Lecture 30 - Paging

CprE 308

March 27, 2015

Paging

Review: Scenario

Ideal World (for the programmer)

- I'm the only process in the world
- I have more memory than I need at my disposal

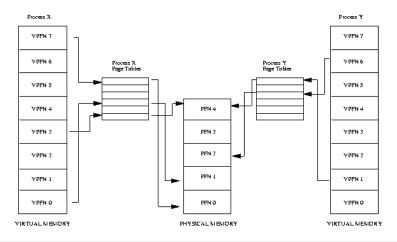
Real World

- Many processes in the system
- Not enough memory for them all
- Not all processes play nicely

Review: Goal of Memory Management

- Present the ideal world view to the programmer, yet implement it on a real system
- Add memory protections without getting in the way of the programmer

Review: Virtual Memory



Structuring Virtual Memory

- Paging
 - Divides the address space into fixed-sized pages
 - Reduces fragmentation, increases efficiency
- Segmentation
 - Divides the address space into variable-sized segments
 - Enables memory protections (Example: data, code, uninitialized, shared memory, etc.)
- Modern OS's use a mixture of both schemes (paged segmentation)

Typical Page Table Entry

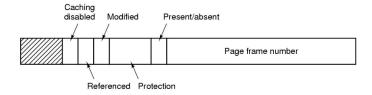


Figure 2: Page Table Entry Fields

Paging Example

- Consider a virtual memory system with two processes
 - Let the physical memory consist of 24 words and the page frame size of four words
 - Process 1 consists of 16 words (a through p)
 - Process 2 consists of 12 words (A through L)

Paging Example (Process 1 Virtual Memory)

Process 1 Virtual Memory

Virtual Address	Memory Contents
0	a
1	b
2	С
3	d
4	e
5	f
6	g
7	h
8	i
9	j
10	k
11	T .
12	m
13	n
14	0
15	р

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Paging Example (Process 1 Virtual Memory)

Process 1 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	a
_	1	b
0	2	С
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
3	12	m
	13	n
	14	О
	15	р

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Paging Example (Process 2 Virtual Memory)

Process 2 Virtual Memory

Virtual Address	Memory Contents
0	А
1	В
2	С
3	D
4	E
5	F
6	G
7	Н
8	1
9	J
10	K
11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Figure 5: Process 2 Virtual Memory



Paging Example (Process 2 Virtual Memory)

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	А
	1	В
0	2	С
	3	D
1	4	Е
	5	F
	6	G
	7	Н
	8	1
2	9	J
	10	K
	11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Figure 6: Process 2 Virtual Memory



Process 1 Virtual Memory

riocess i viitual Melliory		
Virtual Page	Virtual Address	Memory Contents
0	0	a
	1	b
v	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
2	8	i
	9	j
	10	k
	11	1
3	12	m
	13	n
	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	A
	1	В
0	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	н
	8	1
2	9	J
	10	К
	11	L

Process 1 Page Table

•	
Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	
0	1	
U	2	
	3	
	4	
1	5	
1	6	
	7	
	8	
2	9	
2	10	
	11	
	12	
3	13	
,	14	
	15	
	16	
4	17	
_	18	
	19	
	20	
5	21	
,	22	
	23	

Process 1 Virtual Memory

riocess i viituai wemory		
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
v	2	с
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
3	14	0
	15	р

Process 2 Virtual Memory

Virtual Address	Memory Contents
0	A
1	В
2	С
3	D
4	E
5	F
6	G
7	н
8	1
9	J
10	K
11	L
	0 1 2 3 4 5 6 7 8 9

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	E
0	1	F
U	2	G
	3	н
	4	
1	5	
1	6	
	7	
	8	
2	9	
2	10	
	11	
	12	
3	13	
3	14	
	15	
	16	
4	17	
-	18	
	19	
	20	
5	21	
,	22	
	23	

Process 1 Page Table

	Virtual Page	Physical Page
	0	2
	1	1
	2	invalid
	3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Process 1 Virtual Memory

1 10cc33 1 VII tual Memory		
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
v	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
,	13	n
3	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	А
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	н
	8	1
2	9	J
2	10	К
	11	L

