CSE 451: Operating Systems
Winter 2024

Module 14
Windows MM

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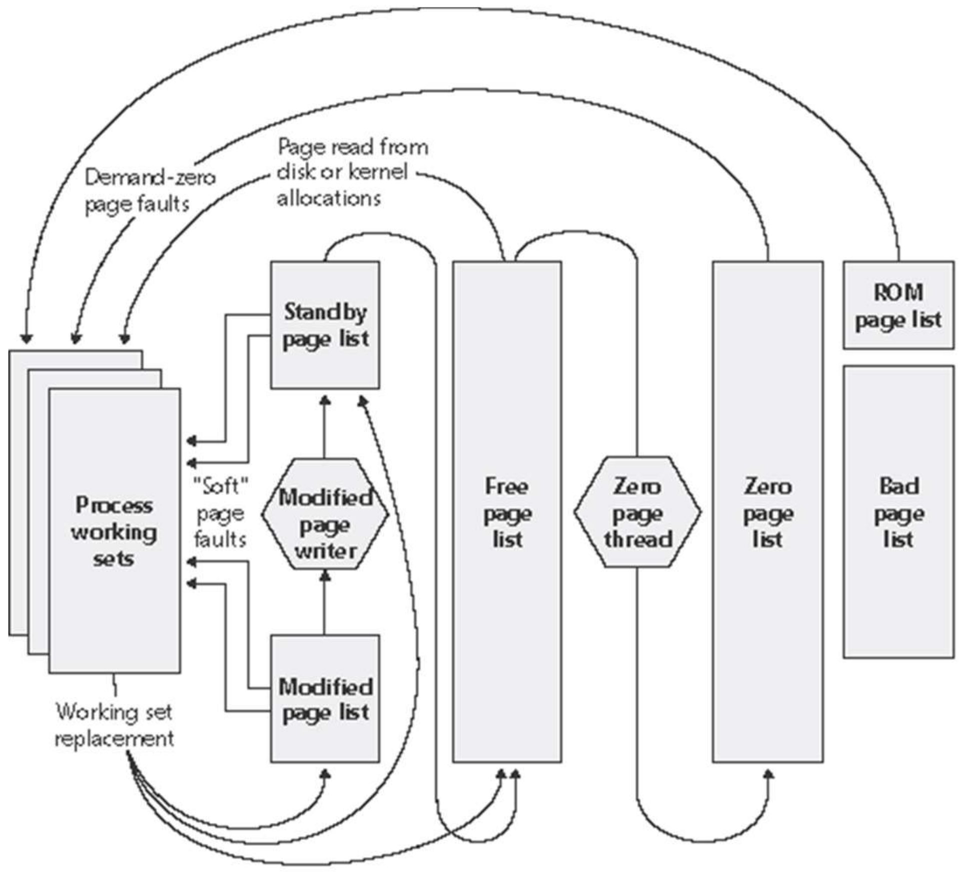
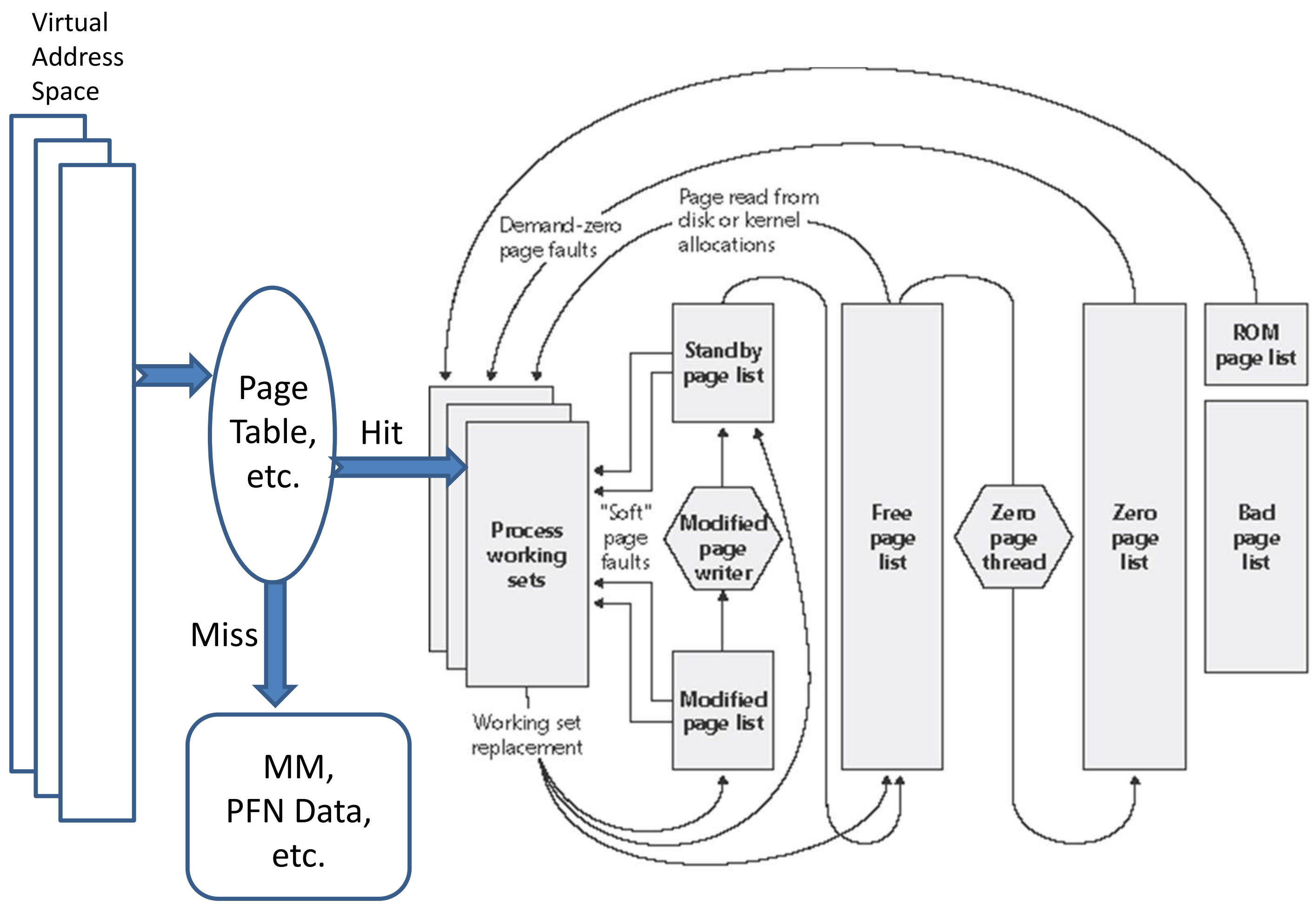
Memory Management (continued)

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

