/INFOMOV/

Optimization & Vectorization

J. Bikker - Sep-Nov 2019 - Lecture 7: “Data-Oriented Design”

Welcome!

Today’s Agenda:

- OOP Performance Pitfalls
- DOD Concepts
- DOD or OO?

Fact Checking

"Floating point code is (typically) undeterministic"

```
float v0 = 1;
float v1 = 1;
float v2 = 1;
float v3 = 1;
float v4 = 1;
float v5 = 1;
float v6 = 1;
float v7 = 1;
for (int i = 0; i < 2000000; i++)
{
   v0 *= 1.00001f;
   v1 *= 1.00001f;
   v2 *= 1.00001f;
   v3 *= 1.00001f;
   v4 *= 1.00001f;
   v5 *= 1.00001f;
   v6 *= 1.00001f;
   v7 *= 1.00001f;
}
```

```
fld1
fld st(0)
fld st(1)
fld st(2)
fld st(3)
fld st(4)
fld st(5)
fld st(6)

fmul st(7),st ; fxch st(7) ; fstp [v0]
fxch st(5) ; fmul st,st(6)
fxch st(4) ; fmul st,st(6)
fxch st(3) ; fmul st,st(6)
fxch st(2) ; fmul st,st(6)
fxch st(1) ; fmul st,st(6)
fxch st(5) ; fmul st,st(6)
fld [v7] fmul st,st(7) fstp [v7]
```

Fact Checking

"Doubles are slower than floats (4x)"

This statement is **mostly true**. The real story, CPU (win32, x64):

- A `float` takes 32-bit in memory, but gets promoted to 80 bits in an FPU register.
- A `double` takes 64-bit in memory, but gets promoted to 80 bits in an FPU register.
- A `long double` takes 64-bit in memory, but gets promoted to 80 bits in an FPU register.

Calculation time on 80-bit FPU registers does not depend on the source of the data.
HOWEVER: the fp registers are rarely used anymore…

The real story, GPU (Nvidia, AMD): https://www.geeks3d.com/20140305/amd-radeon-and-nvidia-geforce-fp32-fp64-gflops-table-computing

- Titan V: FP64 = 1/2 * FP32 (6900 vs 13800 GFLOPS)
- Titan X Pascal: FP64 = 1/32 * FP32 (350 vs 11300 GFLOPS) (same for all 10xx)
- Radeon RX Vega 64: FP64 = 1/16 * FP32 (790 vs 12700 GFLOPS)
- Radeon HD 7990: FP64 = 1/4 * FP32 (1946 vs 7782)

FP16 (GPU only): https://www.anandtech.com/show/10325/the-nvidia-geforce-gtx-1080-and-1070-founders-edition-review/5

- GTX 1080Ti: FP16 = 1/64 * FP32 (ouch)
- Radeon RX Vega 64: FP16 = 2 * FP32 (!)

Today’s Agenda:

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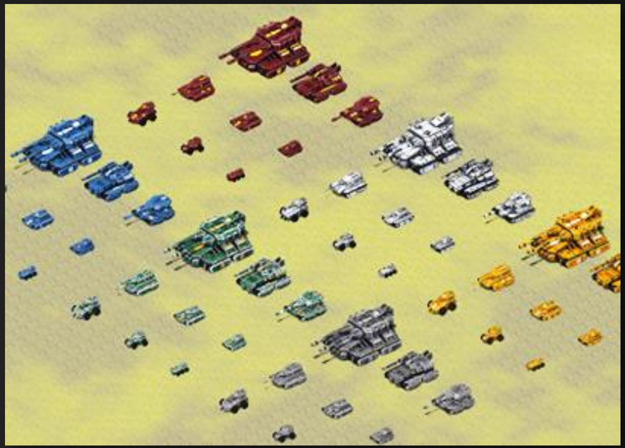
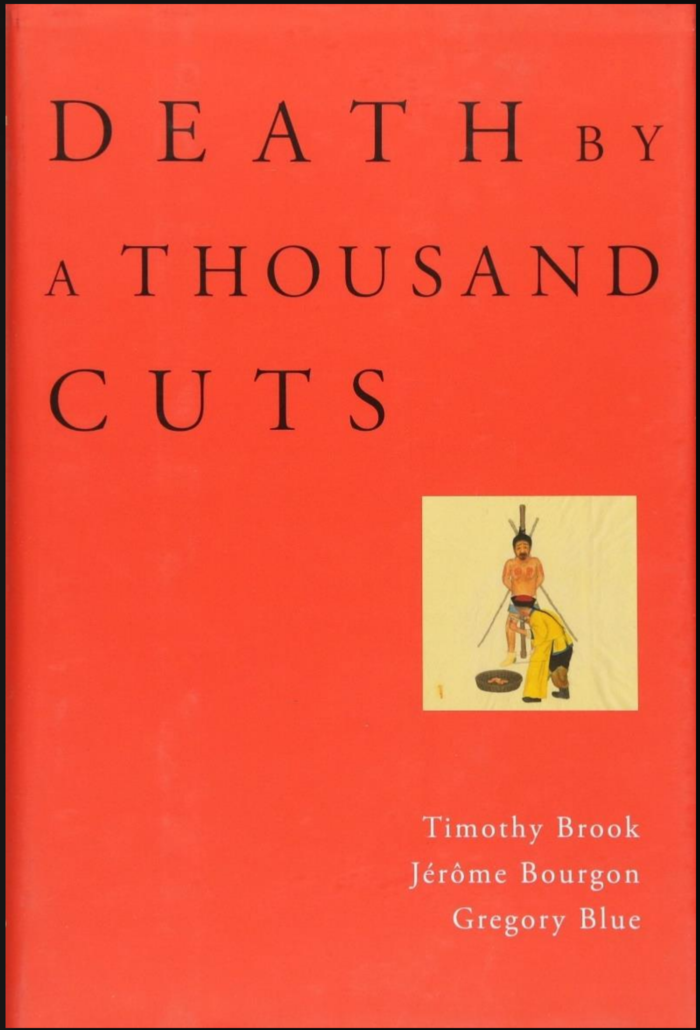
OOP

