CSE 451: Operating Systems
Winter 2026

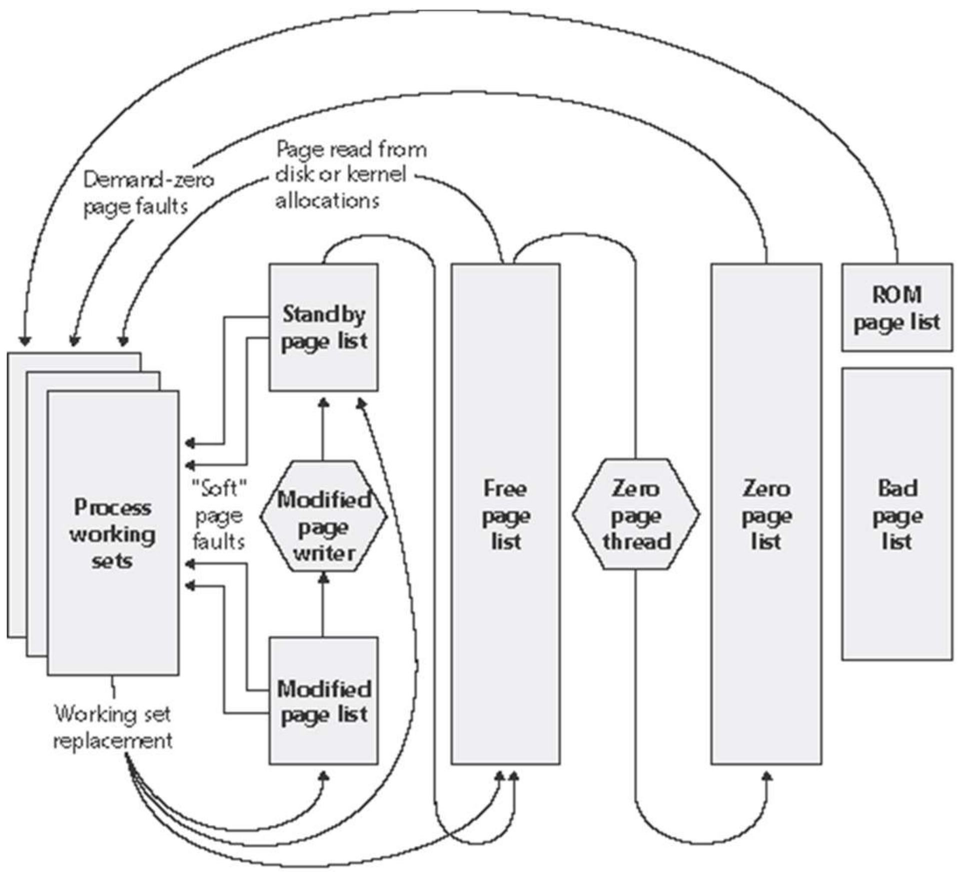
Module 14
Windows MM

Gary Kimura

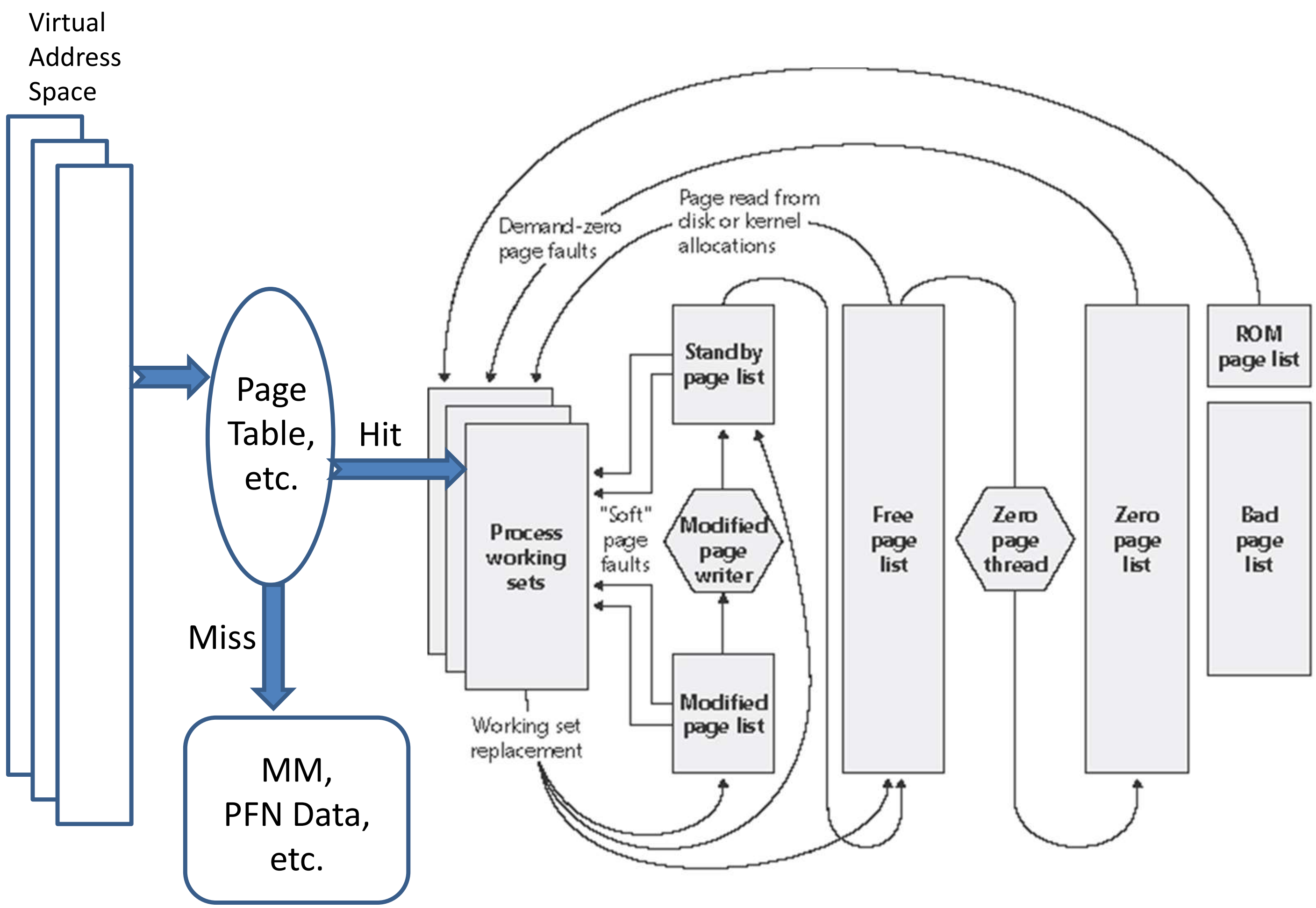
Memory Management (continued)