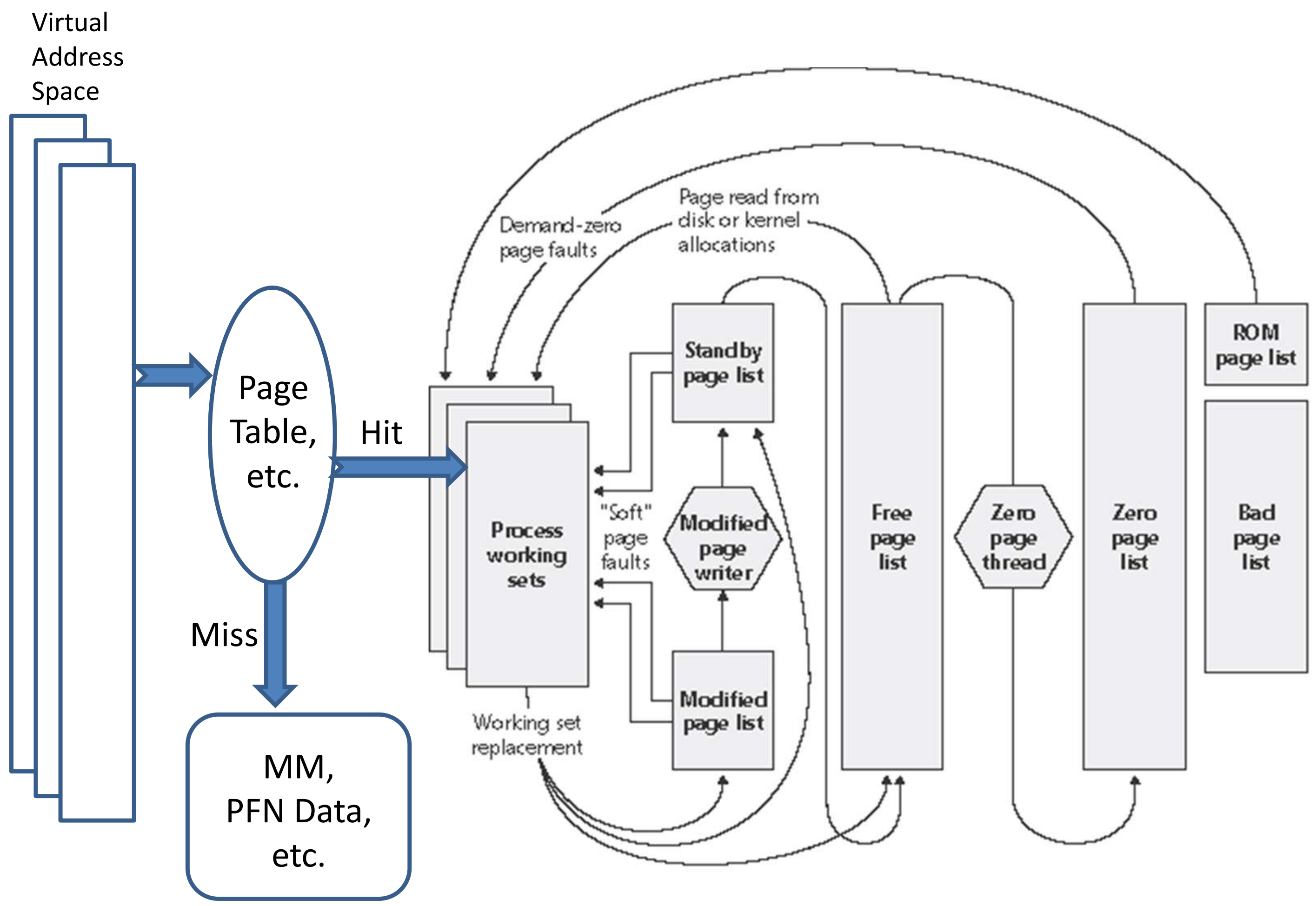
Windows Page Frame State Diagram



Windows Page Frame State Diagram



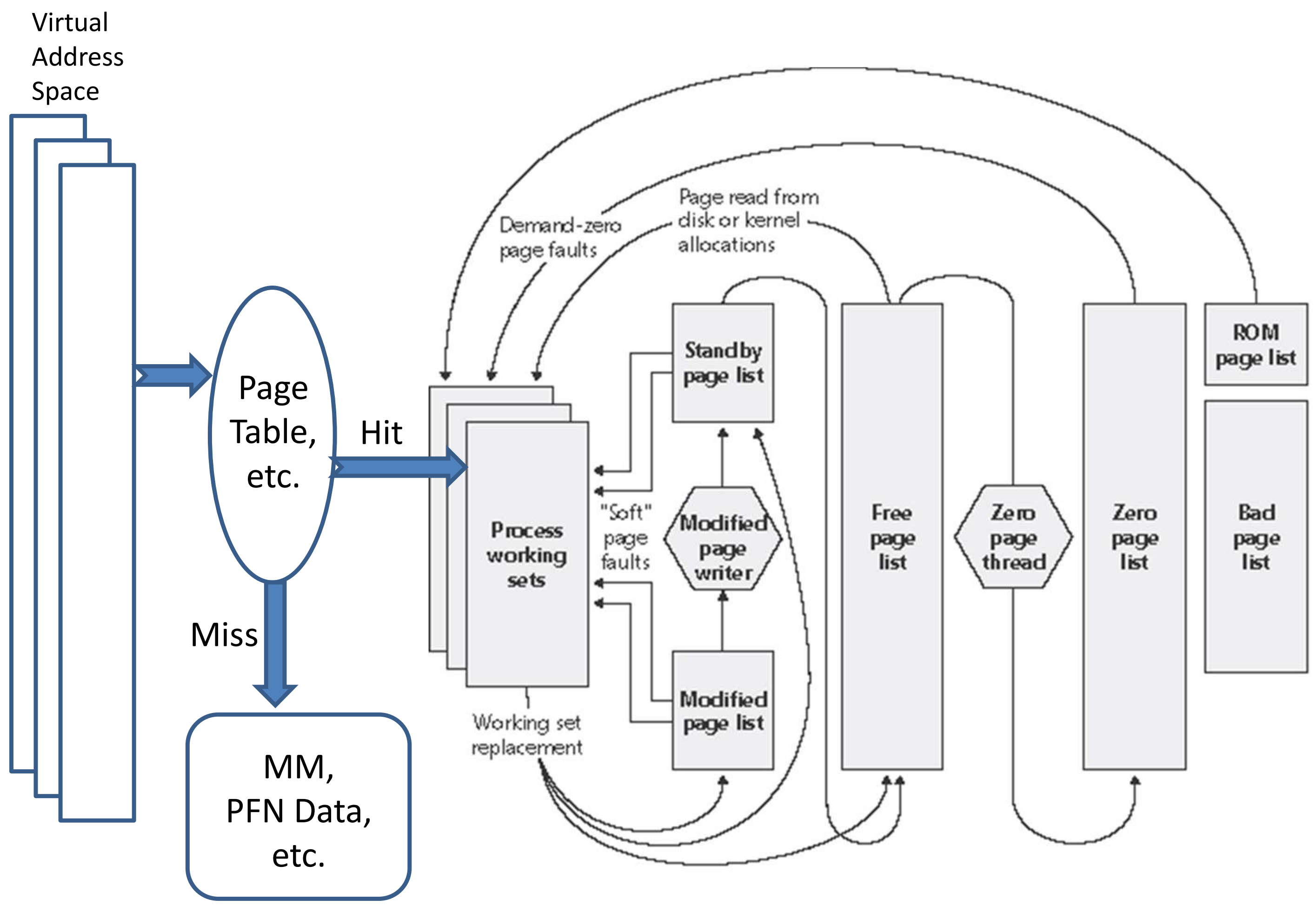
Windows Page Frame State Diagram



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.

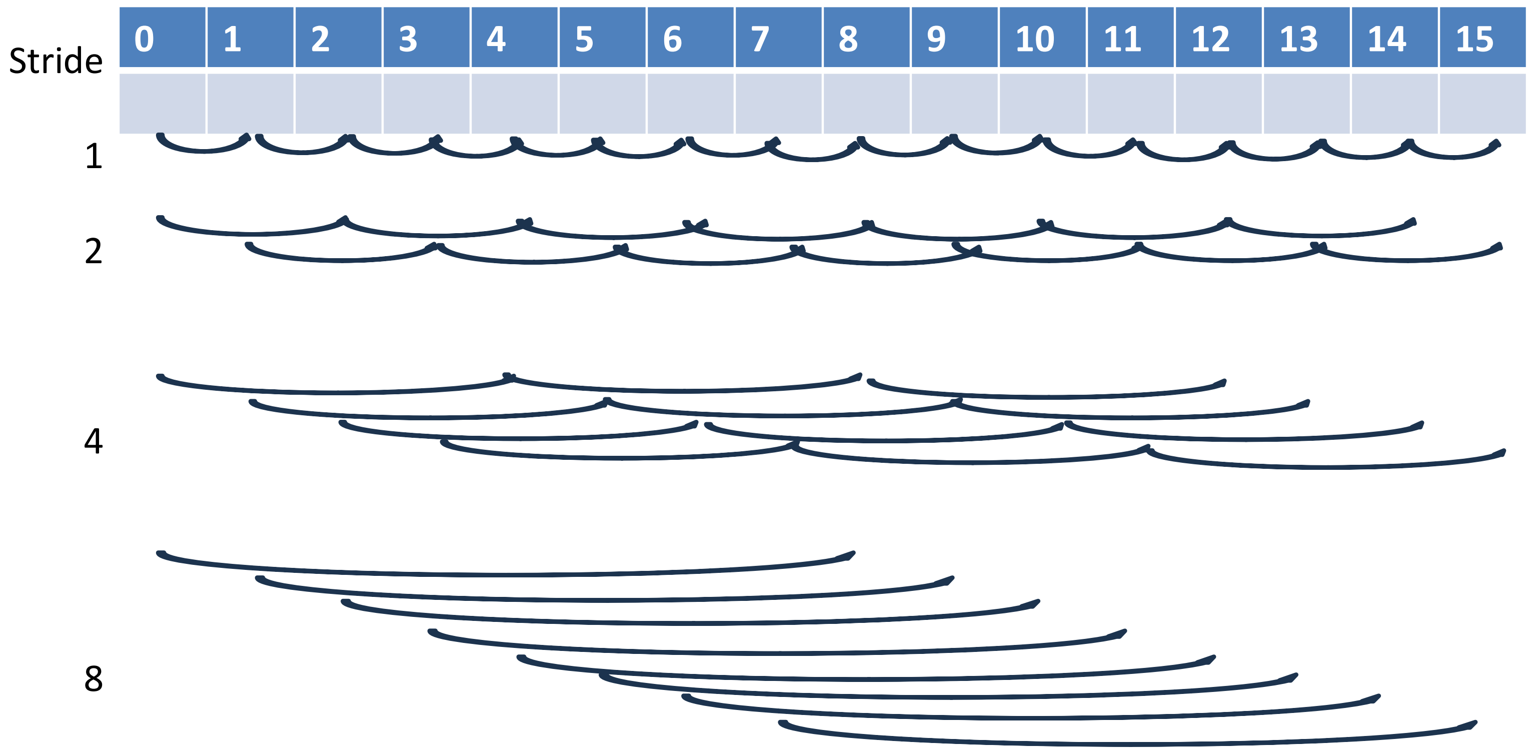