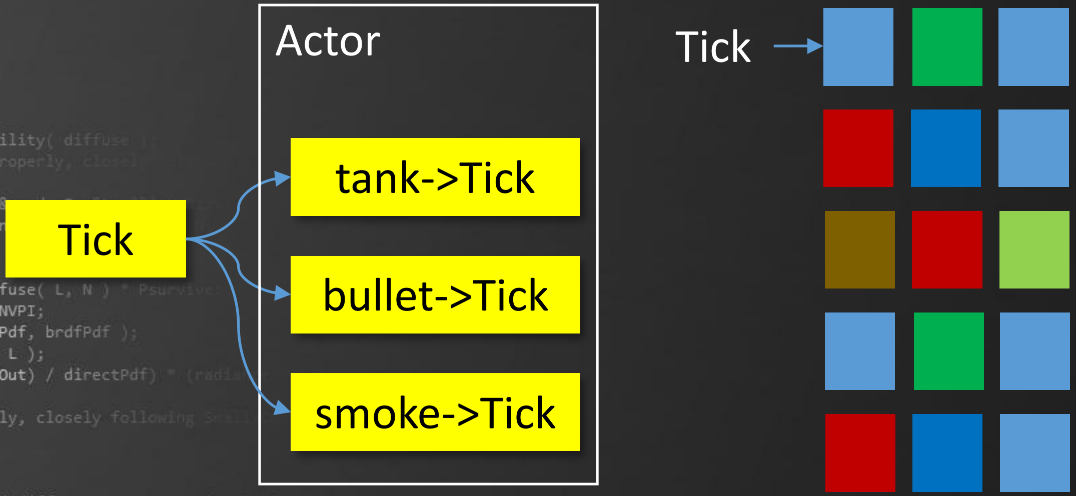
“Death by a Thousand Cuts”

Object Oriented Programming:

- Objects
  - Data
  - Methods
  - Instances





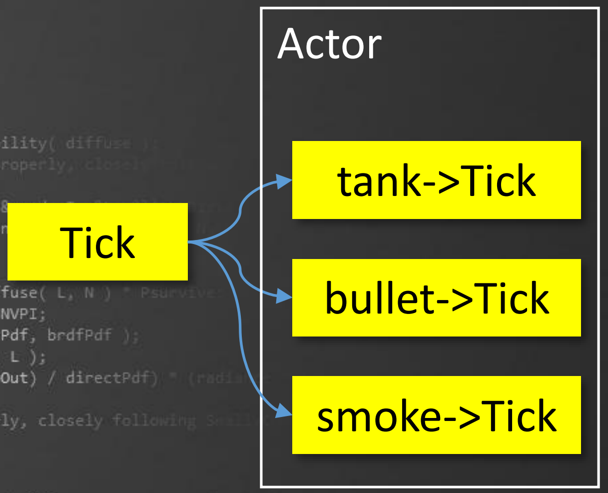


OOP

"Death by a Thousand Cuts"

Object Oriented Programming:

- Objects
  - Data
  - Methods
  - Instances



Cost of a virtual function call:

1. Virtual Function Table
2. No inlining

…

Calling such a function:

1. Read pointer to VFT of base class — cache miss
2. Add function offset
3. Read function address from VFT — cache miss
4. Load address in PC (jump) — branch

But, that isn't realistic, right?

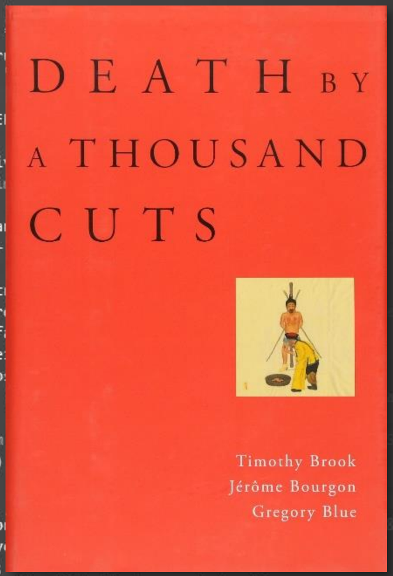
It is, if we use OO for what it was designed for: operating on heterogeneous objects.

OOP

"Death by a Thousand Cuts"

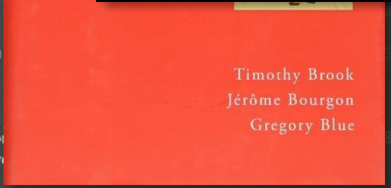
Characteristics of OO:

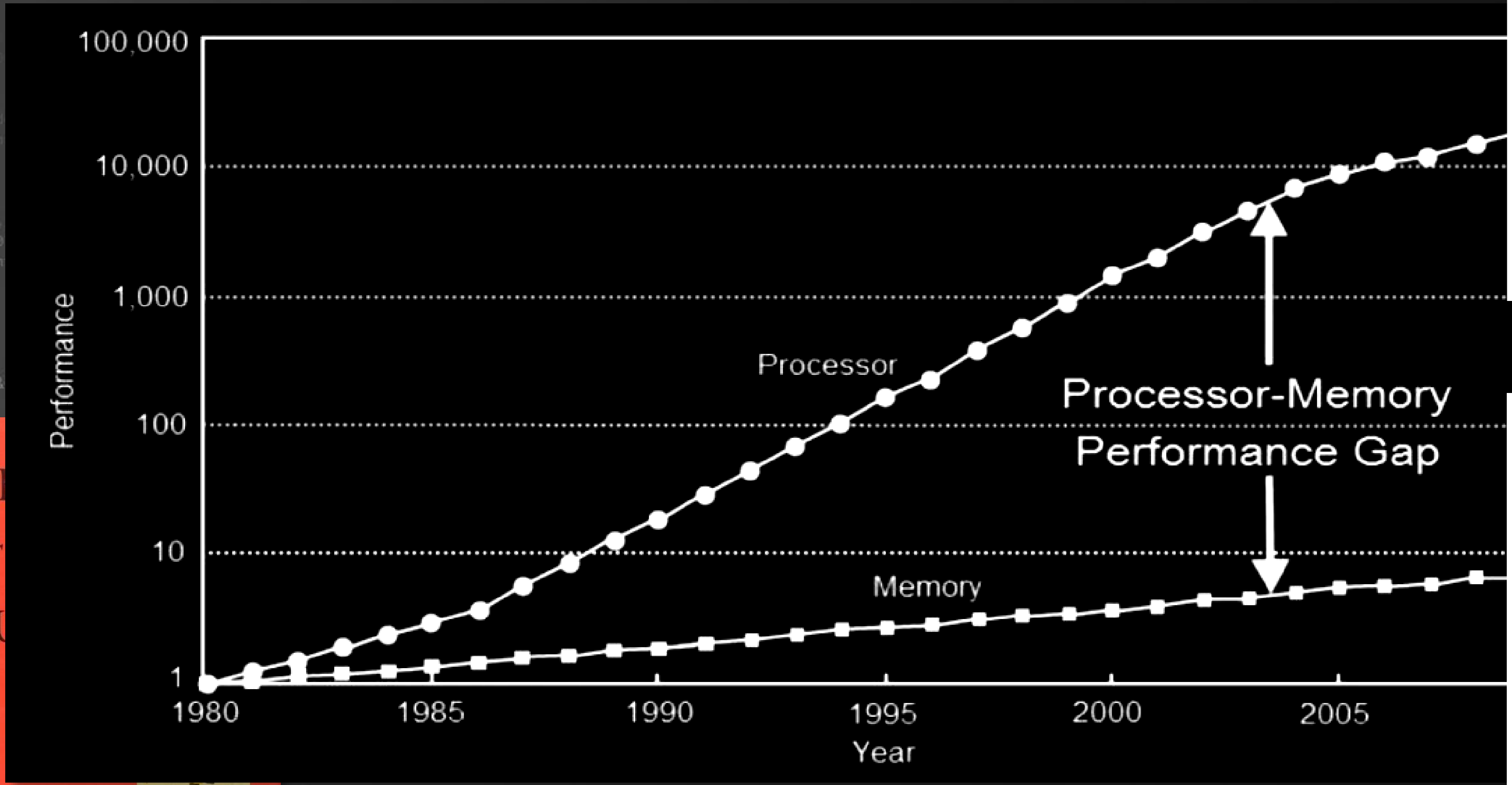
- Virtual calls
- Scattered individual objects



