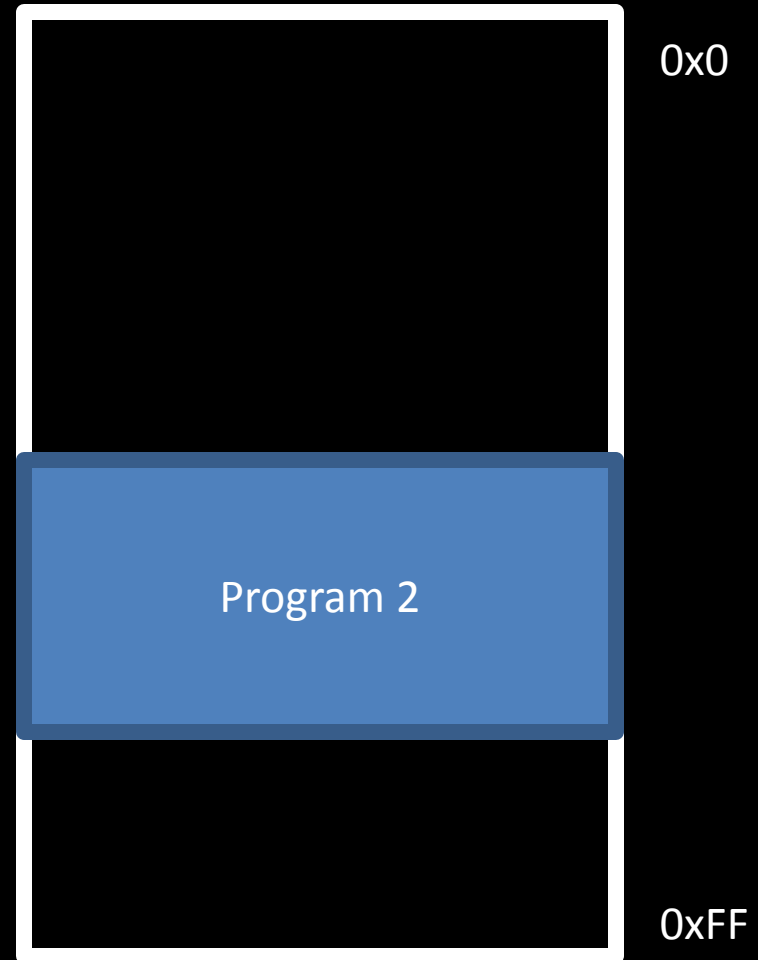0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