For example a stride of 1 makes one pass through the array accessing locations 0,1,2,… until the end of the array is reached. A stride of 2 makes two passes through the array, first accessing locations 0,2,4,… and then accessing locations 1,3,5,… until the end of the array is reached. The program starts 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.

```
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

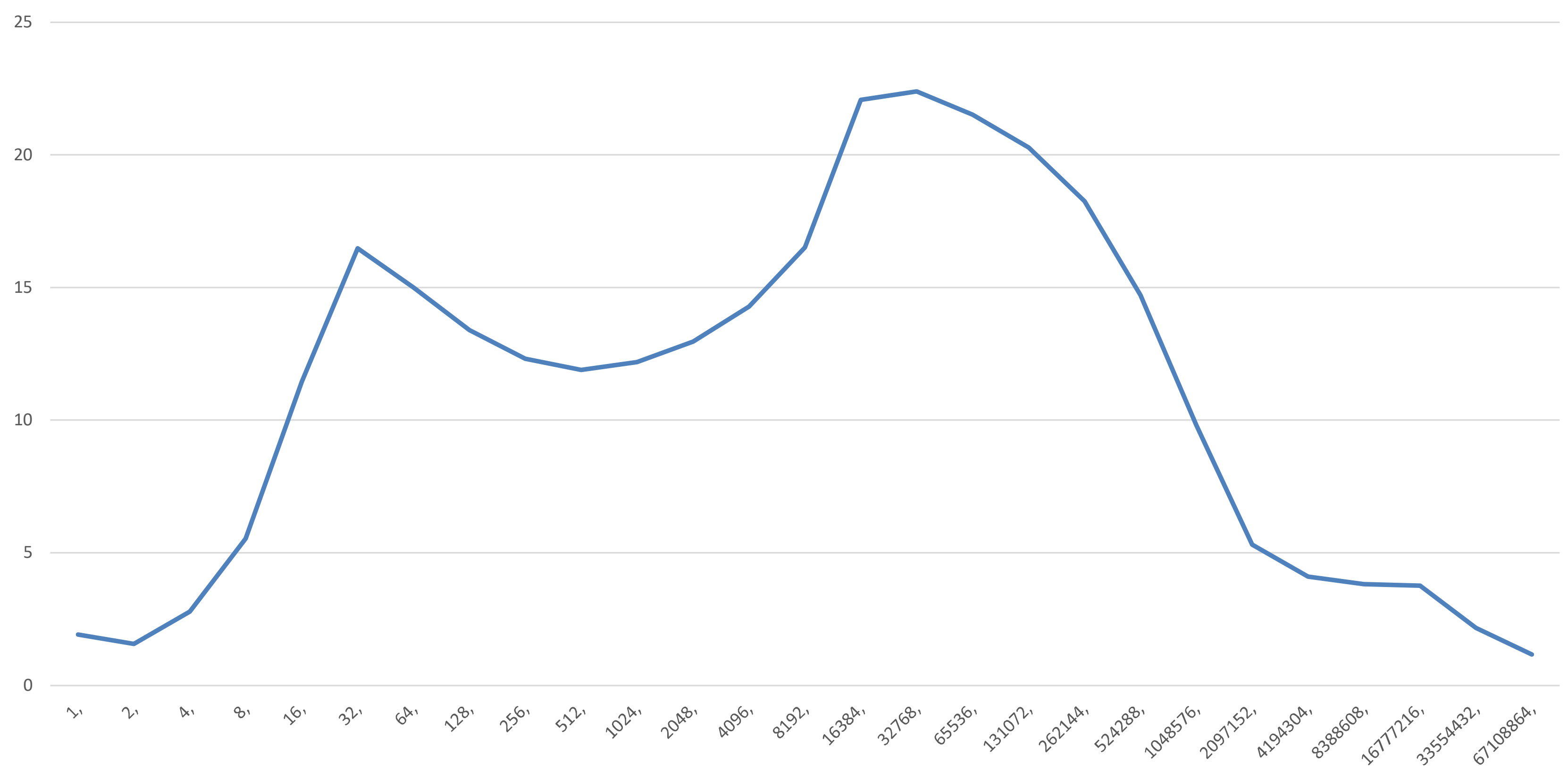
Stride	Seconds	Stride	Seconds	Stride	Seconds
1,	1.920	512,	11.890	262144,	18.250