OOP

“Death by a Thousand Cuts”





Reading memory: 40 cycles @ 300Mhz

Reading memory: 600 cycles @ 3.2Ghz

The problem is growing with time.

OOP

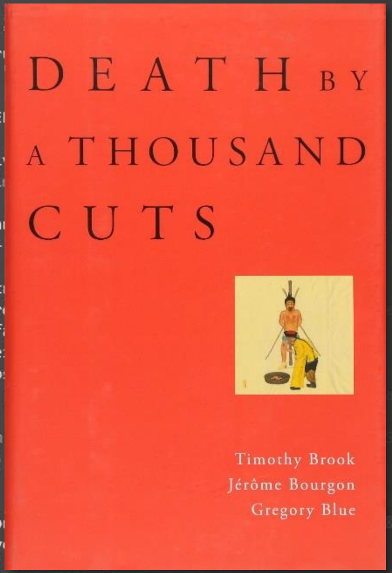
"Death by a Thousand Cuts"

Dealing with "bandwidth starvation":

Caching

Continuous memory access (full cache lines)

Large array continuous memory access



(caches 'read ahead')

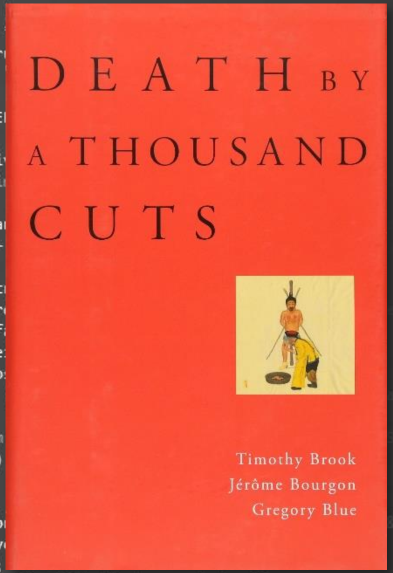
OOP

"Death by a Thousand Cuts"

Code performance is typically bound by memory access.

"The ideal data is in a format that we can use with the least amount of effort."

➔ Effort = CPU-effort.



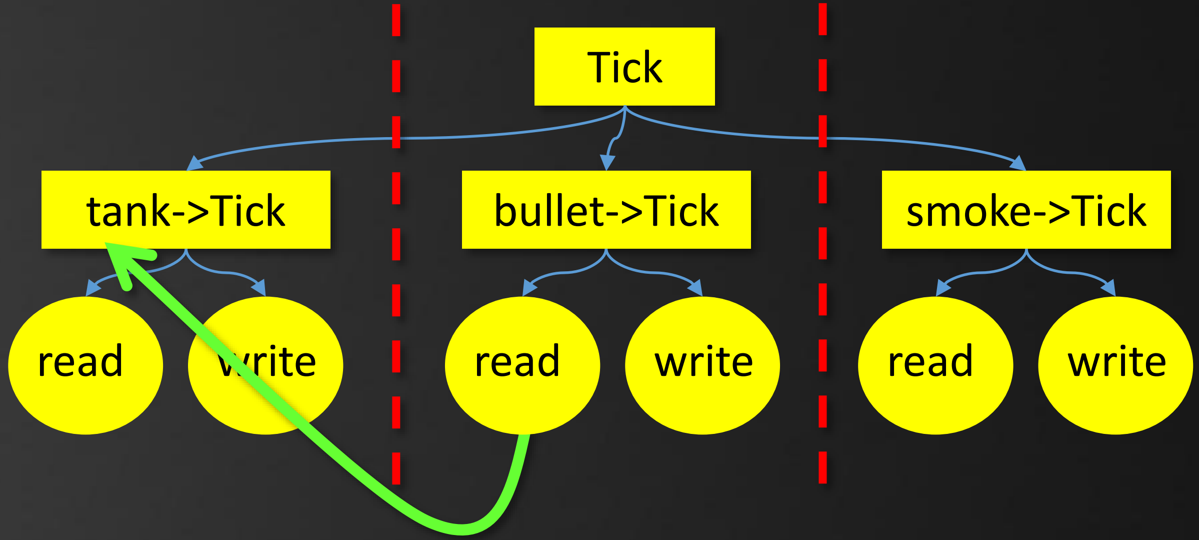
"Most programs are made faster if we improve their memory access patterns."
(this will be more true every year)

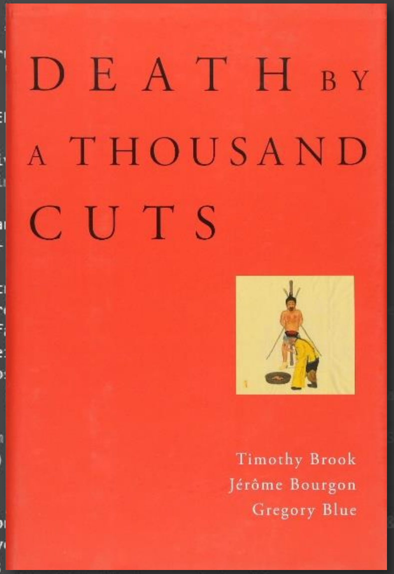
"You cannot be fast without knowing how data is touched."