Address Space

Program 1

Program 2

Program 3

Program 1

0x0

0xFF

EECS 370 Discussion

Virtual Memory

Address Space

Motivation - Efficiency

Program 1

Program 2

Program 3

Program 1

0x0

Program 2

0xFF

EECS 370 Discussion
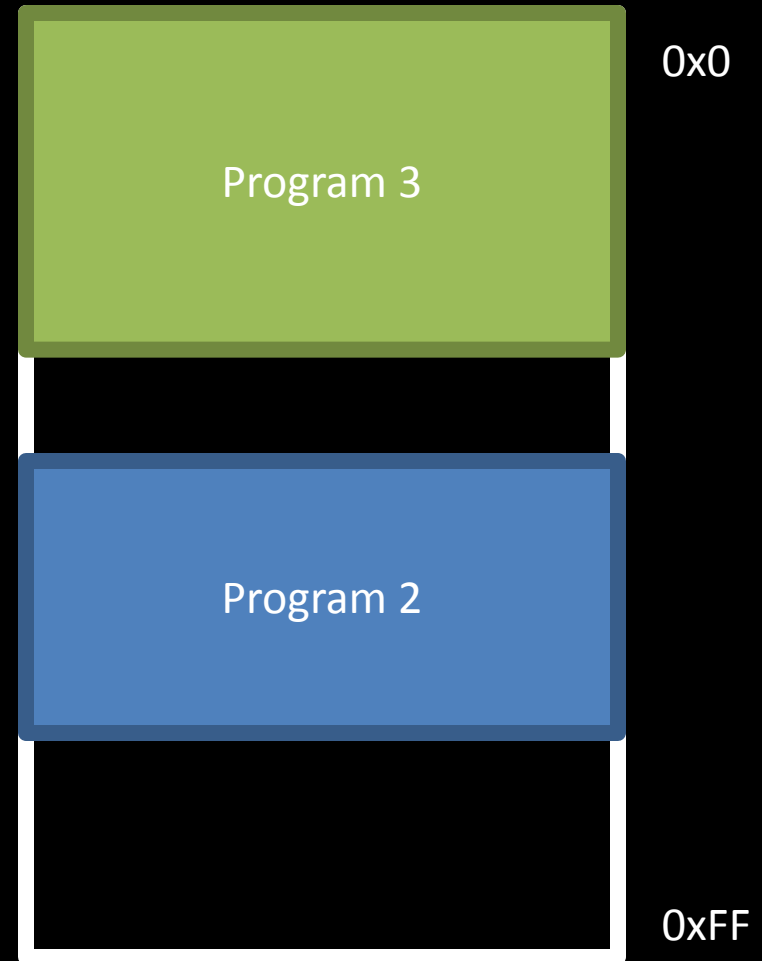
Virtual Memory

Address Space

Motivation - Efficiency

Program 1

Program 2

Program 3

0x0

Program 2

0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

Address Space

Program 1

Program 2

Program 3

0x0