2,	1.560	1024,	12.190	524288,	14.710
4,	2.780	2048,	12.960	1048576,	9.810
8,	5.530	4096,	14.280	2097152,	5.310
16,	11.450	8192,	16.510	4194304,	4.100
32,	16.470	16384,	22.070	8388608,	3.820
64,	15.000	32768,	22.390	16777216,	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



Things to consider

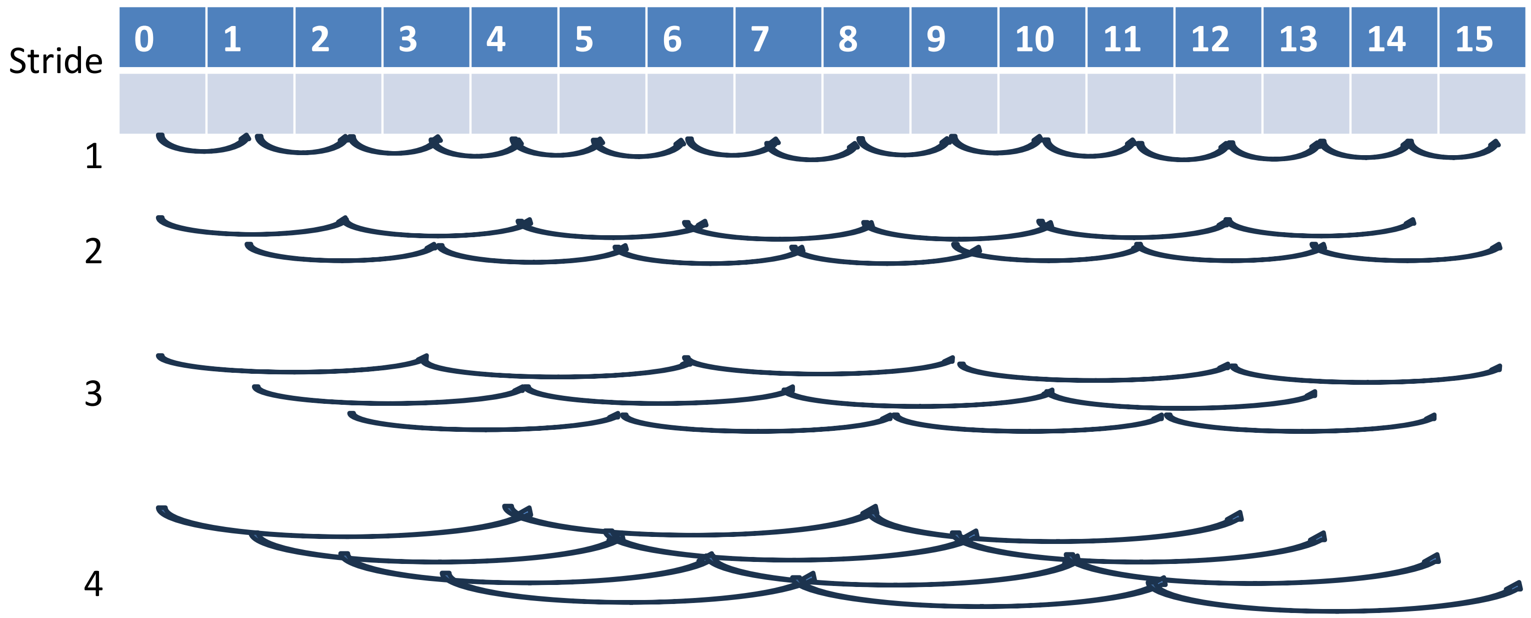
- Zero pages – for question 1
- TLB behavior – for question 2
- Various cache levels and Cache line sizes – for the question not asked about the big dip in the curve

Zero Pages

TLB

Cache Levels and Cache lines size