OOP

“Death by a Thousand Cuts”

Parallel processing typically requires synchronization.



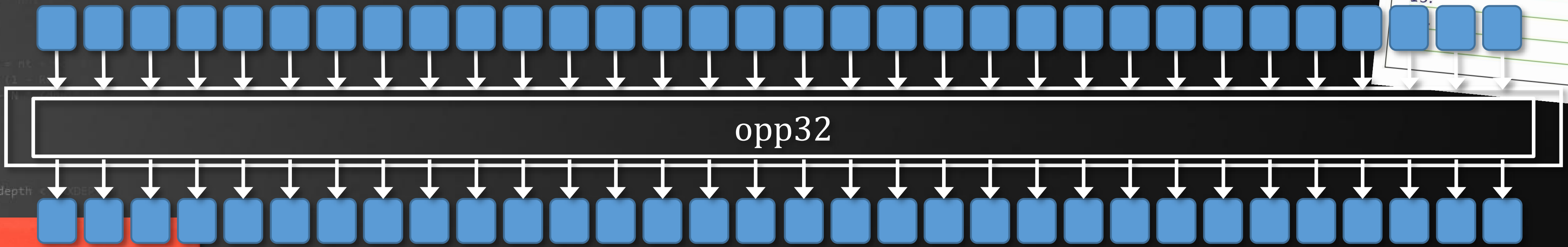


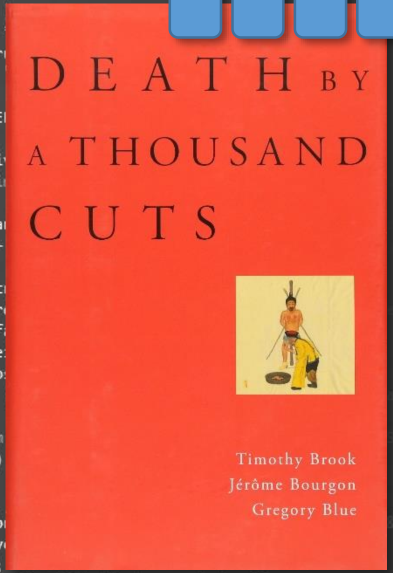
*“You cannot **multi-thread** without knowing how data is touched.”*

OOP

"Death by a Thousand Cuts"

Parallel processing requires coherent program flow.





*"You cannot **multi-thread** without knowing how data is touched."*

OOP

“Death by a Thousand Cuts”

```
class Bot : public Enemy
{
    ...
    vec3 m_position;
    ...              cached but not used
    float m_mod;
    ...              cached but not used
    float m_aimDirection;
    ...
    virtual void updateAim( vec3 target )
    {
        m_aimDirection = dot3( m_position, target ) * m_mod;
    }
}
```

branch

cache miss

cache miss

cache miss

cache miss

cache miss

OOP

“Death by a Thousand Cuts”

```
void updateAims(
    float* aimDir,
    const AimingData* aim,
    vec3 target,
    uint count
)
{
   for (uint i = 0; i < count; ++i)
   {
      aimDir[i] = dot3(aim->positions[i],target) * aim->mod[i];
   }
}
```

only reads data that is actually needed to cache

reads from linear array

writes to linear array

actual functionality is unchanged

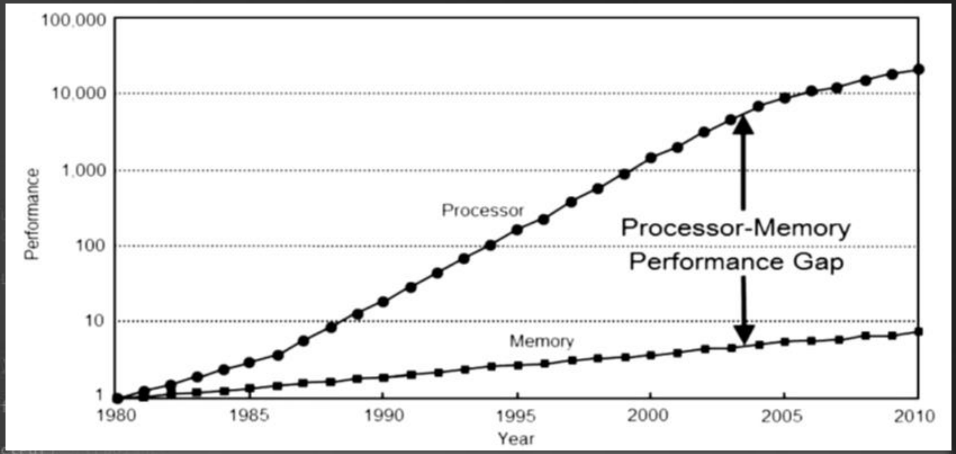
OOP

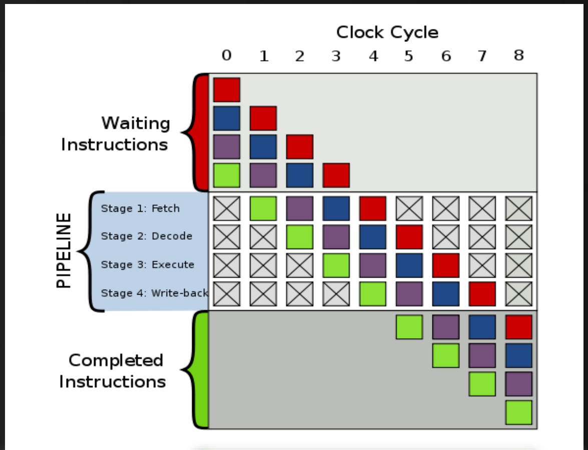
Algorithm Performance Factors

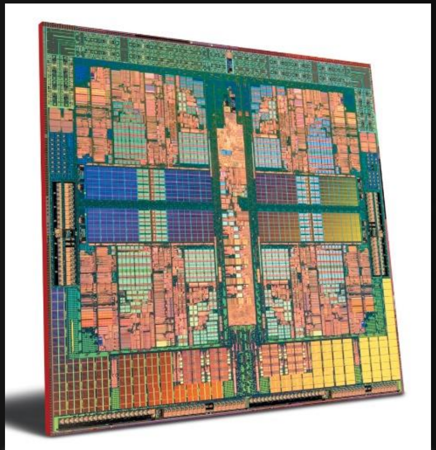
Estimating algorithm cost:

t

1. Algorithmic Complexity : $O(N)$, $O(N^2)$, $O(N \log N)$, …
2. Cyclomatic Complexity* (or: Conditional Complexity)
3. Amdahl’s Law / Work-Span Model
4. Cache Effectiveness







*: McCabe, A Complexity Measure, 1976.