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	E
	1	F
0	2	G
	3	Н
	4	e
1	5	f
1	6	g
	7	h
	8	
2	9	
2	10	
	11	
	12	
3	13	
3	14	
	15	
	16	
4	17	
7	18	
	19	
	20	
5	21	
,	22	
	23	

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Process 1 Virtual Memory

	Tocess i virtual Memory	
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
U	2	с
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
3	14	0
	15	р

Physical Page

invalid

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	А
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	Н
	8	1
2	9	J
	10	К
	11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	E
	1	F
0	2	G
	3	н
	4	e
1	5	f
1	6	g
	7	h
	8	a
2	9	b
2	10	c
	11	d
	12	
3	13	
,	14	
	15	
	16	
4	17	
*	18	
	19	
	20	
5	21	
,	22	
	23	



Process 1 Page Table

Virtual Page

Process 1 Virtual Memory

Process 1 Page Table

Virtual Page

riocess i virtual Memory		
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
v	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
2	8	i
	9	j
	10	k
	11	1
	12	m
3	13	n
	14	0
	15	р

Physical Page

invalid

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	А
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	Н
	8	1
2	9	J
	10	К
	11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	E
	1	F
0	2	G
	3	н
	4	e
1	5	f
1	6	g
	7	h
	8	а
2	9	b
2	10	c
	11	d
	12	A
3	13	В
,	14	С
	15	D
	16	
4	17	
*	18	
	19	
	20	
5	21	
,	22	
	23	



Process 1 Virtual Memory

1 100033 1 VIII. Udal Memory		
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
v	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	A
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	Н
	8	1
	9	J
2	10	К
	11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
	0	E
	1	F
0	2	G
	3	н
	4	e
	5	f
1	6	g
	7	h
	8	а
2	9	b
2	10	c
	11	d
	12	A
3	13	В
3	14	С
	15	D
	16	m
4	17	n
4	18	0
	19	р
	20	
5	21	
3	22	
	23	

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 1 Virtual Memory

Process 1 Virtual Memory		
Virtual Page	Virtual Address	Memory Contents
	0	a
0	1	b
U	2	с
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
3	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	А
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	Н
	8	1
2	9	J
	10	К
	11	L

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
0	0	E
	1	F
U	2	G
	3	н
	4	e
1	5	f
1	6	g
	7	h
	8	a
2	9	b
2	10	c
	11	d
	12	A
3	13	В
3	14	С
	15	D
	16	m
4	17	n
-	18	0
	19	р
	20	1
5	21	J
,	22	К
	23	L



Virtual Page	Physical Page
0	2
1	1
2	invalid
2	4

Suppose process 1 is running and it tries to access the contents of the virtual address 15, what is the result?

Process 1 Virtual Memory

Process i virtual wemory		
Virtual Page	Virtual Address	Memory Contents
	0	a
	1	b
0	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
3	14	o
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Content
	0	Α
0	1	В
U	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	н
	8	1
2	9	J
	10	К
	11	L

Process 1 Page Table

ı	Virtual Page	Physical Page
	0	2
	1	1
	2	invalid
	3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
0	0	E
	1	F
U	2	G
	3	н
	4	e
1	5	f
1	6	g
	7	h
	8	a
2	9	b
2	10	c
	11	d
	12	A
3	13	В
,	14	С
	15	D
	16	m
4	17	n
*	18	0
	19	p
	20	1
5	21	J
5	22	K
	23	L

- Suppose process 1 is running and it tries to access the contents of the virtual address 15, what is the result?
 - Virtual address 15 is in process 1's virtual page 3. According to the page table for process 1, the virtual page 3 is paged in physical memory as page 4, which means the value p will be immediately fetched from memory.

■ Suppose process 1 is running and it tries to access the contents of the virtual address **9**, what is the result?