Increasing stride by 1 each time



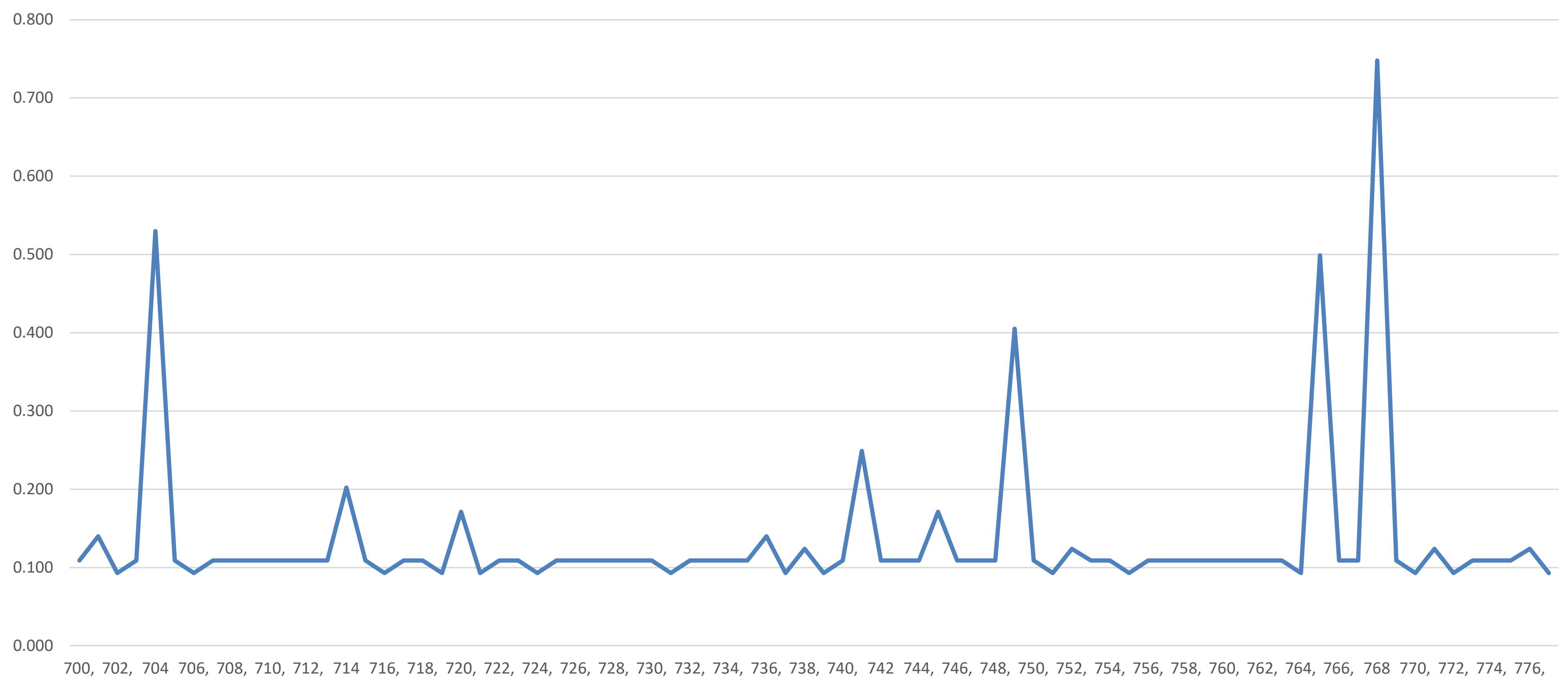
Now consider the same program run with “64 1 1”. The entire output is too long to include here, but the following is a small section of the output that shows another anomaly that occurs on both Windows and Linux.