- Windows Paging
- Windows Kernel Heap
- Wickedly Fun Exam Question

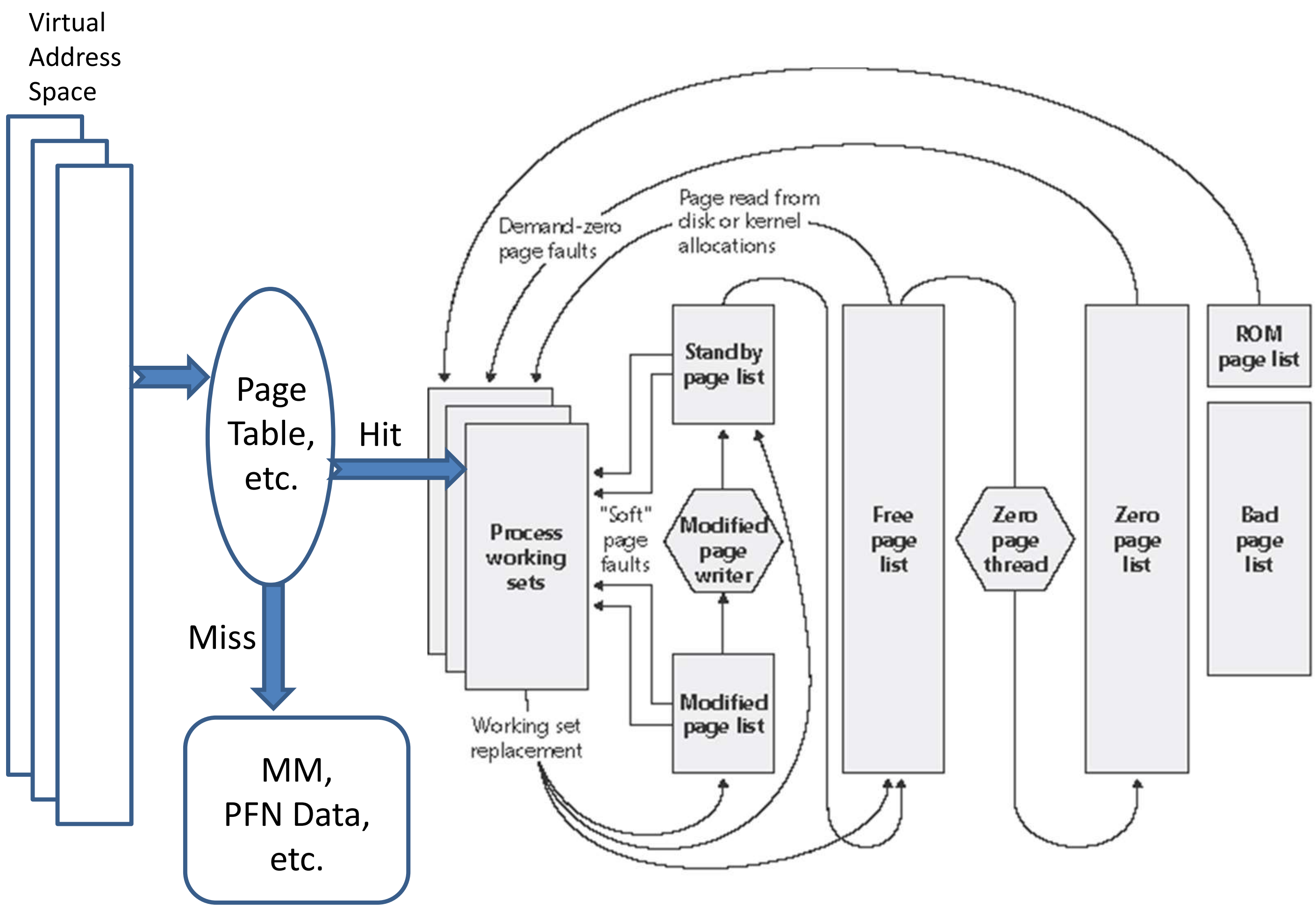
Windows Page Frame State Diagram



Windows Page Frame State Diagram



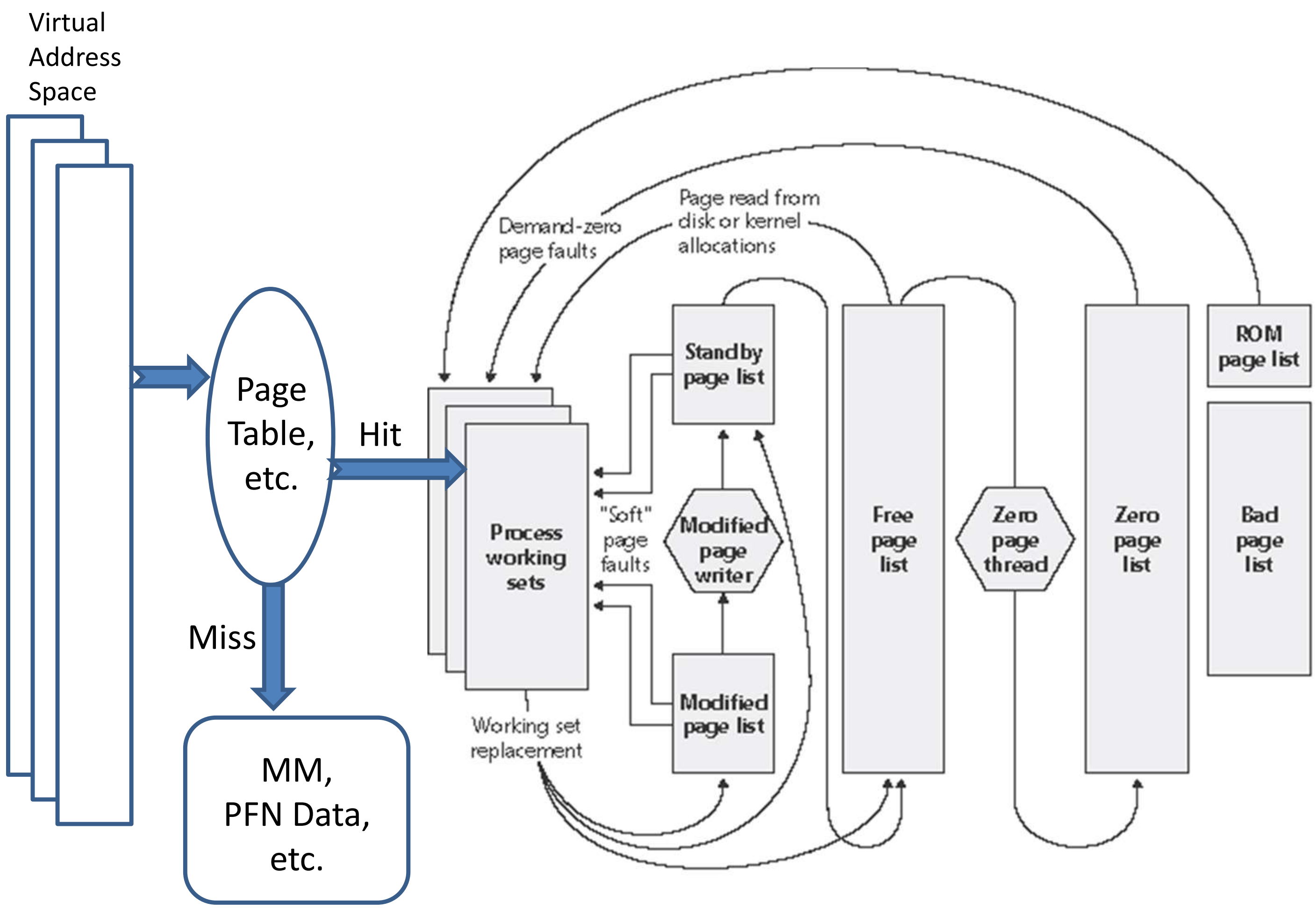
Windows Page Frame State Diagram



Page States

- Active (also called Valid)
- Transition
  - Standby
  - Modified
  - Modified no-write
- Free
- Zeroed
- Rom
- Bad

Windows Page Frame State Diagram



Paging Features

- Local and Global page replacement
- LRU on top of FIFO
- Hard and Soft page faults

Windows Kernel Pool (aka Heap)

- Boundary tagged (tried but rejected Fibonacci and buddy system)
- Paged and Nonpaged (Once had Must Succeed)
- Lookaside lists
- Node type codes to help quickly identify objects in the pool

Overall Pool Layout

Debugging pool corruption

- Checked build versus Free build
- Debugging pool corruption bugs, often stale pointers or allocation overruns
- 0xDEADBEEF and 0xBAADF00D
- Extra code to check for pool corruption
- A pointer hack I used to catch a bad actor (data alignment fault)

Pool Corruption

A Fun Exam Question from 2013

- Examine how long it takes a user mode program writing to an array of integers.
- Assumptions
  - The entire array will fit into physical memory (no paging)
  - The system is pretty much idle except for this program
- First malloc() the array, and then
- Time how long it takes to write to every element of the array using various access patterns.

The Actual Exam Question

Consider the following program that allocates a multi-megabyte sized array of unsigned longs, and then times how long it takes to write to every array location. The program varies the pattern it uses to write to each array location based on a stride that changes between each pass through the array.