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- DOD Concepts
- DOD or OO?

DOD

Data Oriented Design*

Origin: low-level game development.

Core idea: *focus software design on CPU- and cache-aware data layout.*

Take into account:

- Cache line size
- Data alignment
- Data size
- Access patterns
- Data transformations

Strive for a simple, linear access pattern as much as possible.

*: Nikos Drakos, “Data Oriented Design”, 2008. http://www.dataorienteddesign.com/dodmain

DOD

Bad Access Patterns: Linked List

The Perfect LinkedList™:

```
struct LLNode
{
    LLNode* next;
    int value;
};

LLNode* nodes = new LLNode[…];
LLNode* pool = nodes;

for( int i = 0; i < ...; i++ )
    nodes[i].next = &nodes[i + 1];
```

```
LLNode* NewNode( int value )
{
    LLNode* retval = pool;
    pool = pool->next;
    retval->value = value;
    return retval;
}

list = NewNode( -MAXINT );
list->next = NewNode( MAXINT );
list->next->next = 0;
```

nodes: 0 → 0 → 0 → 0 → 0 → 0 → 0 → 0 → …

list: -10000 → 10000 → 0

DOD

Bad Access Patterns: Linked List

The Perfect LinkedList™, experiment:

Insert 25000 random values in the list so that we obtain a sorted sequence.

```
for( int i = 0; i < COUNT; i++ )
{
    LLNode* node = NewNode( rand() & 8191);
    LLNode* iter = list;
    while (iter->next->value < node->value)
        iter = iter->next;
    node->next = iter->next;
    iter->next = node;
}
```

DOD

Bad Access Patterns: Linked List

KISS Array™:

```
data = new int[…];
memset( data, 0, … * sizeof( int ) );
data[0] = -10000;
data[1] =  10000;
N = 2;
```

```
for( int i = 0; i < COUNT; i++ )
{
    int pos = 1, value = rand() & 8191;
    while (data[pos] < value) pos++;
    memcpy( data + pos + 1,
            data + pos,
            (N - pos + 1) * sizeof( int ) );
    data[pos] = value, N++;
}
```

DOD


```
for( int i = 0; i < COUNT; i++ )
{
    LLNode* node = NewNode( rand() & 8191);
    LLNode* iter = list;
    while (iter->next->value < node->value)
        iter = iter->next;
    node->next = iter->next;
    iter->next = node;
}
```

```
for( int i = 0; i < COUNT; i++ )
{
    int pos = 1, value = rand() & 8191;
    while (data[pos] < value) pos++;
    memcpy( data + pos + 1, data + pos,
            (N - pos + 1) * sizeof( int ) );
    data[pos] = value, N++;
}
```

DOD

Bad Access Patterns: Linked List*

Inserting elements in an array by shifting the remainder of the array is *significantly faster* than using an optimized linked list.

Why?

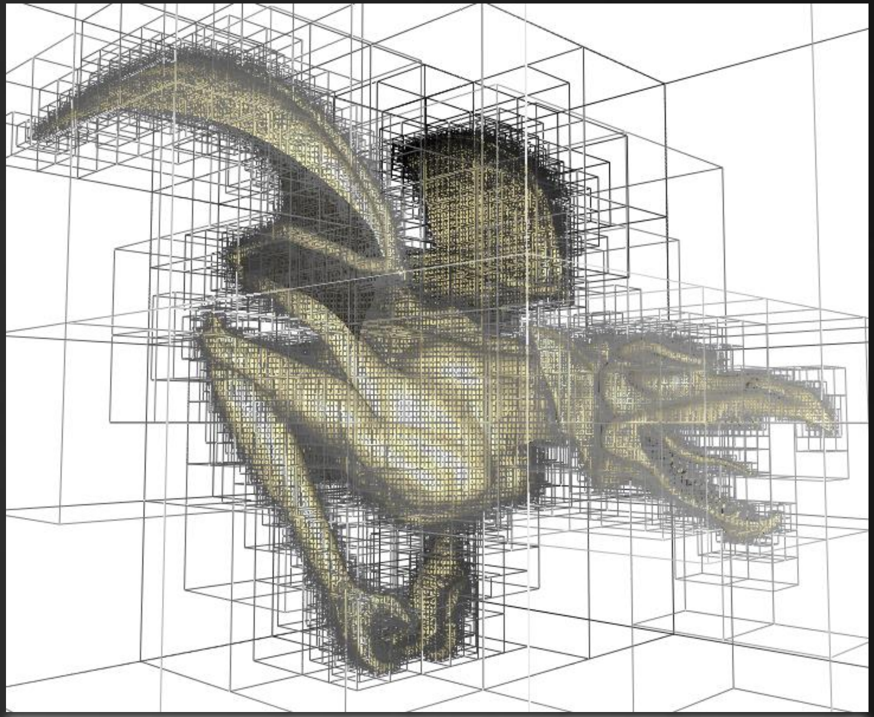
- Finding the location in the array: pure linear access
- Shifting the remainder: pure linear access.

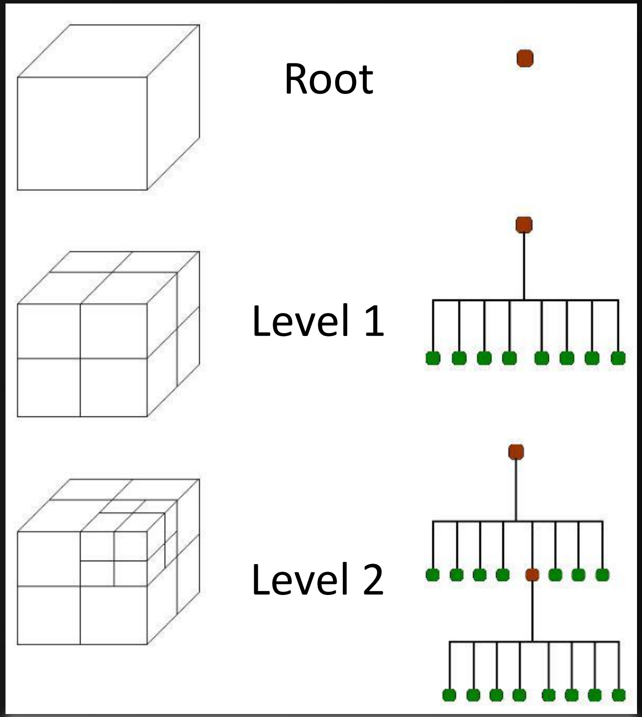
➔ Even though the amount of transferred memory is huge, this approach wins.