Process 1 Virtual Memory

1 100000 1 VII taal Wollion		
Virtual Page	Virtual Address	Memory Contents
	0	a
	1	b
0	2	С
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
3	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
	0	A
	1	В
0	2	С
	3	D
	4	E
1	5	F
1	6	G
	7	н
2	8	1
	9	J
	10	К
	11	L

P

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 1 Page Table

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory		
Physical Page	Physical Address	Memory Contents
0	0	E
	1	F
U	2	G
	3	н
	4	e
1	5	f
1	6	g
	7	h
	8	а
2	9	b
2	10	с
	11	d
	12	A
3	13	В
,	14	С
	15	D
	16	m
4	17	n
_	18	0
	19	р
	20	1
5	21	J
5	22	К
	23	L

- Suppose process 1 is running and it tries to access the contents of the virtual address 9, what is the result?
 - Virtual address 9 is in process 1's virtual page 2. According to the page table for process 1, virtual page 2 is not paged in physical memory (flagged as invalid in the page table). A page fault occurs, and physical memory will need to be swapped before the value j can be fetched from memory.

Paging Example (Address Translation)

Process 1

- Virtual Address 2 to Physical Address
- Physical Address 5 to Virtual Address

Process 2

- Virtual Address 2 to Physical Address
- Physical Address 22 to Virtual Address

Paging Example (Address Translation)

Process 1 Virtual Memory

1 100033 1 VIIIuai Welliory		
Virtual Page	Virtual Address	Memory Contents
0	0	a
	1	b
v	2	c
	3	d
	4	e
1	5	f
1	6	g
	7	h
	8	i
2	9	j
2	10	k
	11	1
	12	m
3	13	n
	14	0
	15	р

Process 2 Virtual Memory

Virtual Page	Virtual Address	Memory Contents
0	0	А
	1	В
	2	С
	3	D
1	4	E
	5	F
	6	G
	7	Н
2	8	1
	9	J
	10	К
	11	L

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

Physical Memory			
Physical Page	Physical Address	Memory Contents	
0	0	E	
	1	F	
U	2	G	
	3	н	
	4	e	
1	5	f	
1	6	g	
	7	h	
	8	a	
2	9	b	
2	10	c	
	11	d	
	12	A	
3	13	В	
,	14	С	
	15	D	
	16	m	
4	17	n	
_	18	0	
	19	р	
5	20	1	
	21	J	
	22	К	
	23	L	

Paging Example (Address Translation)

Process 1

- Virtual Address 2 to Physical Address
 - **10**
- Physical Address 5 to Virtual Address
 - **5**

Process 2

- Virtual Address 2 to Physical Address
 - **14**
- Physical Address 22 to Virtual Address
 - **10**



- Virtual memory is just a concept
 - It's addresses/values are always contiguous
 - It's values only really exist in physical memory
 - Page frames are just logical groupings (that can be calculated on the fly)
- Only need to store page tables

Process 1 Page Table

Virtual Page	Physical Page
0	2
1	1
2	invalid
3	4

Process 2 Page Table

Virtual Page	Physical Page
0	3
1	0
2	5

Physical Memory

r nysicai ivieniory		
Physical Address	Memory Contents	
0	E	
1	F	
2	G	
3	н	
4	e	
5	f	
6	g	
7	h	
8	а	
9	b	
10	c	
11	d	
12	A	
13	В	
14	С	
15	D	
16	m	
17	n	
18	0	
19	р	
20	1	
21	J	
22	К	
22		

- Virtual page frames are always in order starting at 0
 - No need to store virtual page numbers in page table (just store physical page numbers in order)
- Techinically we don't "store" addresses either

Physical Page	
2	
1	
invalid	
4	

Process 1 Page Table Process 2 Page Table

Physical Page	
3	
0	
5	
,	

Physical Memory

,
Memory Contents
E
F
G
Н
е
f
g
h
a
b
С
d
A
В
С
D
m
n
0
p
1
J
К
L

- If our page table stores 4 virtual pages mappings how many bits do we need to represent each page?
- If our page size is 4 words, how many bits do we need to represent each possible page offset?

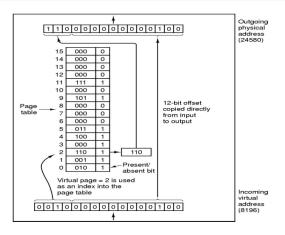


Figure 19: Address Translation



Quiz

Any questions before the quiz?