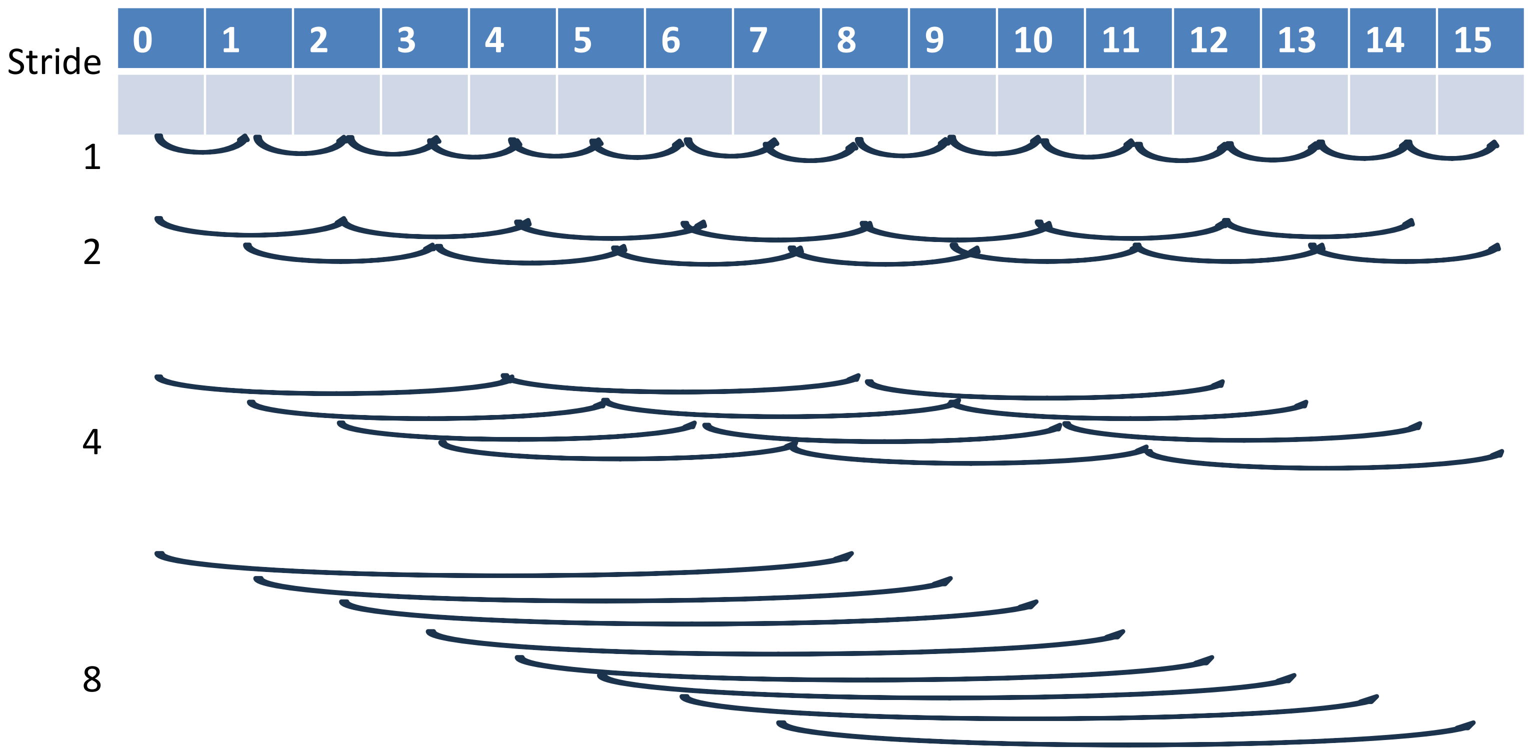
For example a stride of 1 makes one pass through the array accessing locations 0,1,2,… until the end of the array is reached. A stride of 2 makes two passes through the array, first accessing locations 0,2,4,… and then accessing locations 1,3,5,… until the end of the array is reached. The program starts with a stride value of 1 and then increases it, based on user input, until the stride is equal to half the size of the array. The program times how long it takes, in seconds, for each new stride through the array.

The program takes three parameters, first is the number of megabytes to allocate to the array, the second and third parameters are the multiplication and additive factors used to compute the stride. For example, the parameters "2 1 1" allocate a 2MB array testing stride values of 1,2,3,4,…, 131072. Note that 131072 is the halfway point in a 2MB integer array. The parameters "2 2 0" allocate a 2MB array testing stride values of 1,2,4,8,16,…,131072. In other words the stride value doubles each time.

```c
void main (int argc, char *argv[])
{
    clock_t StartTime, EndTime;
    unsigned long *Array, Size, StrideTimes, StridePlus, i,j,k;

    sscanf(argv[1], "%lu", &Size);
    sscanf(argv[2], "%lu", &StrideTimes);
    sscanf(argv[4], "%lu", &StridePlus);

    printf("Size = %luMB\n", Size);

    //  Allocate a test array
    Size = 1024*1024*Size;
    if ((Array = malloc(Size)) == NULL) {
        printf("malloc failed\n");
        return;
    }
    Size /= 4;

    //  Now test it for strides from 1 to size/2
    printf("  Stride   Seconds\n");
    for (i = 1; i < Size/2; i = (i*StrideTimes)+StridePlus) {
        printf("%8lu", i);
        StartTime = clock();
        for (j = 0; j < i; j++) {
            for (k = j; k < Size; k += i) {
                Array[k] = k;
            }
        }
        EndTime = clock();
        printf(", %8.3f\n", ((double)(EndTime - StartTime)/CLOCKS_PER_SEC));
    }
}
```

What about calling free()
when the program exits?

Doubling stride each time



This program was run on both Windows and Linux systems with 4GB of RAM. Here is the data for a run of "1024 2 0" on a Linux system.

Size = 1024 MB

Stride	Seconds	Stride	Seconds	Stride	Seconds
1,	1.920	512,	11.890	262144,	18.250
2,	1.560	1024,	12.190	524288,	14.710
4,	2.780	2048,	12.960	1048576,	9.810
8,	5.530	4096,	14.280	2097152,	5.310
16,	11.450	8192,	16.510	4194304,	4.100
32,	16.470	16384,	22.070	8388608,	3.820
64,	15.000	32768,	22.390	16777216,	3.760
128,	13.390	65536,	21.510	33554432,	2.170
256,	12.310	131072,	20.270	67108864,	1.170

Two questions to answer

[20 points] Notice how the first pass with a stride of 1 takes longer then the second pass with a stride of 2. This behavior showed up consistently on Linux but not Windows. Please give a plausible explanation for what causes this phenomenon (it might be a mix of both hardware and software), and what the operating system can do to prevent it. You will need to justify your answer.

[20 points] Also notice how the time for each pass increases and then decreases as the stride values grow from 1 to 67108864. Both Windows and Linux exhibited this behavior. Please give a plausible explanation for this phenomenon (it might be a mix of both hardware and software), and what the operating system can do to prevent it. You will need to justify your answer.