*: Also see: Nathan Reed, Data Oriented Hash Table, 2015.
http://www.reedbeta.com/blog/data-oriented-hash-table

DOD

Bad Access Patterns: Octree

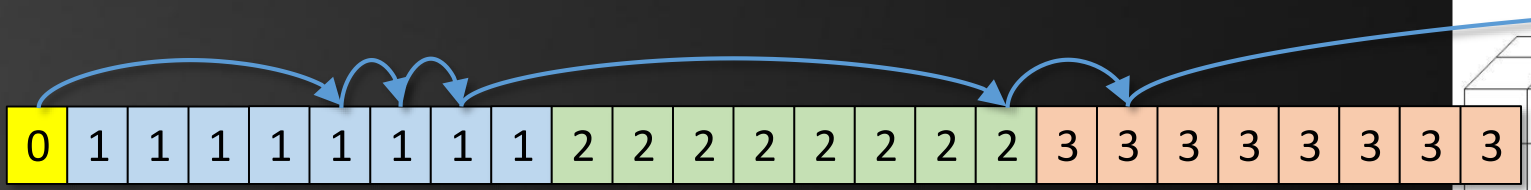


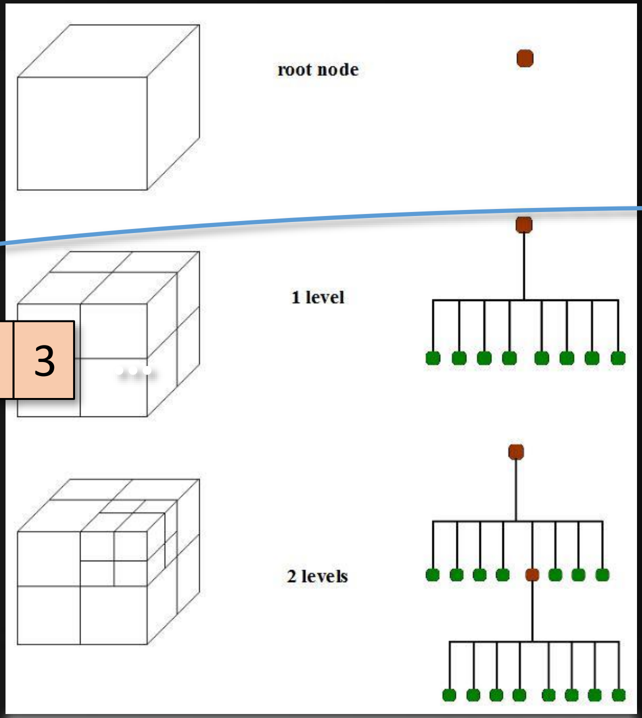


DOD

Bad Access Patterns: Octree

Query: find the color of a voxel visible through pixel (x,y).
Operation: ‘3DDDA’ (basically: Bresenham).
Data layout:





Color data: 32-bit (ARGB).

DOD

Bad Access Patterns: Octree

Alternative layout:

1. Tree 1: occlusion (1 bit per voxel);
2. Tree 2: color information (32 bits per voxel).

Use tree 1 to find the voxel you are looking for.
Lookup the correct voxel (incurring a single cache miss) in tree 2.

Caching in tree 1:

- A cache line holds 64*8=512 voxels
- Accessing the root gets several levels in L1 cache

DOD

Bad Access Patterns: Octree

Alternative layout (part 2):

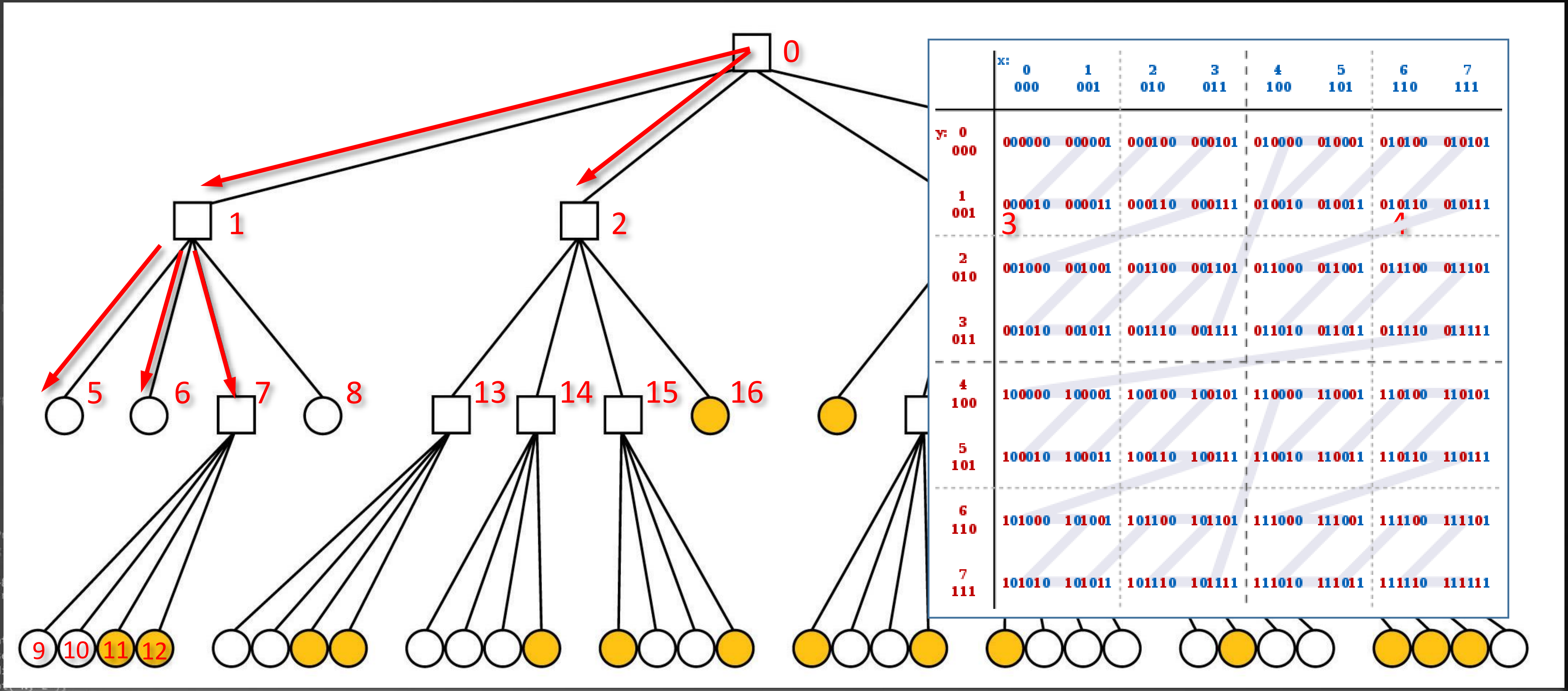
0	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3

Trees are typically generated by a divide-and-conquer algorithm, in a depth-first fashion.