```
                              Size = 64MB
Stride      Seconds         Stride    Seconds         Stride      Seconds
   700,       0.109            726,     0.109            752,       0.124
   701,       0.140            727,     0.109            753,       0.109
   702,       0.093            728,     0.109            754,       0.109
   703,       0.109            729,     0.109            755,       0.093
  704,       0.530             730,     0.109            756,       0.109
   705,       0.109            731,     0.093            757,       0.109
   706,       0.093            732,     0.109            758,       0.109
   707,       0.109            733,     0.109            759,       0.109
   708,       0.109            734,     0.109            760,       0.109
   709,       0.109            735,     0.109            761,       0.109
   710,       0.109            736,     0.140            762,       0.109
   711,       0.109            737,     0.093            763,       0.109
   712,       0.109            738,     0.124            764,       0.093
   713,       0.109            739,     0.093           765,       0.499
  714,       0.202             740,     0.109            766,       0.109
   715,       0.109           741,     0.249            767,      0.109
   716,       0.093           742,      0.109           768,       0.748
   717,       0.109            743,     0.109            769,       0.109
   718,       0.109            744,     0.109            770,       0.093
   719,       0.093            745,     0.171            771,       0.124
   720,       0.171            746,     0.109            772,       0.093
   721,       0.093            747,     0.109            773,       0.109
   722,       0.109            748,     0.109            774,       0.109
   723,       0.109           749,     0.405             775,       0.109
   724,       0.093            750,     0.109            776,       0.124
   725,       0.109            751,     0.093            777,       0.093
```

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

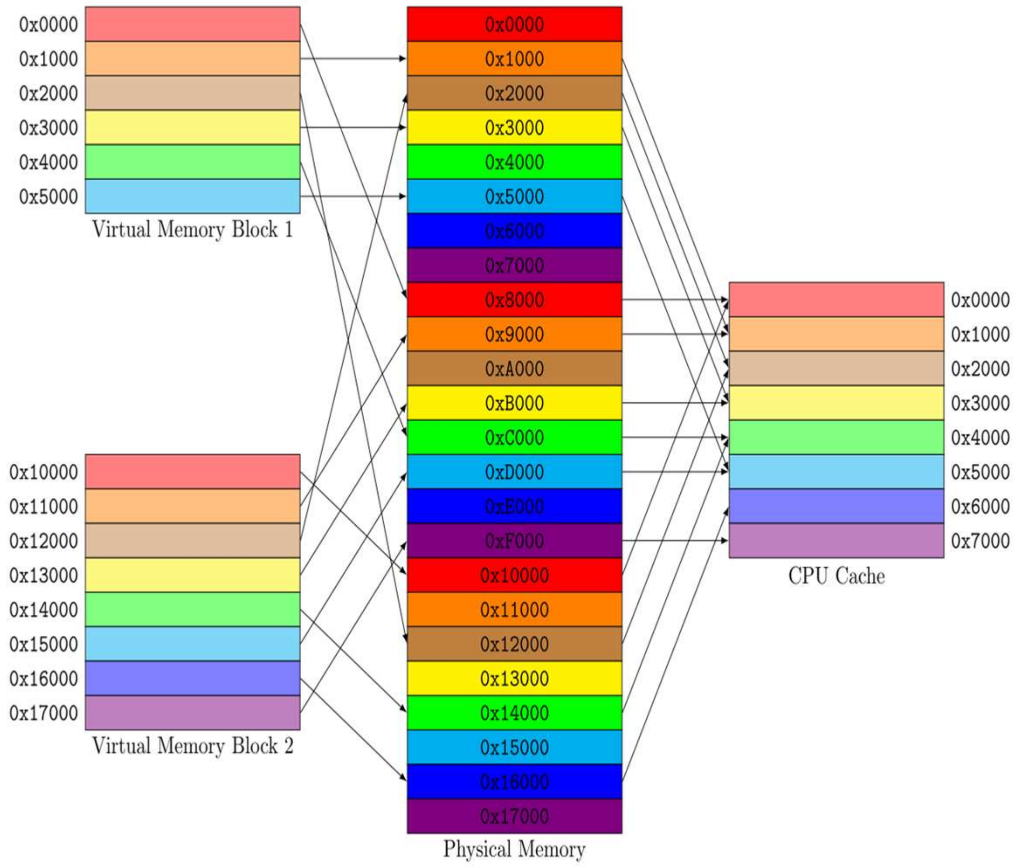
Virtual and Physical caches

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

Deeper dive into page coloring



Final comment

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