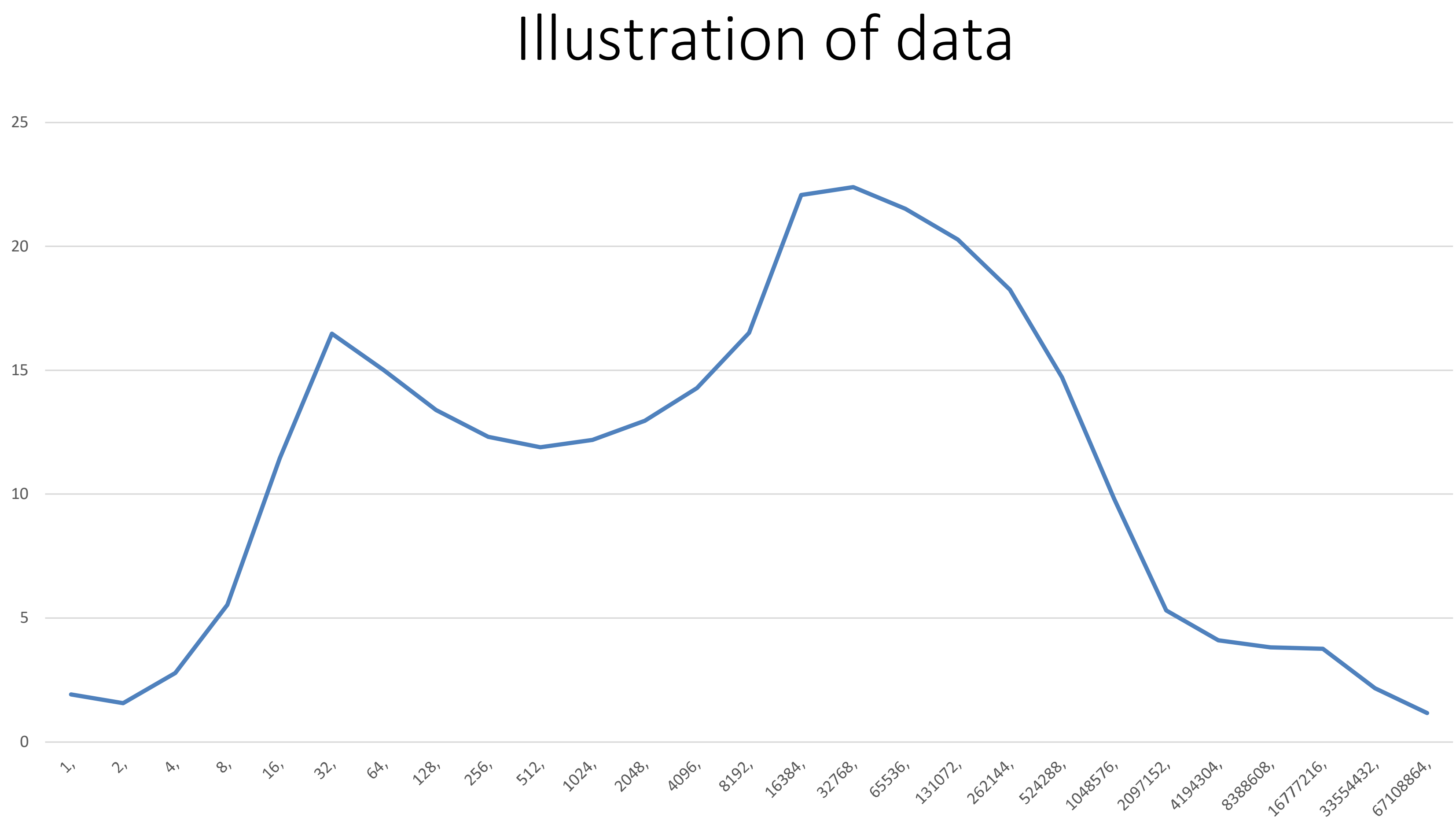


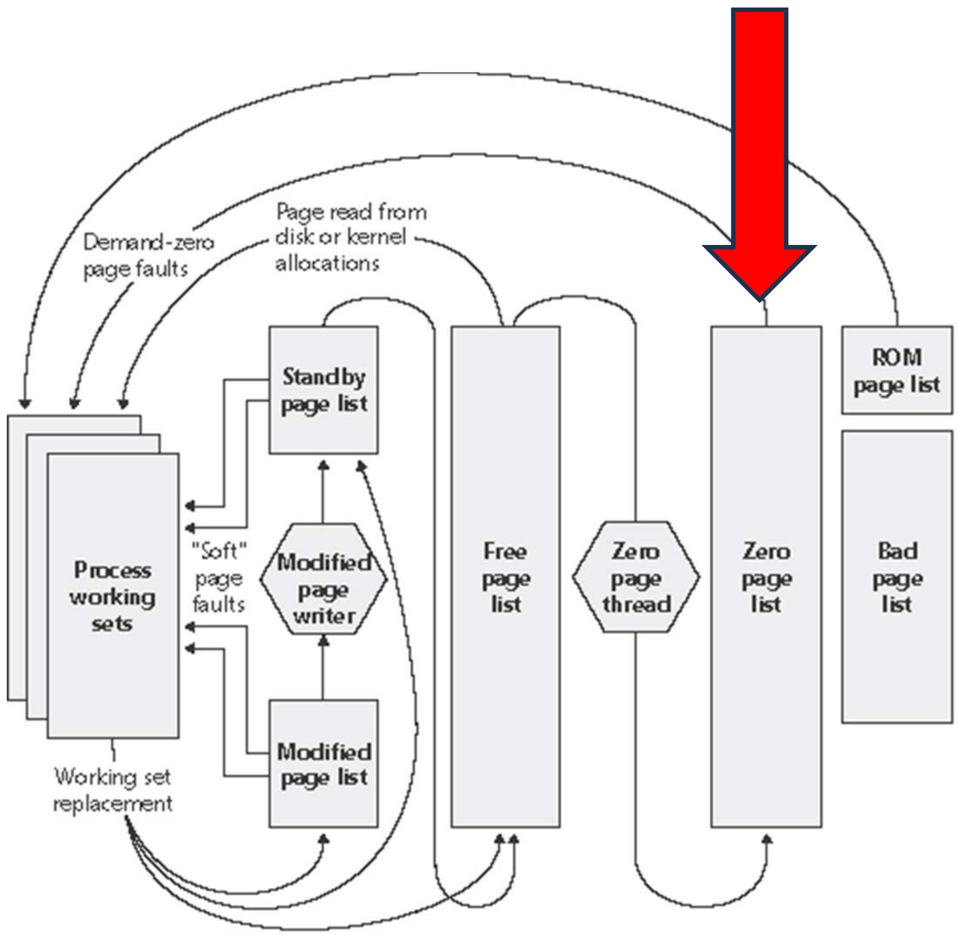
Illustration of data
25
20
15
10
5
0
1,
2,
4,
8,
16,
32,
64,
128,
256,
512,
1024,
2048,
4096,
8192,
16384,
32768,
65536,
131072,
262144,
524288,
1048576,
2097152,
4194304,
8388608,
16777216,
33554432,
67108864,

Things to consider

- Zero pages – for question 1
- TLB behavior – for question 2
- Various cache levels and Cache line sizes – for the question not asked about the big dip in the curve