Compact storage:

```
struct OTNode
{
   int firstChild;
   // bit 31 set: empty
};
```

DOD



	x: 0 000	1 001	2 010	3 011	4 100	5 101	6 110	7 111
y: 0 000	000000	000001	000100	000101	010000	010001	010100	010101
1 001	000010	000011	000110	000111	010010	010011	010110	010111
2 010	001000	001001	001100	001101	011000	011001	011100	011101
3 011	001010	001011	001110	001111	011010	011011	011110	011111
4 100	100000	100001	100100	100101	110000	110001	110100	110101
5 101	100010	100011	100110	100111	110010	110011	110110	110111
6 110	101000	101001	101100	101101	111000	111001	111100	111101
7 111	101010	101011	101110	101111	111010	111011	111110	111111

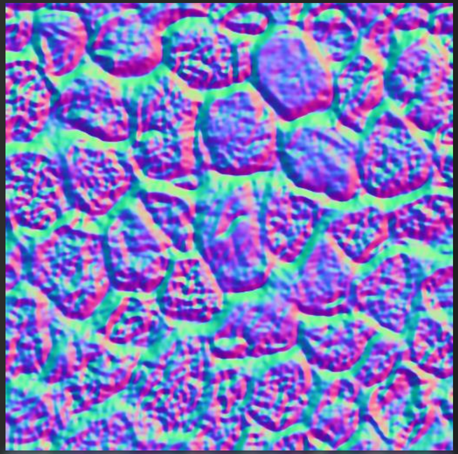
DOD

Bad Access Patterns: Textures in a Ray Tracer

Typical process for tracing a ray:

- Traverse a tree (multiple kilobytes)
- Intersect triangles in the leaf nodes (quite a few bytes)
- If a hit is found, fetch texture.

This is almost always a cache miss.

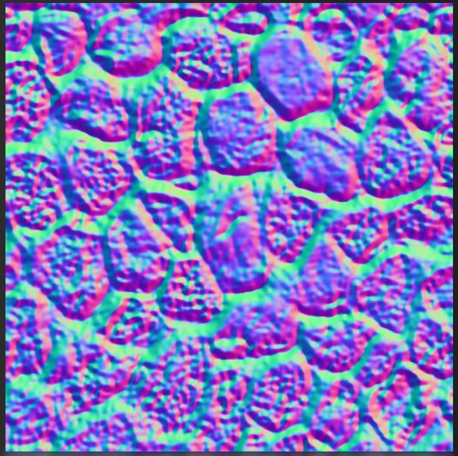

DOD

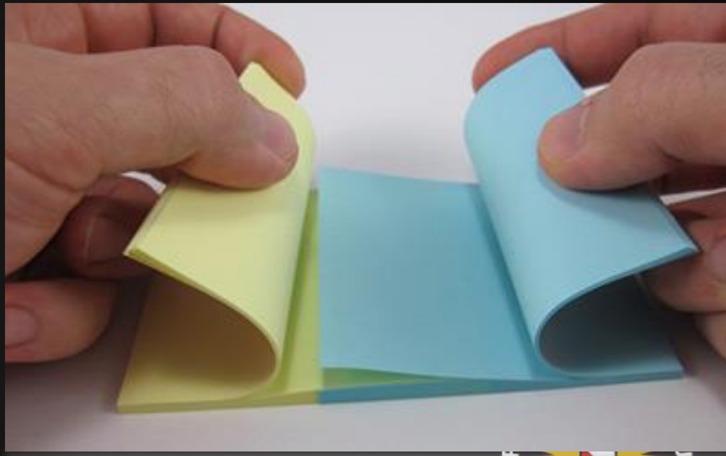
Bad Access Patterns: Textures in a Ray Tracer

We suffer the cache miss *twice:*

- Once for the texture;
- Once for the normal map.

Note: both values are 32-bit.





DOD

Bad Access Patterns: Textures in a Ray Tracer

Interleaved texture / normal:

- One value now becomes 64-bit and contains the normal and the color.
- We still suffer a cache miss –
- But only once.

DOD

Previously in INFOMOV

```
struct Particle
{
   float x, y, z;
   float vx, vy, vz;
   float mass;
};
// size: 28 bytes
```

Better:

```
struct Particle
{
   float x, y, z;
   float vx, vy, vz;
   float mass, dummy;
};
// size: 32 bytes
```

DOD

Previously in INFOMOV

```
struct Particle
{
   float x, y, z;
   int mass;
};
Particle particle[512];
```

AOS

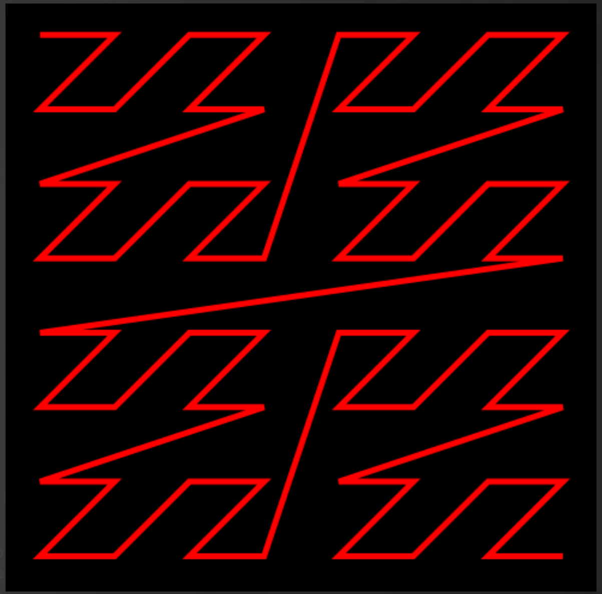
```
union {  float x[512]; __m128 x4[128]; };
union {  float y[512]; __m128 y4[128]; };
union {  float z[512]; __m128 z4[128]; };
union {  int mass[512];__m128i mass4[128]; };
```

SOA

structure of arrays

DOD

Previously in INFOMOV



Method:

```
X =  1 1 0 0 0 1 0 1 1 0 1 1 0 1
Y = 1 0 1 1 0 1 1 0 1 0 1 1 1 0
--------------------------------
M = 1101101000111001110011111001
```

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2B|~2B

OO = Evil, DO = Good?