Program 3

Program 2

0xFF

EECS 370 Discussion

Virtual Memory

Address Space

Motivation - Efficiency

Program 1

Program 2

Program 3

Program 3 — 0x0

Wasted Space

Program 2

Wasted Space — 0xFF
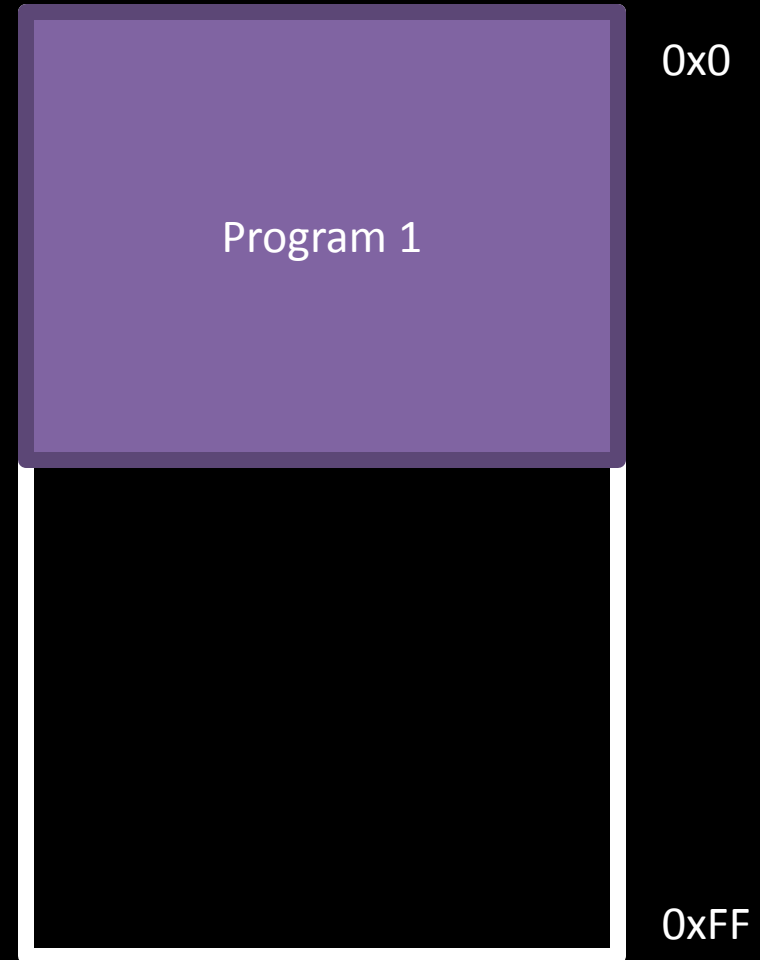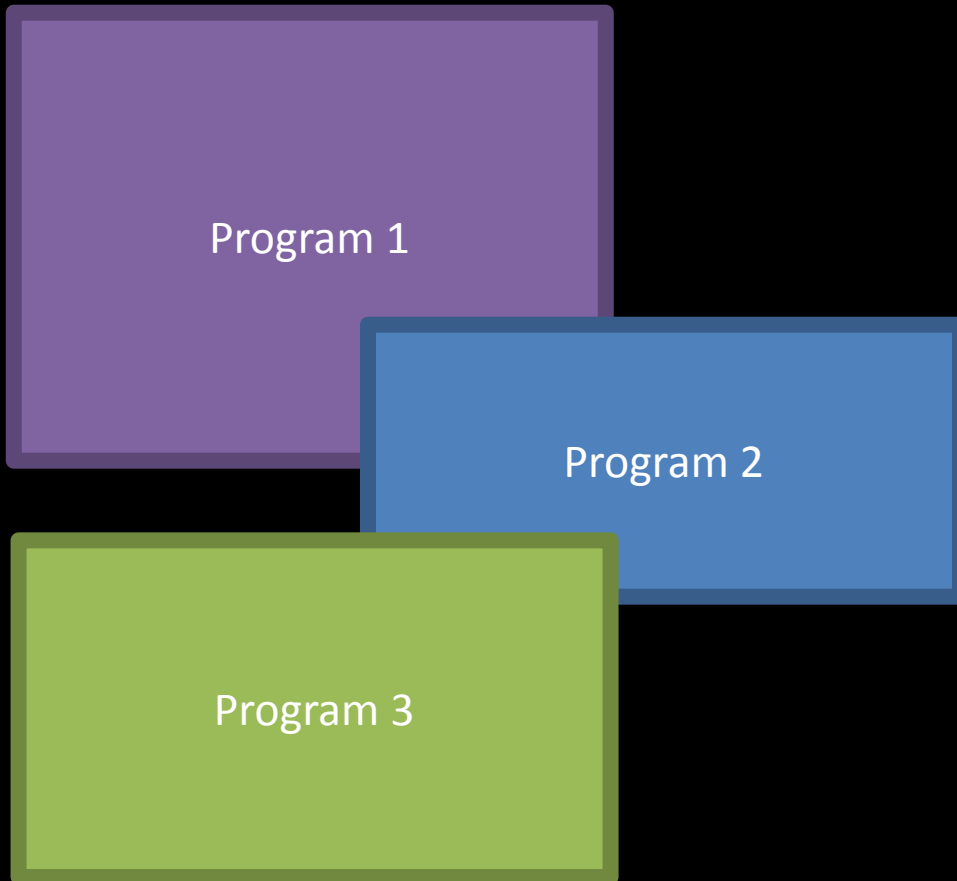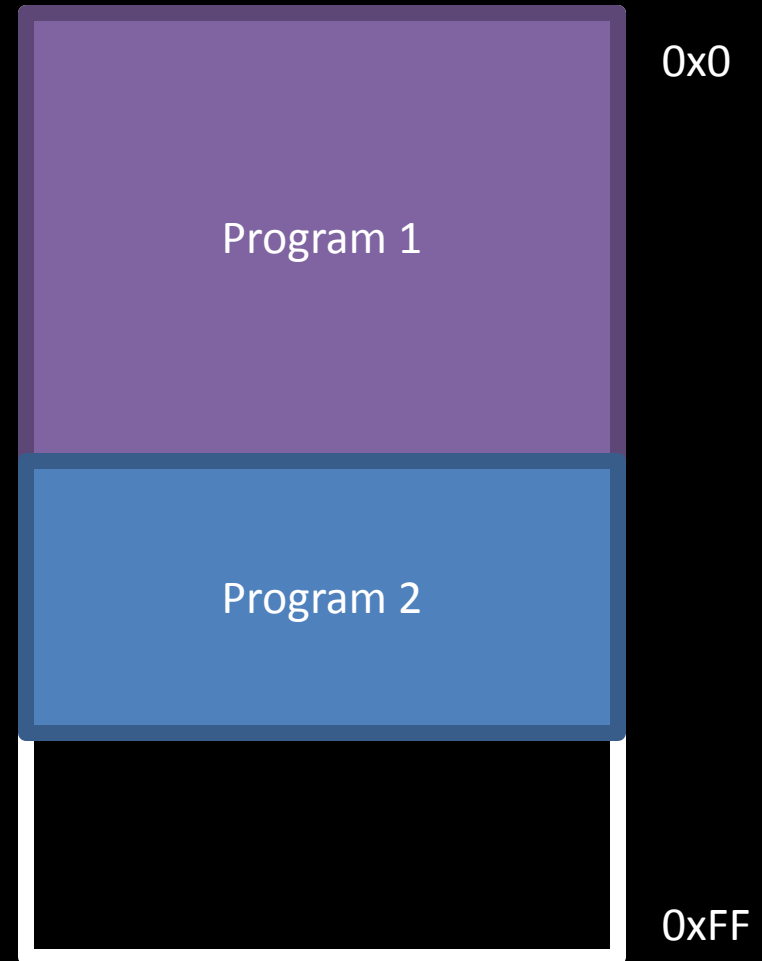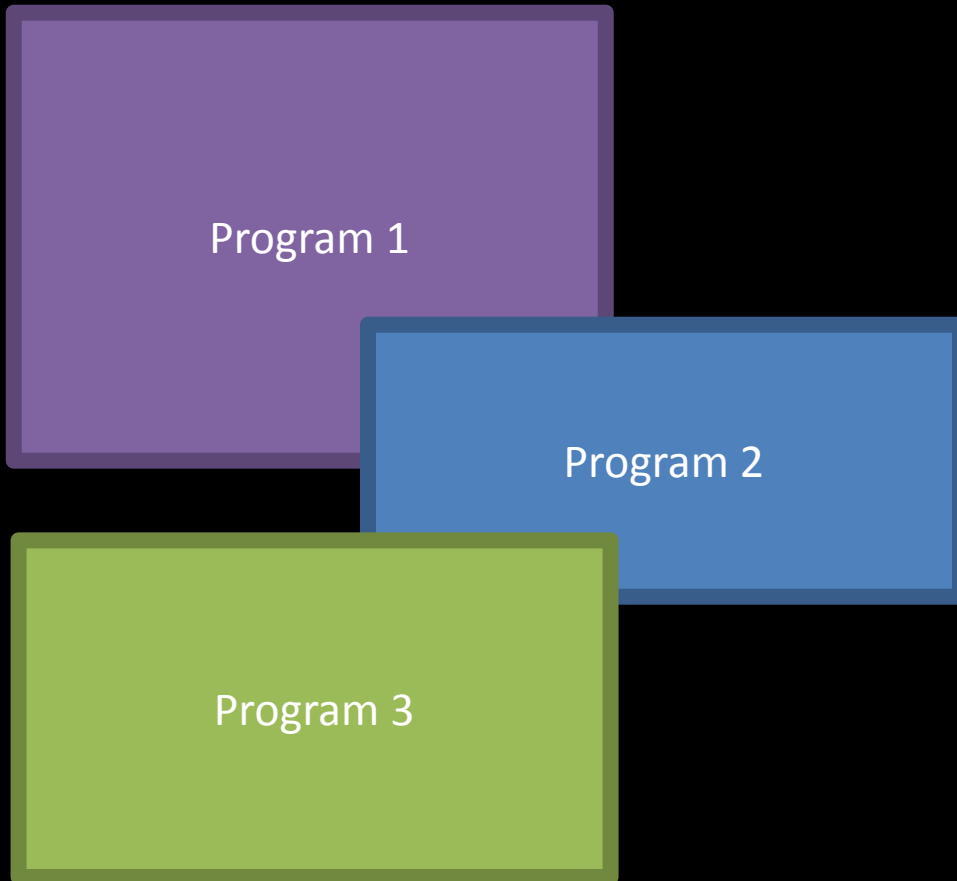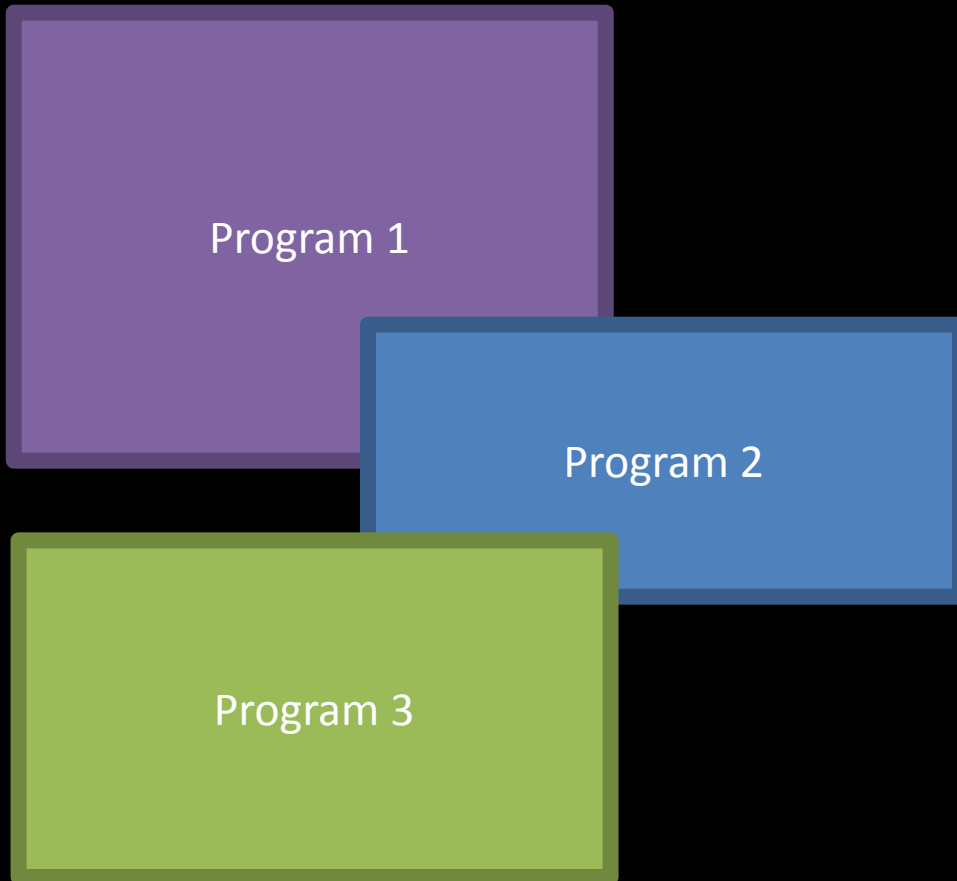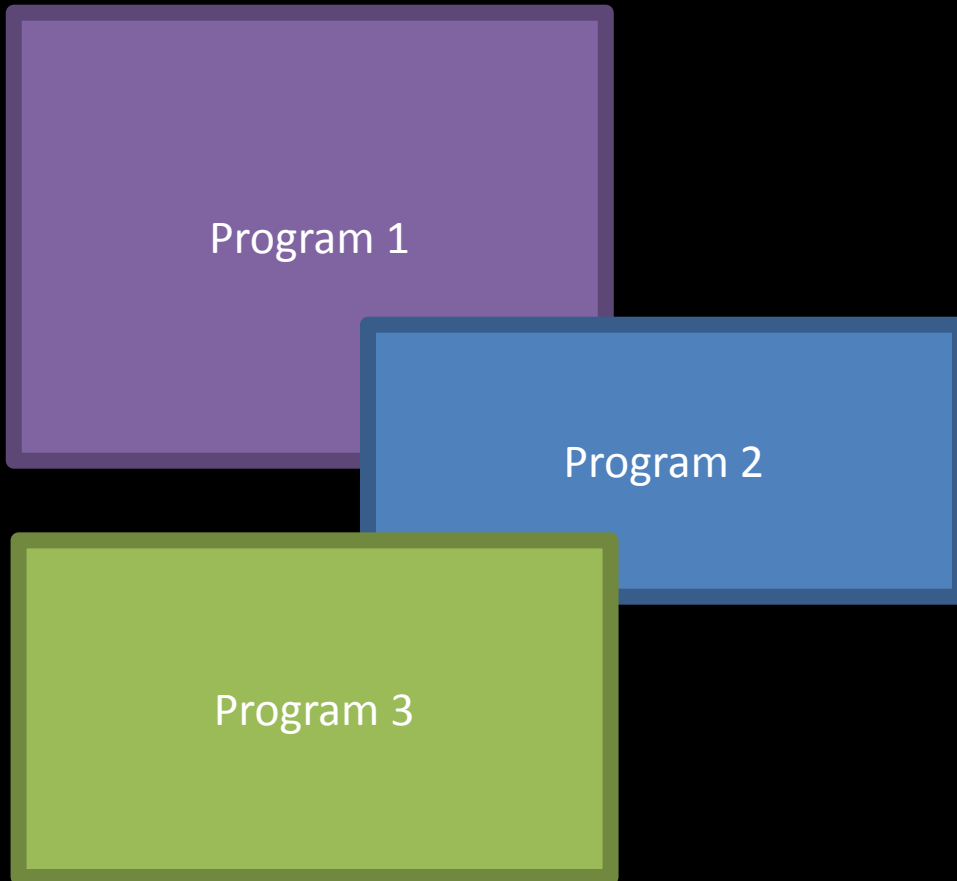
EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