Zero Pages

Zero Pages

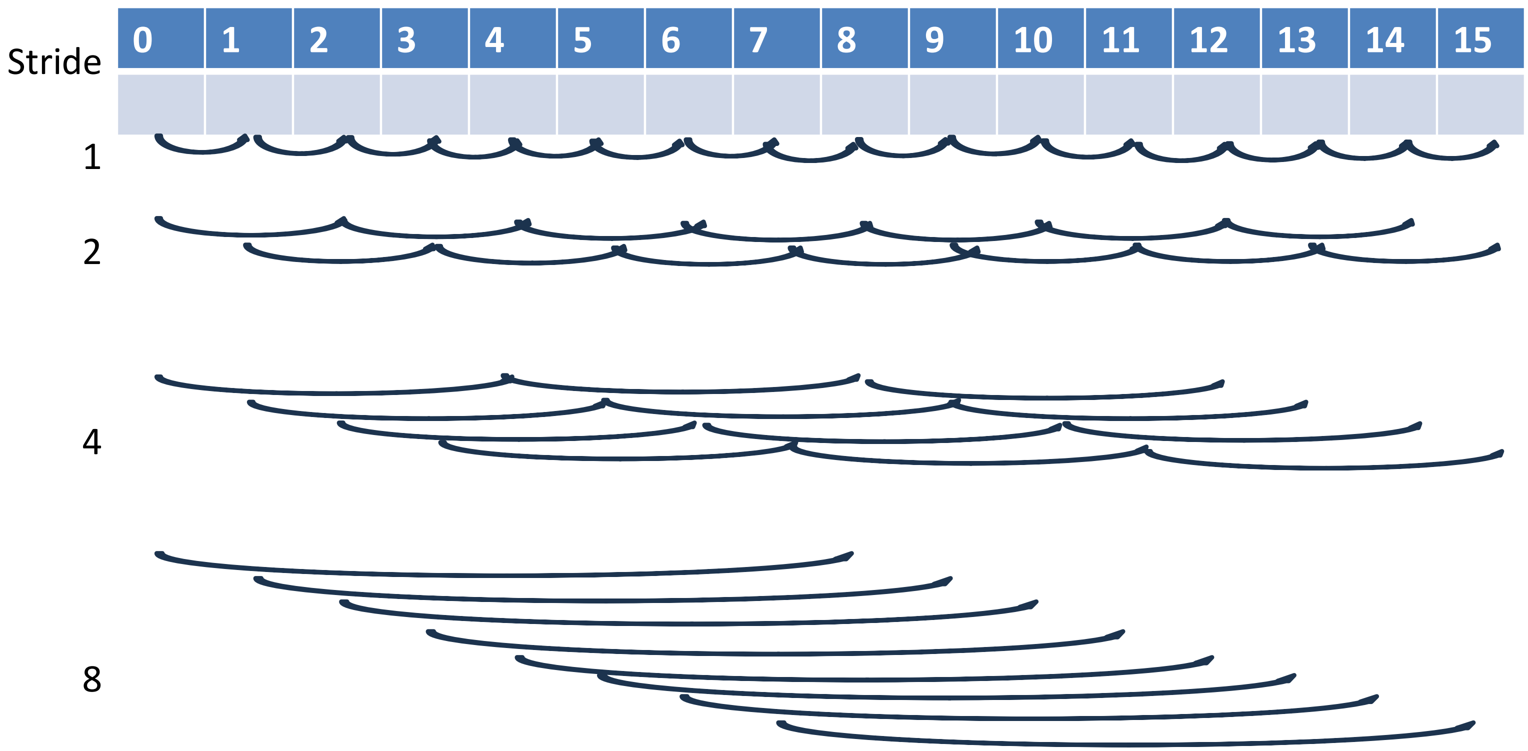

Demand-zero page faults
Page read from disk or kernel allocations
Standby page list
Process working sets
"Soft" page faults
Modified page writer
Modified page list
Working set replacement
Free page list
Zero page thread
Zero page list
ROM page list
Bad page list

TLB

TLB

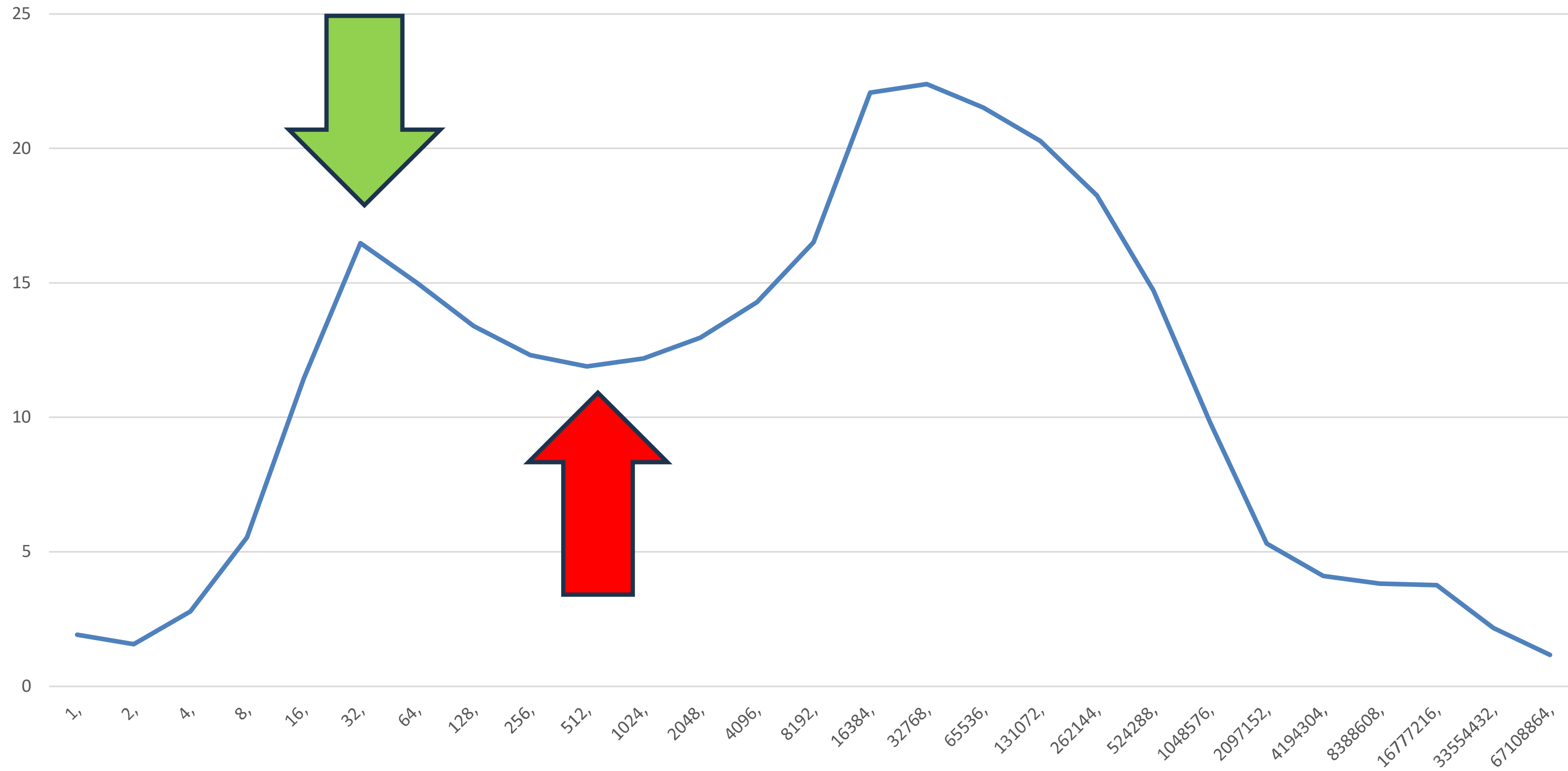
- Most Efficient TLB access: every lookup is a TLB hit
- Least Efficient TLB access: every lookup is a TLB miss

TLB



Cache Levels and Cache lines size

Cache Levels and Cache lines size



Are we having fun yet?

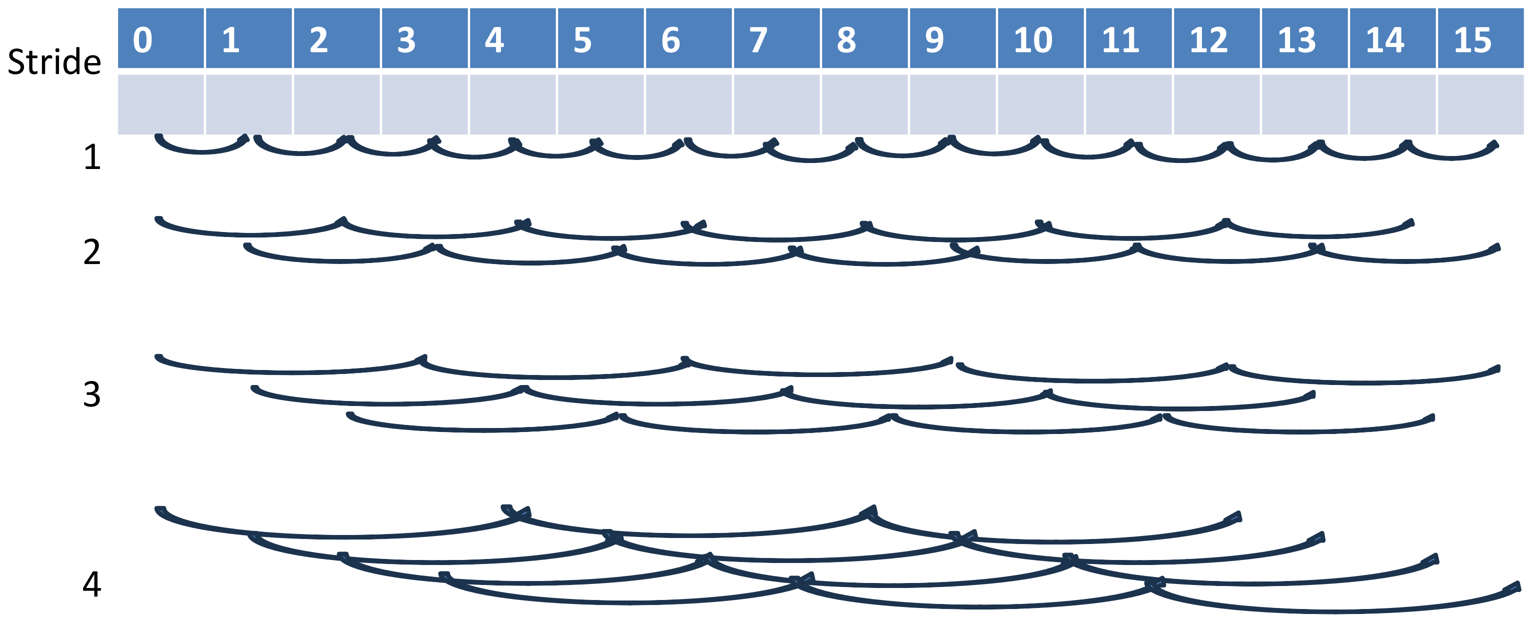
- Now for a more interesting slightly harder problem