10% of your code runs 90% of the time. DO is good for this 10%.

For all other code, please:

- Use STL
- Apply OO
- Program in C#
- Use event handling
- Check return values
- Focus on productivity

2B|~2B

https://www.youtube.com/watch?v=rX0ItVEVjHc

2B|~2B

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Next: Contents **Contents**

Online release of Data-Oriented Design :
This is the free, online, reduced version. Some inessential chapters are excluded from this version, but in the spirit of this being an education resource, the essentials are present for anyone wanting to learn about data-oriented design.
Expect some odd formatting and some broken images and listings as this is auto generated and the Latex to html converters available are not perfect. If the source code listing is broken, you should be able to find the referenced source on github. If you like what you read here, consider purchasing the real paper book from here, as not only will it look a lot better, but it will help keep this version online for those who cannot afford to buy it. Please send any feedback to support@dataorienteddesign.com

Data-Oriented Design

Richard Fabian

- Contents
- Data-Oriented Design
  - It's all about the data
  - Data is not the problem domain
  - Data and statistics
  - Data can change
  - How is data formed?
  - The framework
  - Conclusions and takeaways

http://www.dataorienteddesign.com/dodbook/

Data Oriented Design Resources

A curated list of awesome data oriented design resources.

Feel free to contribute by sending PR!

- Data Oriented Design
  - Presentations
  - Blog Posts
  - Videos
  - Other
  - Code Examples

Presentations

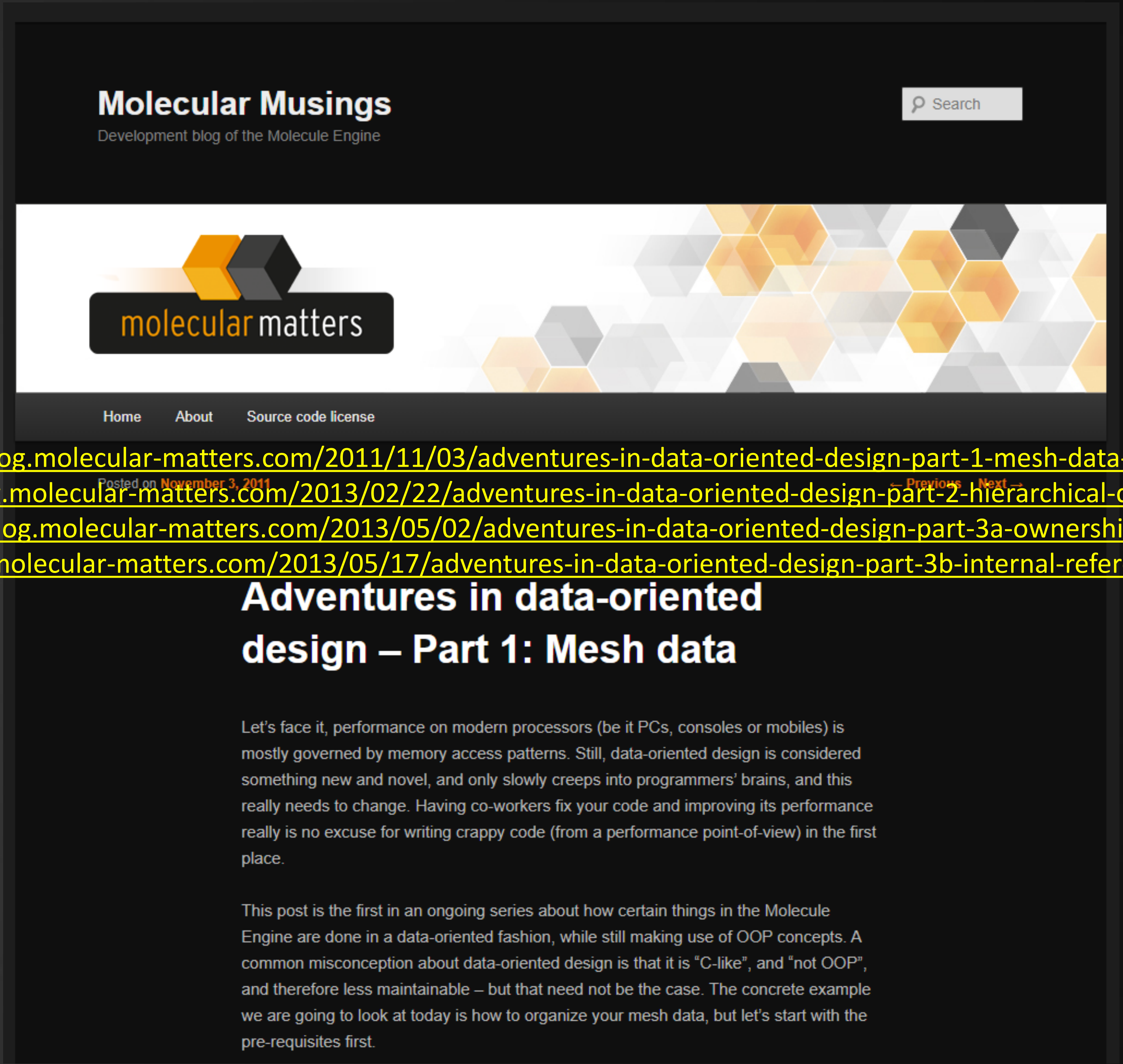
- A Step Towards Data Orientation (2010) - Johan Torp
- Introduction To Data Oriented Design (2010) - DICE
- Memory Optimization (2003) - Christer Ericson
- Practical Examples In Data Oriented Design (2013) - Niklas Frykholm
- Three Big Lies (2008) - Mike Acton
- Typical C++ Bullshit (2008) - Mike Acton
- Data-Oriented Design and C++ (2014) - Mike Acton
- Entity Component Systems & Data Oriented Design (2018) - Aras Pranckevičius

Blog Posts

https://github.com/dbartolini/data-oriented-design

- Adventures in data-oriented design – Part 1: Mesh data (2011) - Stefan Reinalter

2B|~2B



https://blog.molecular-matters.com/2011/11/03/adventures-in-data-oriented-design-part-1-mesh-data-3/
https://blog.molecular-matters.com/2013/02/22/adventures-in-data-oriented-design-part-2-hierarchical-data/
https://blog.molecular-matters.com/2013/05/02/adventures-in-data-oriented-design-part-3a-ownership/
https://blog.molecular-matters.com/2013/05/17/adventures-in-data-oriented-design-part-3b-internal-references/

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END of “Data-Oriented Design”

next lecture: “GPGPU (1)”