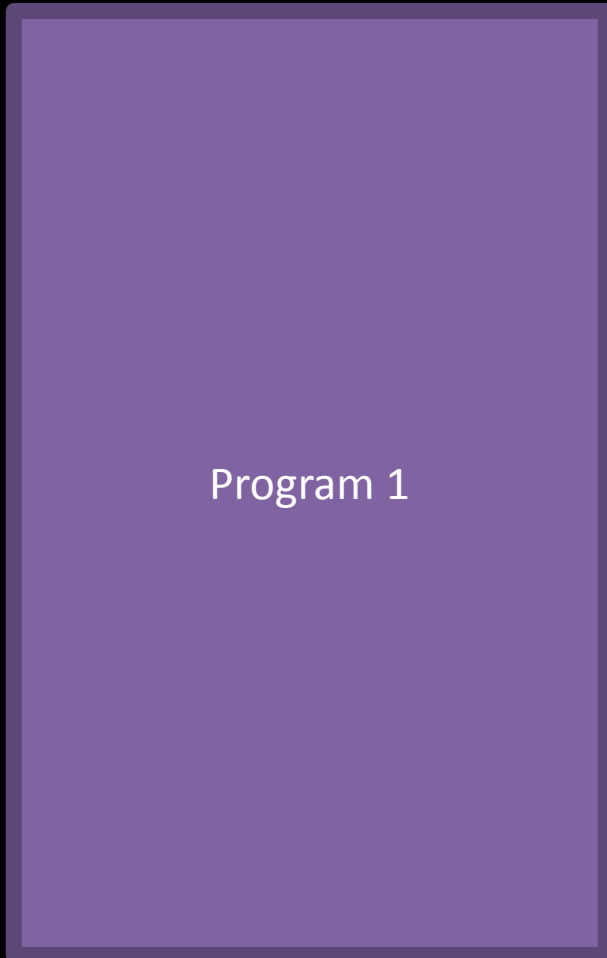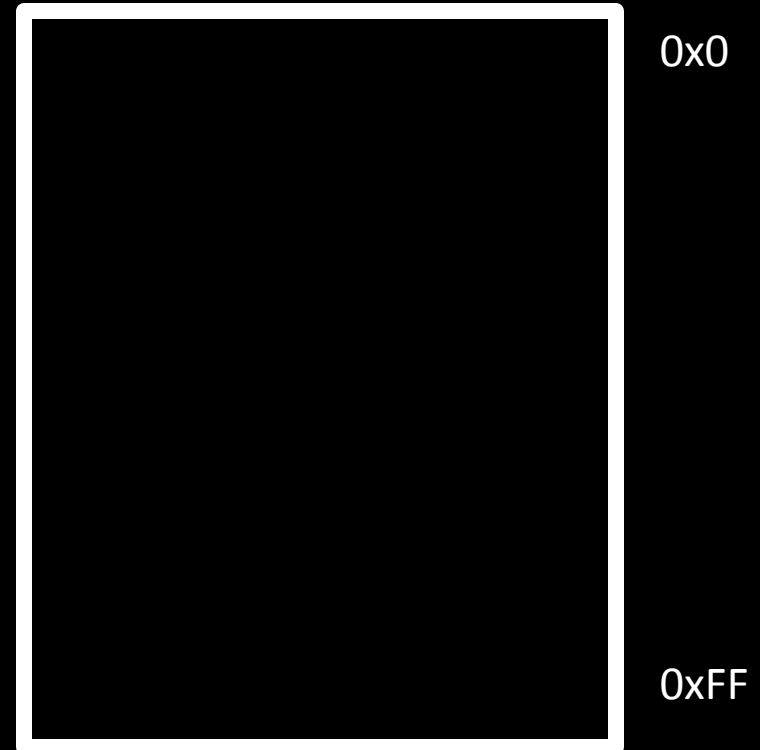This wouldn't happen if we could split up programs into smaller chunks

Address Space

Program 3	0x0
Wasted Space	
Program 2	
Wasted Space	0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Size