Now consider the same program run with “64 1 1”. The entire output is too long to include here, but the following is a small section of the output that shows another anomaly that occurs on both Windows and Linux.

Size = 64MB

Stride	Seconds
700,	0.109
701,	0.140
702,	0.093
703,	0.109
704,	**0.530**
705,	0.109
706,	0.093
707,	0.109
708,	0.109
709,	0.109
710,	0.109
711,	0.109
712,	0.109
713,	0.109
714,	**0.202**
715,	0.109
716,	0.093
717,	0.109
718,	0.109
719,	0.093
720,	0.171
721,	0.093
722,	0.109
723,	0.109
724,	0.093
725,	0.109
726,	0.109
727,	0.109
728,	0.109
729,	0.109
730,	0.109
731,	0.093
732,	0.109
733,	0.109
734,	0.109
735,	0.109
736,	0.140
737,	0.093
738,	0.124
739,	0.093
740,	0.109
741,	**0.249**
742,	0.109
743,	0.109
744,	0.109
745,	0.171
746,	0.109
747,	0.109
748,	0.109
749,	**0.405**
750,	0.109
751,	0.093
752,	0.124
753,	0.109
754,	0.109
755,	0.093
756,	0.109
757,	0.109
758,	0.109
759,	0.109
760,	0.109
761,	0.109
762,	0.109
763,	0.109
764,	0.093
765,	**0.499**
766,	0.109
767,	0.109
768,	**0.748**
769,	0.109
770,	0.093
771,	0.124
772,	0.093
773,	0.109
774,	0.109
775,	0.109
776,	0.124
777,	0.093

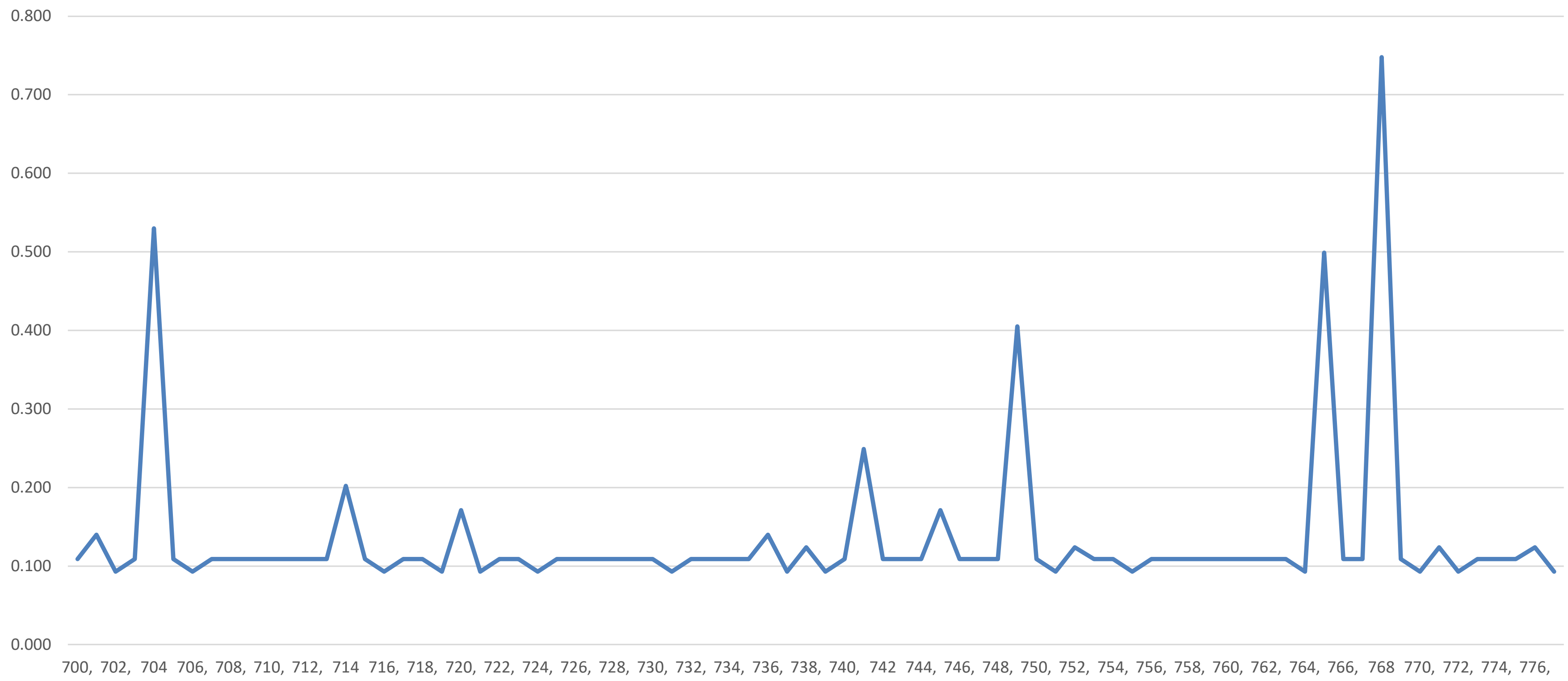
Increasing stride by 1 each time



Question to ponder

[20 points] Notice how the times are consistently in the low 100ms range except for an occasional blip in the 200ms to 700ms range. These blips have been underlined. Please offer an explanation for these blips. Your answer needs to offer a plausible explanation of what is causing this anomaly (it might be a mix of both hardware and software), and what the operating system can do to prevent it, if anything. You will need to justify your answer. If you do cannot offer an educated guess on what causes this phenomenon explain what you could do to determine its cause.

Graph of data



Things to consider

- Virtual and physical caches – doesn't answer the question, but good to know
- Page coloring – answers the question

Virtual and Physical caches

Virtual and Physical caches

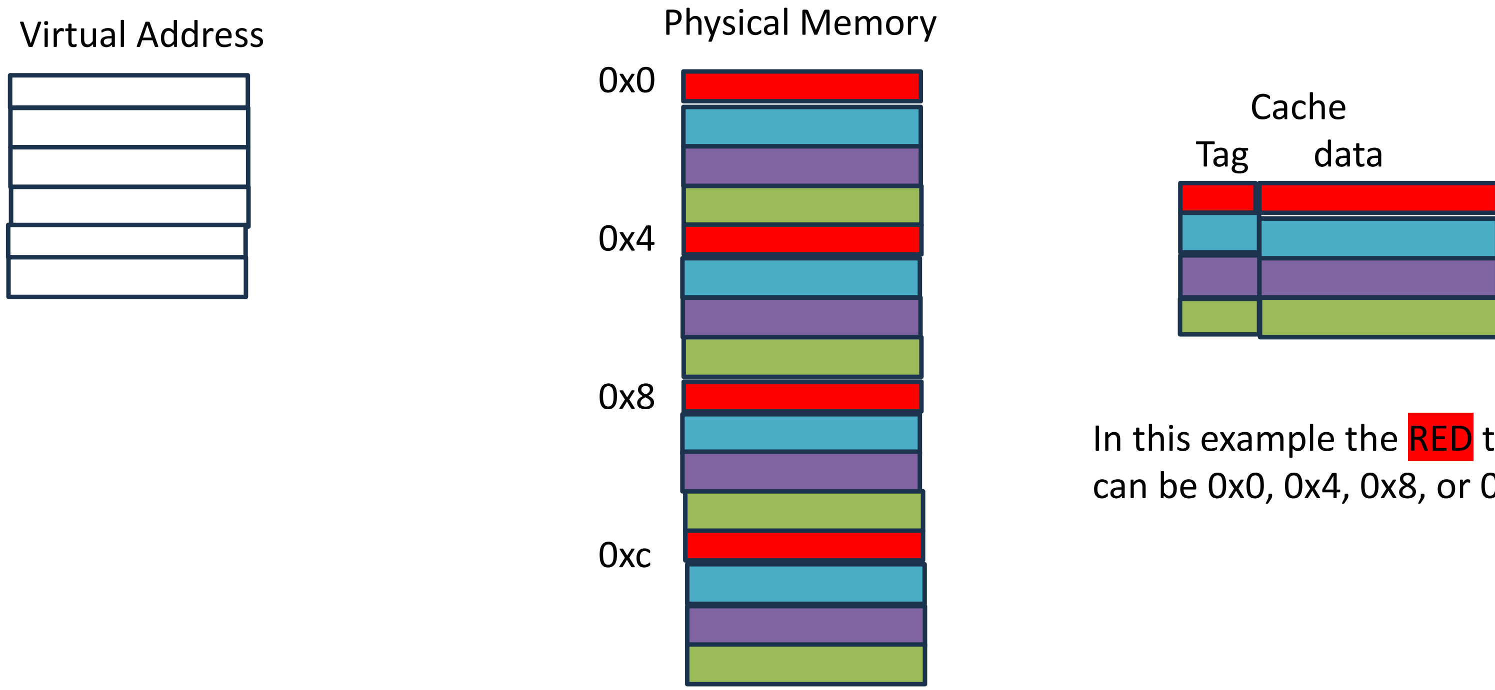
- Is the tag of a virtual or physical nature?
- For example, a virtual address or a physical address.
- Another example, a cache of data in a file or physical disk sectors.
- Different behavioral characteristics

Page Coloring

Page Coloring

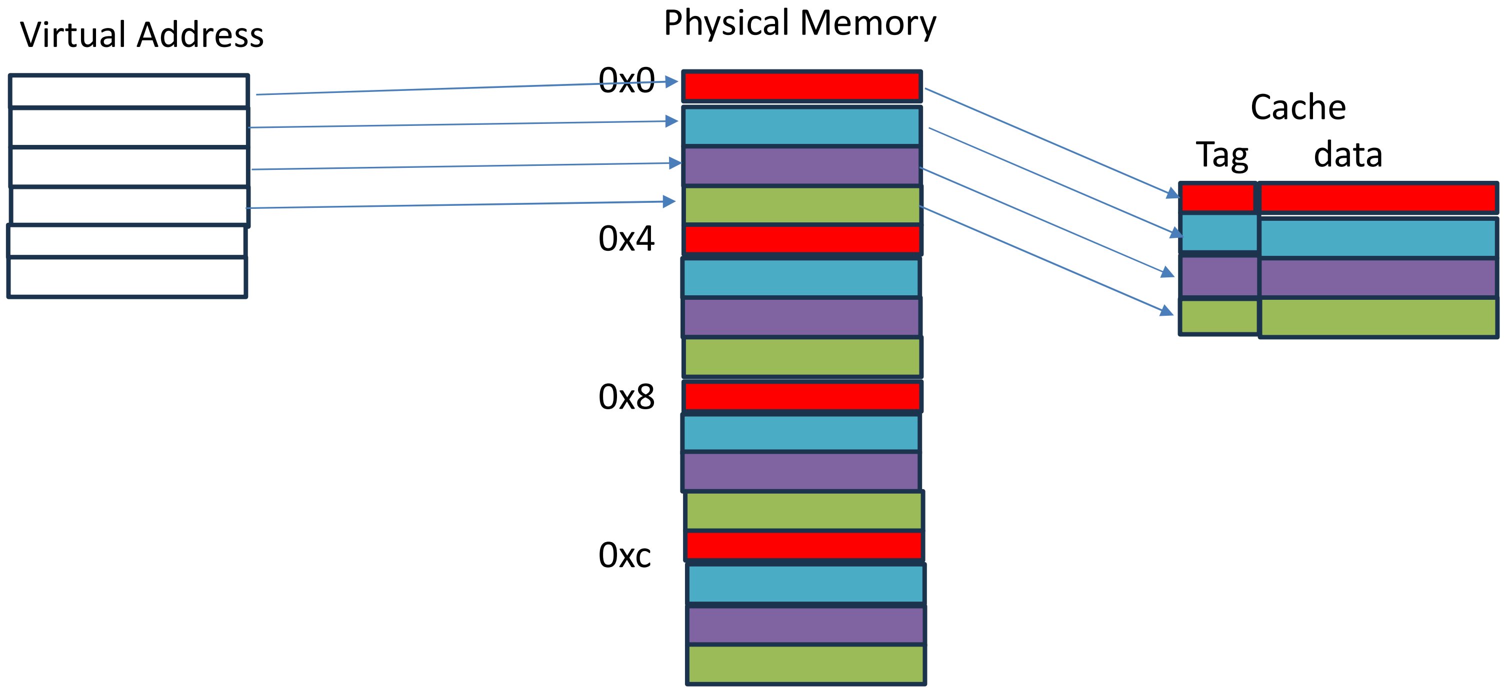
- Some caches are direct mapped
- For example, with a 1MB cache, physical address 0x0 maps to location 0 in the cache. So do locations 0x100000, 0x200000, 0x300000, etc
- One goal of MM is to spread out a process's virtual address to not map onto the same cache line
- For example, every page a process will not be mapped to frames that are mapped to the same cache line