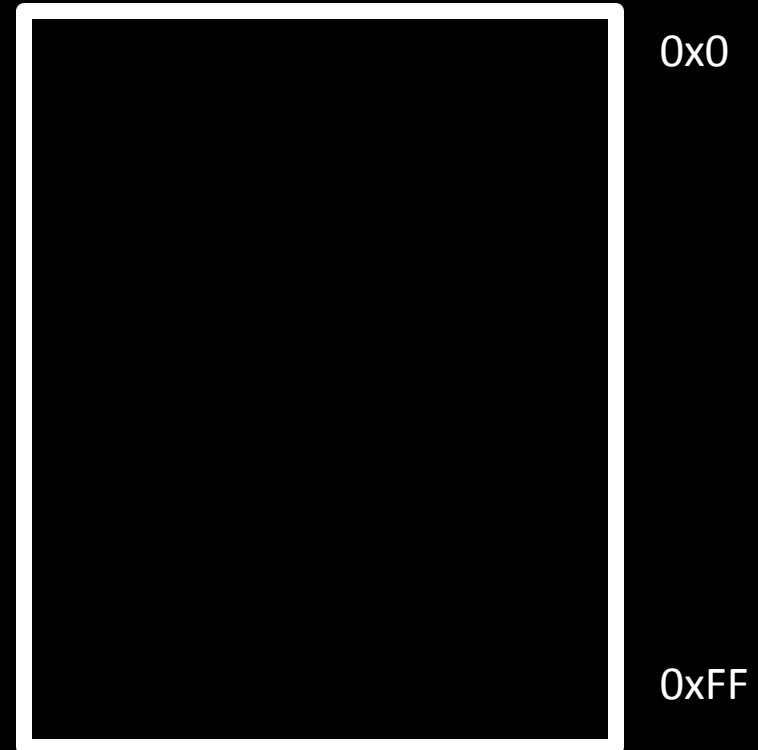Program 1

Address Space

0x0

0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Size

Address Space

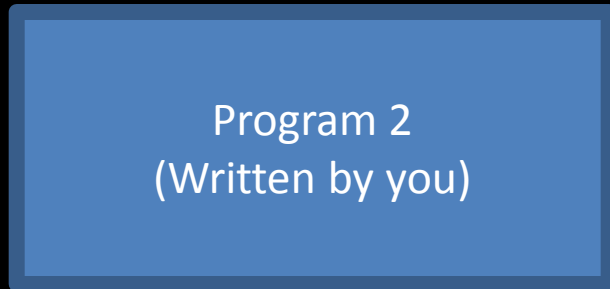Programs bigger than main memory simply can't be run?
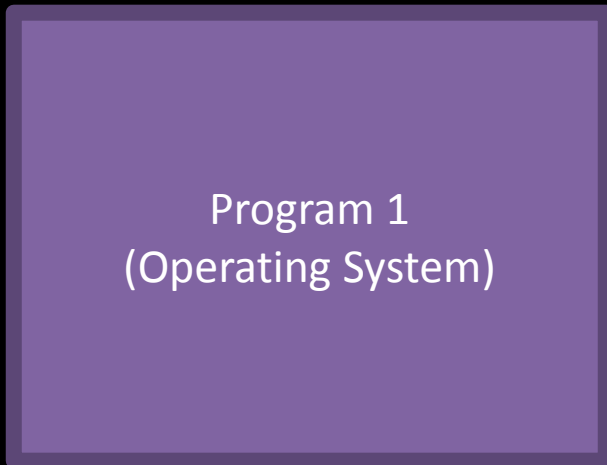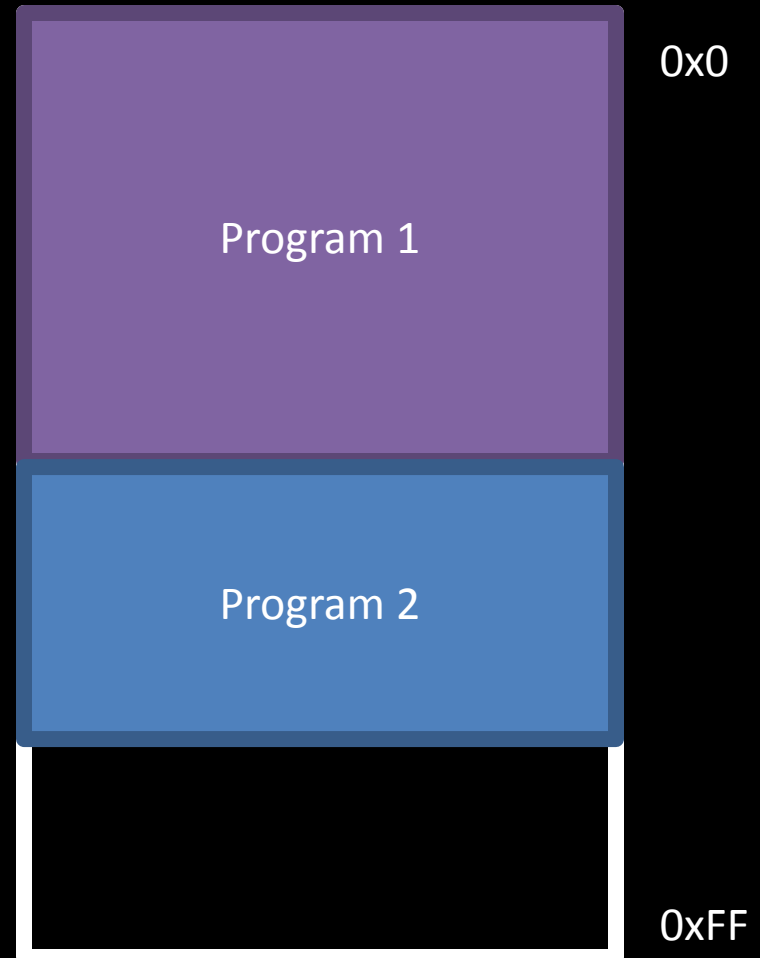
How do I play Civ 5 then? (6.98 GB)

0x0

0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Security

Address Space
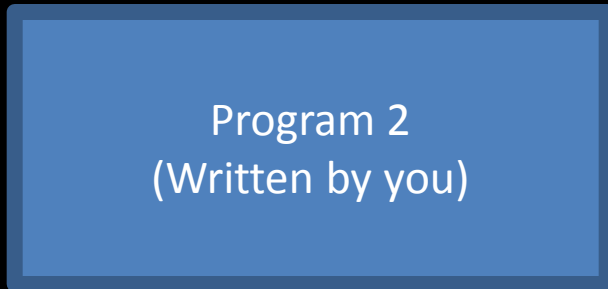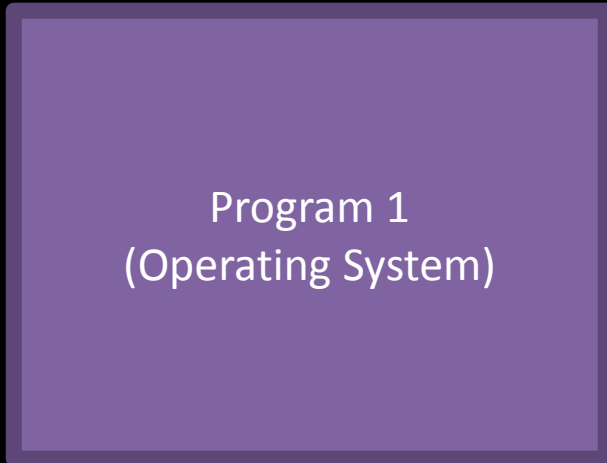
Program 1
(Operating System)

Program 2
(Written by you)

Program 1

Program 2

0x0

0xFF

EECS 370 Discussion

Virtual Memory

Address Space

Motivation - Security

Program 1
(Operating System)

Program 2
(Written by you)

Writes to memory...

Program 1

0x0

Program 2

0xFF

EECS 370 Discussion

Virtual Memory

Address Space

Motivation - Security

Program 1
(Operating System)

Writes to memory...

0x0

Program 1

Crashes
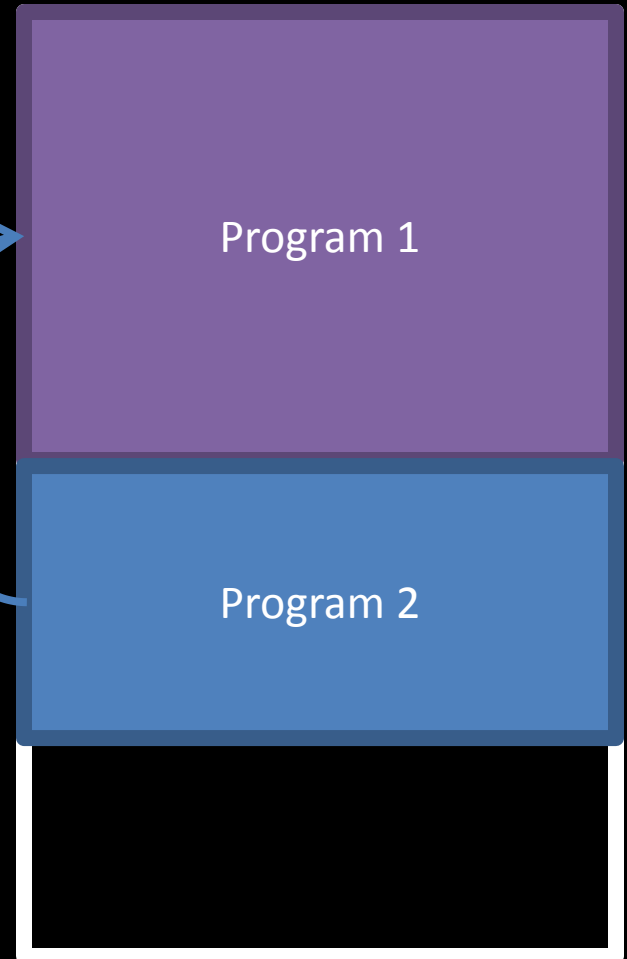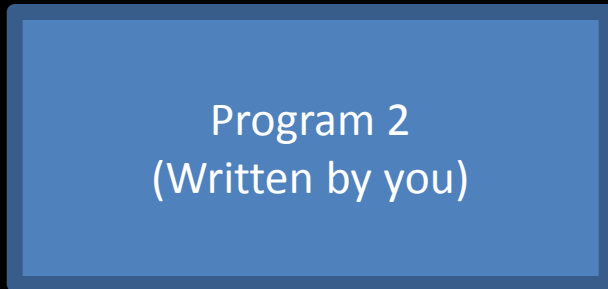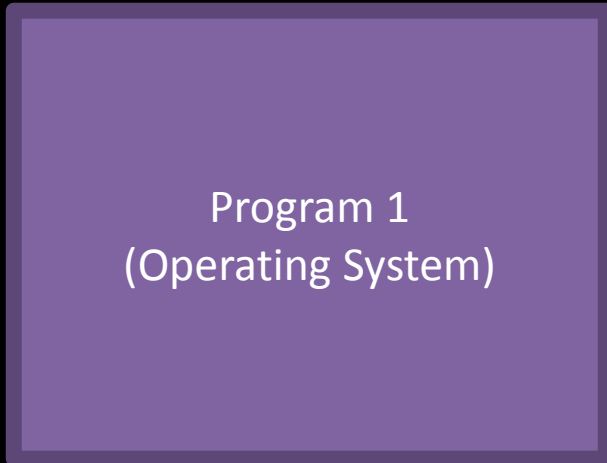
Program 2