Page Coloring

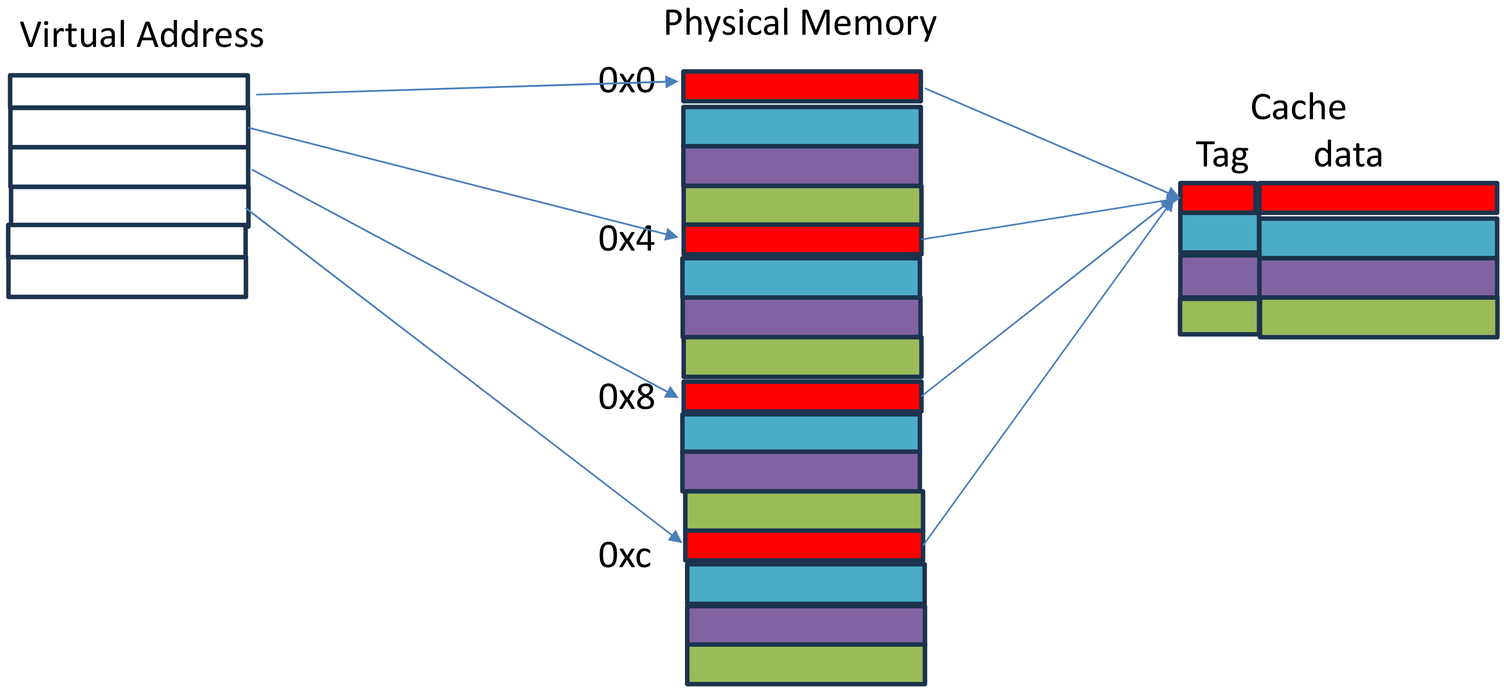


In this example the RED tag can be 0x0, 0x4, 0x8, or 0xc

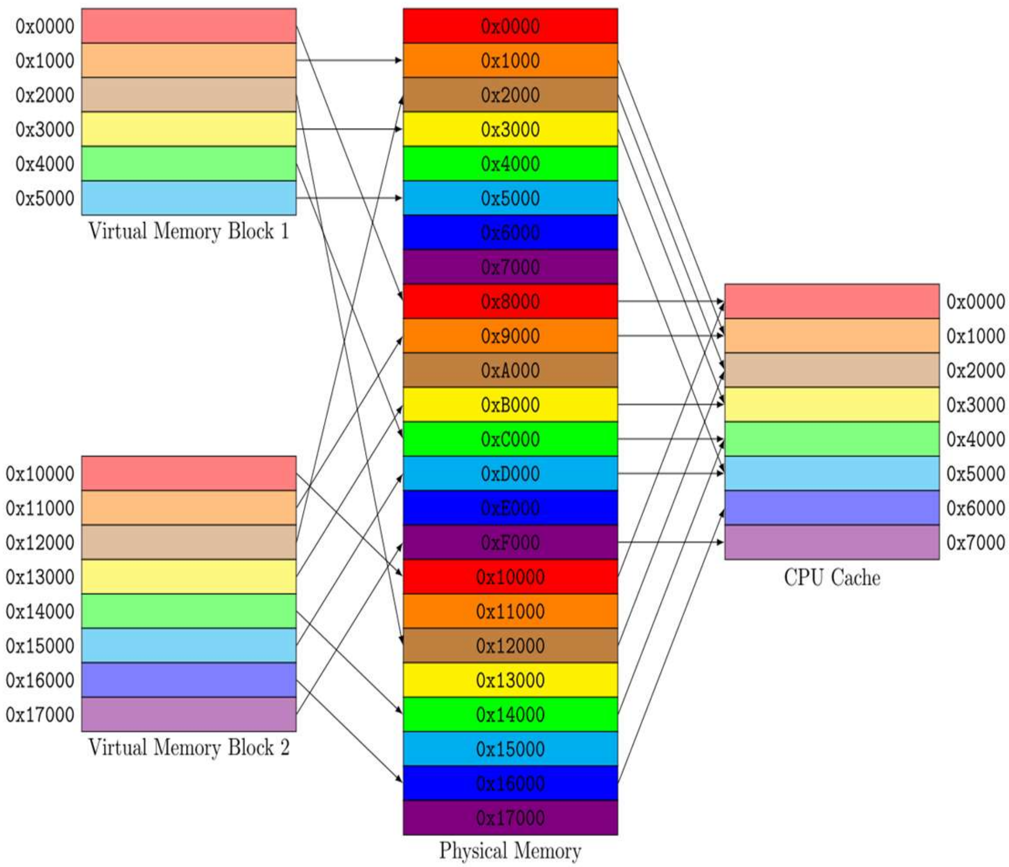
Page Coloring (good mapping)



Page Coloring (poor mapping)



Deeper dive into page coloring

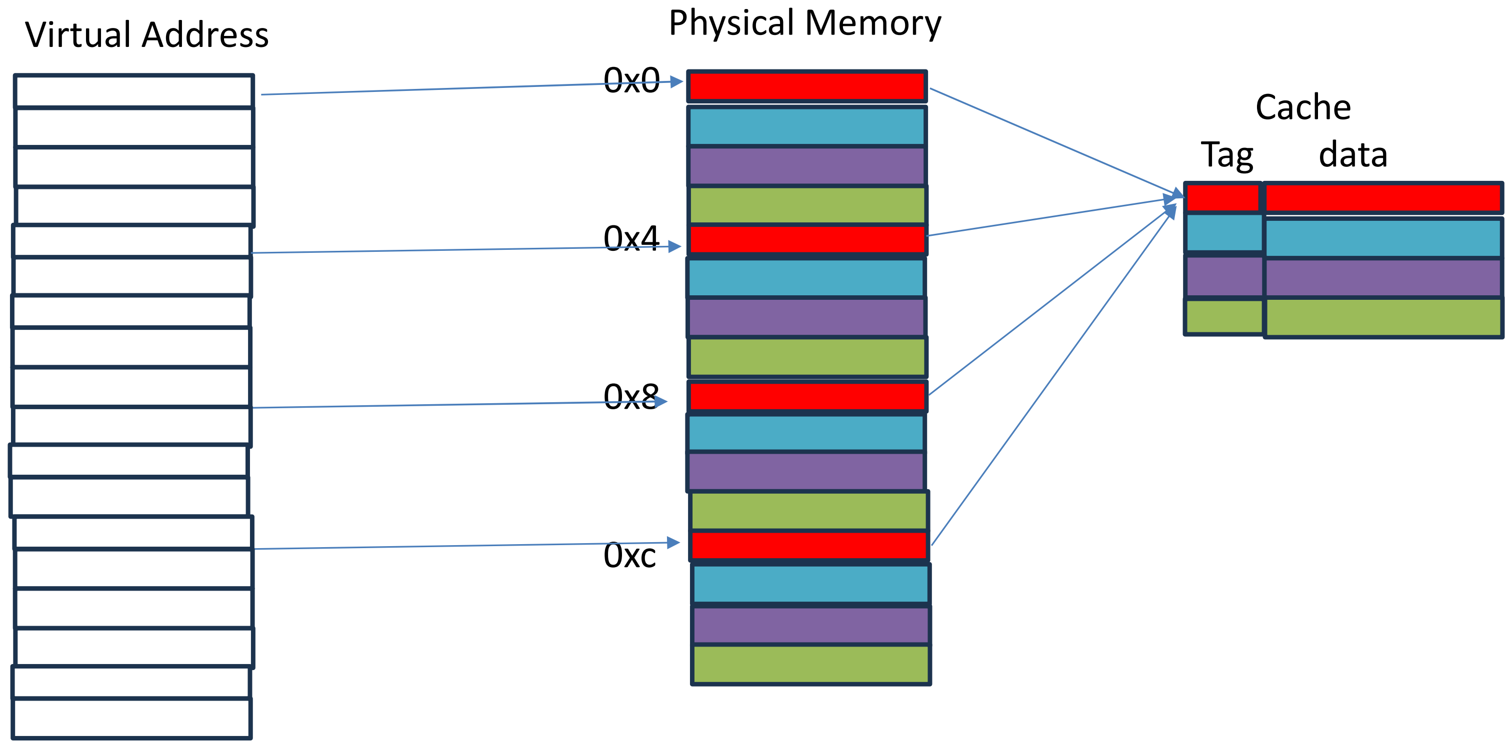


How does this answer the question?

- MM tries to make some assumptions about a program behavior when it assigns a process’s pages to physical frames

- However the program, as demonstrated here, can pick a pattern that is counter to that assignment

A “bad” stride can defeat even a good mapping



Final comment

- “Caches work great, except when they don’t.”