Program 2
(Written by you)
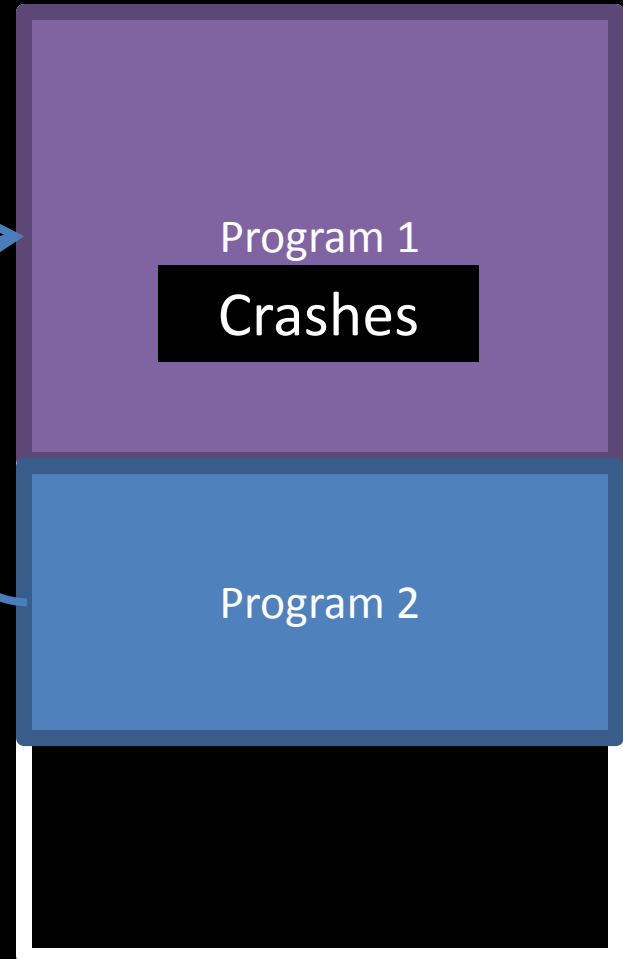
0xFF

EECS 370 Discussion

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

EECS 370 Discussion

Virtual Memory

Motivation - Efficiency

Address Space
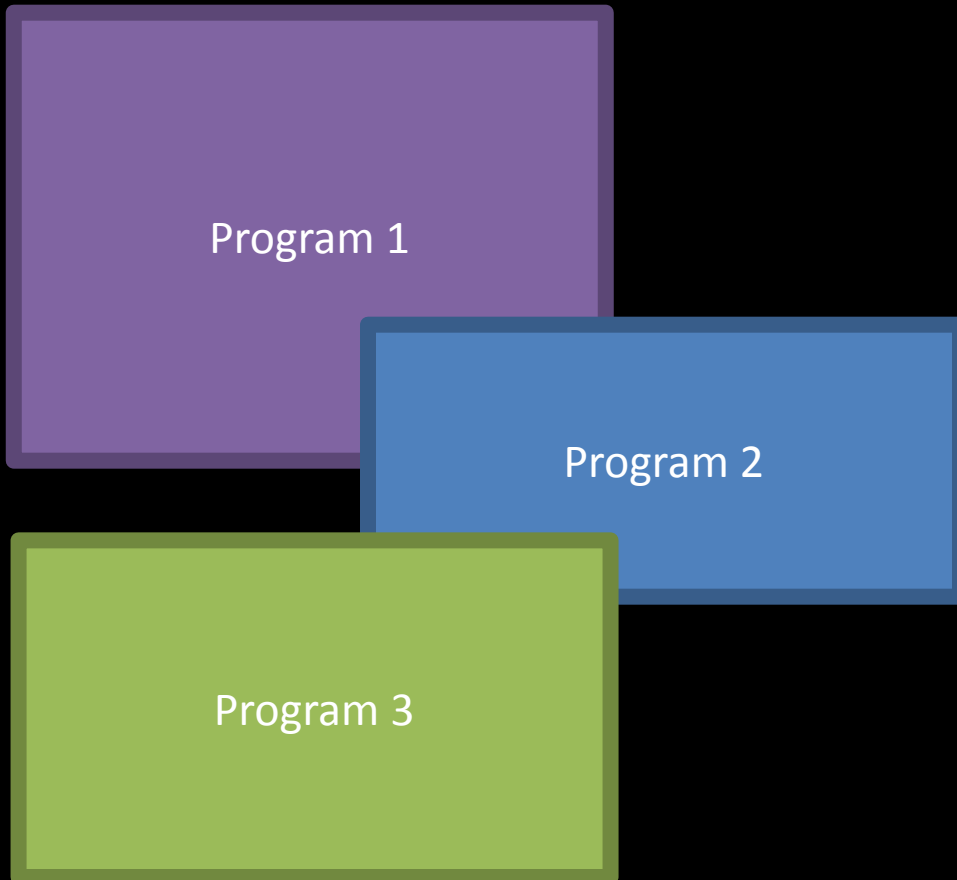
Program 1

Program 2

Program 3

Program 3

Part of Program 1

Program 2

Part of Program 1

0x0

0xFF

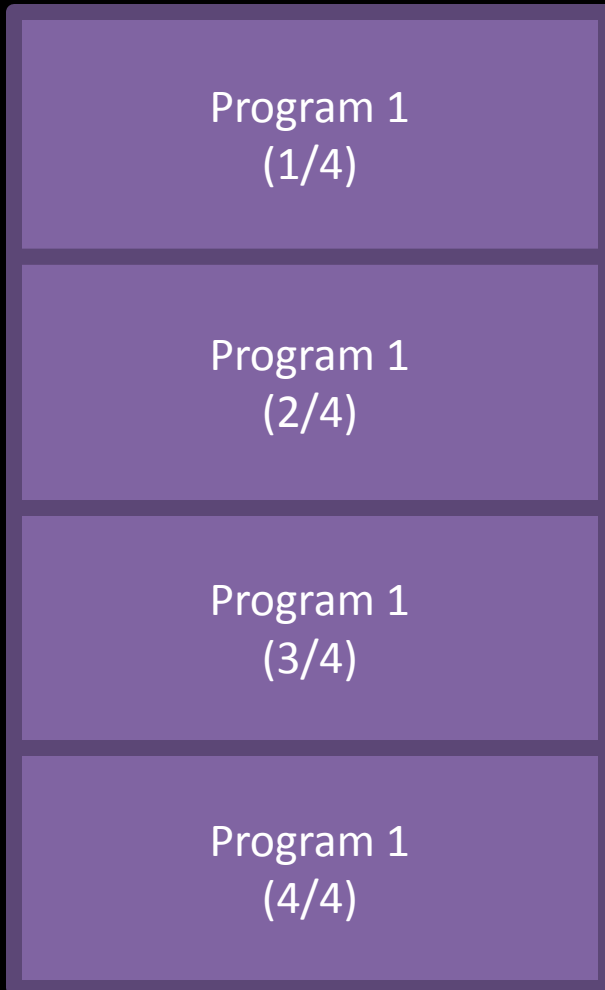# EECS 370 Discussion

Virtual Memory

Motivation - Size

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

Address Space

0x0

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

0xFF

EECS 370 Discussion

Virtual Memory

Motivation - Size

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

Address Space

0x0

| Program 1 (1/4) |
| Program 1 (4/4) |
| Program 1 (3/4) |

0xFF

EECS 370 Discussion

Virtual Memory

We can also protect memory

Check addresses during translation
only allow writes from the correct programs

Mark entire pages as read-only

EECS 370 Discussion

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

EECS 370 Discussion

Virtual Memory

Page Table is usually stored in Main Memory

What's the problem here?

EECS 370 Discussion

Virtual Memory

Page Table is usually stored in Main Memory

What's the problem here?

      Two memory accesses per memory access

      SUPER SLOW!

EECS 370 Discussion

Virtual Memory

Solution:

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

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Virtual Memory

TLB Hit

Page Table

Processor

Virtual Page Number →

Translation Lookaside Buffer

← Physical Page Number

Physical Page Number →

Data

← Data

EECS 370 Discussion

Virtual Memory

Main Memory

TLB Hit

Processor

Virtual Page Number → Translation Lookaside Buffer

Virtual Page Number → Page Table

Physical Page Number ←

Physical Page Number →

Data ←

Data
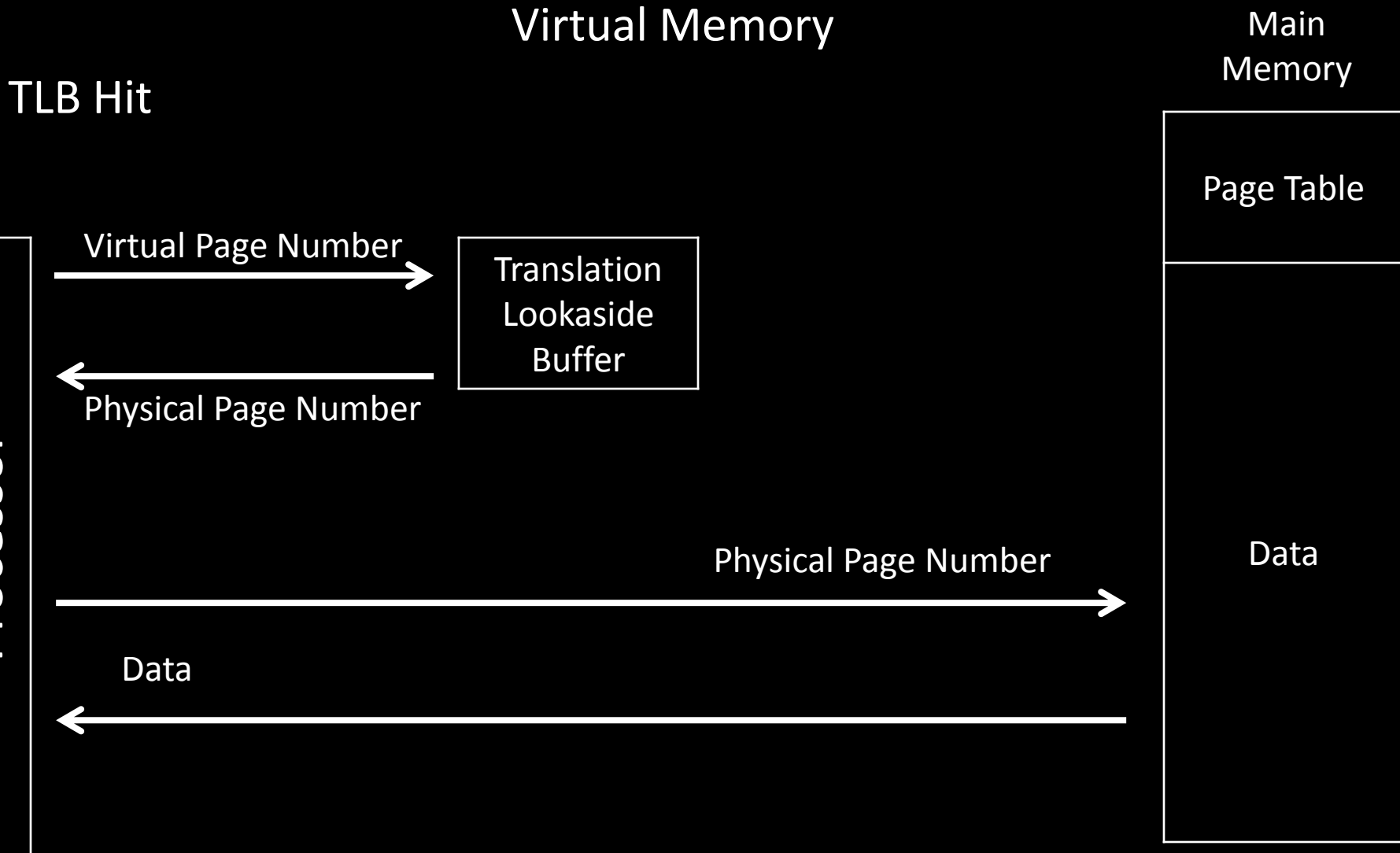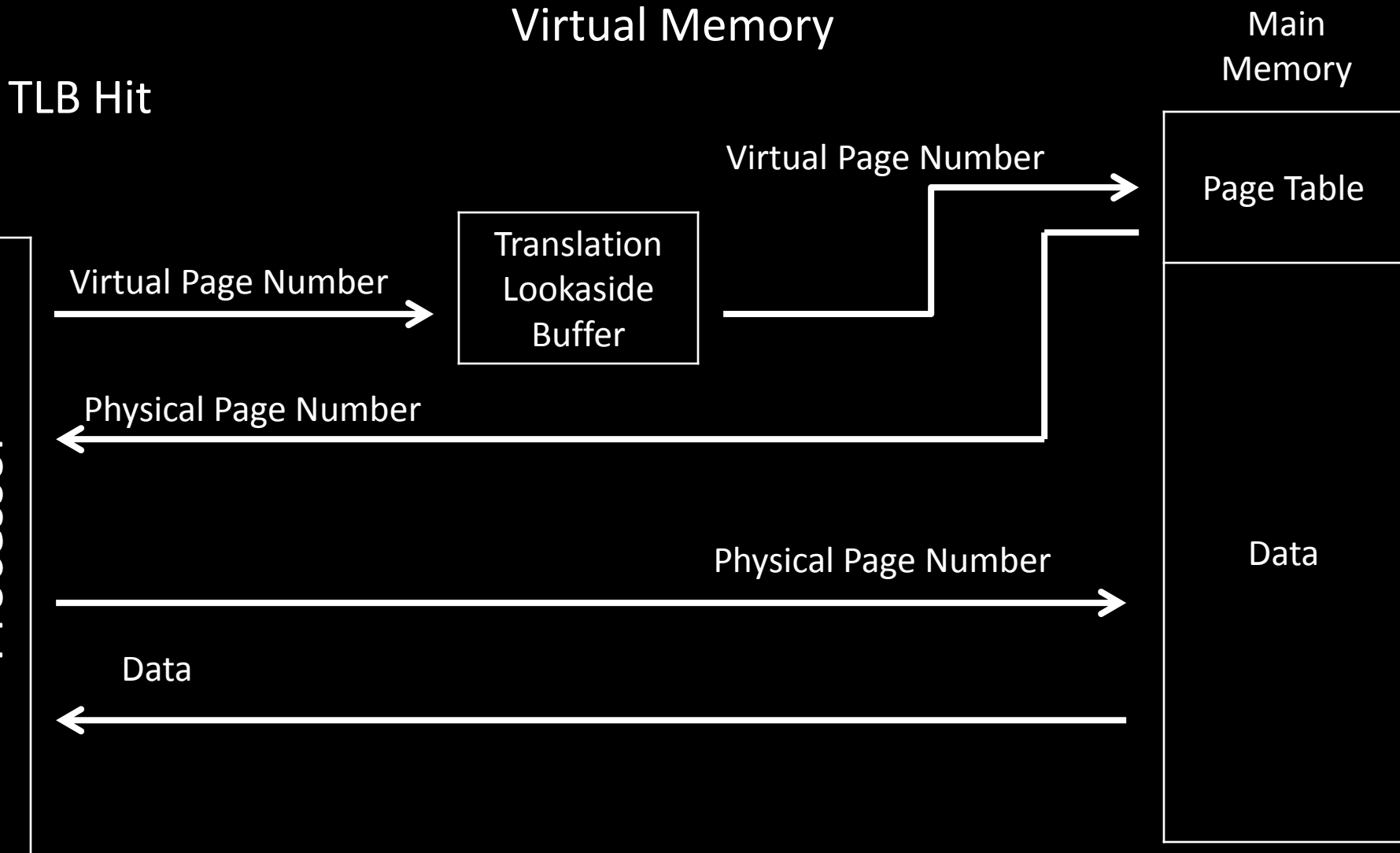
EECS 370 Discussion

Virtual Memory

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

EECS 370 Discussion

Virtual Memory