Ray Tracing for Games

Dr. Jacco Bikker - IGAD/BUAS, Breda, January 31

Welcome!

4

Ray Tracing for Games

Wednesday
13:00 – 17:00

course intro
LH2
template
Whitted
refactoring
RT-centric games

LAB 1

Thursday
09:00 – 14:00

advanced Whitted
audio, AI & physics
faster Whitted
Heaven7

LAB 2

work @ home

End result day 2:

A solid Whitted-style ray tracer, as a basis for subsequent work.

Friday
09:00 – 17:00

optimization
profiling, rules of engagement
threading

LAB

SIMD
applied SIMD
SIMD triangle
SIMD AABB

LAB 4

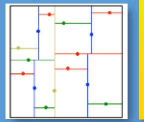
End result day 3:

A 5x faster tracer.

GLOBAL GAME JAM

Monday
09:00 – 17:00

acceleration
grid, BVH, kD-tree
SAH
binning



LAB 5

refitting
top-level BVH
threaded building

LAB 6

End result day 4:

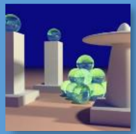
A real-time tracer.

Tuesday
09:00 – 17:00

Monte-Carlo
Cook-style
glossy, AA
area lights, DOF

LAB 7

path tracing



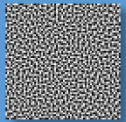
LAB 8

End result day 5:

Cook or Kajiya.

Thursday
09:00 – 17:00

random numbers
stratification
blue noise



LAB 9

importance sampling
next event estimation

LAB 10

End result day 6:

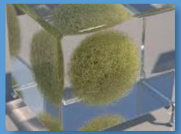
Efficiency.

Friday
09:00 – 17:00

future work

LAB 11

path guiding



LAB 10

End result day 6:

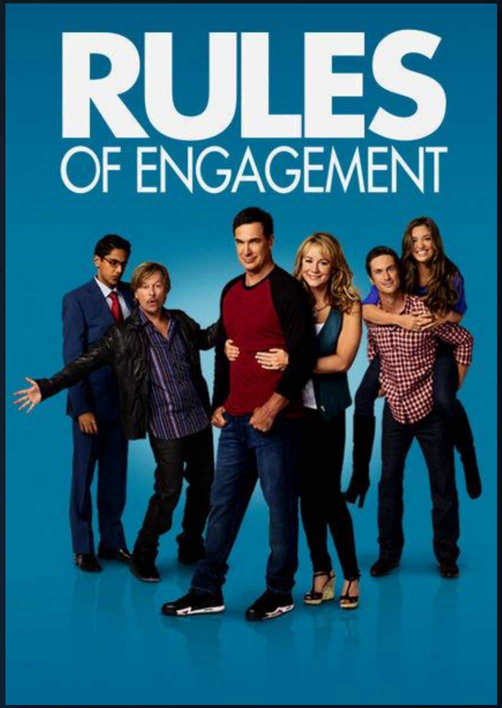
Great product.

Agenda:

- Introduction
- SSE / AVX
- Streams
- Vectorization

Consistent Approach

(0.) Determine optimization requirements
1. Profile: determine hotspots
2. Analyze hotspots: determine scalability
3. Apply high level optimizations to hotspots
4. Profile again.
5. Parallelize / vectorize / use GPGPU
6. Profile again.
7. Apply low level optimizations to hotspots
8. Repeat steps 7 and 8 until time runs out
9. Report.



Rules of Engagement

1. Avoid Costly Operations
2. Precalculate
3. Pick the Right Data Type
4. Avoid Conditional Branches
5. Early Out
6. Use the Power of Two
7. Do Things Simultaneously

S.I.M.D.

Single Instruction Multiple Data:
Applying the same instruction to several input elements.

In other words: if we are going to apply the same sequence of instructions to a large input set, this allows us to do this in parallel (and thus: faster).

SIMD is also known as *instruction level parallelism*.

Examples:

```
union { uint a4; unsigned char a[4]; };
do
{
   GetFourRandomValues( a );
}
while (a4 != 0);
```

```
unsigned char a[4] = { 1, 2, 3, 4 };
unsigned char b[4] = { 5, 5, 5, 5 };
unsigned char c[4];
*(uint*)c = *(uint*)a + *(uint*)b;
// c is now { 6, 7, 8, 9 }.
```

```
void Game::Tick( float deltaTime )
{
0000000140002C40  movss       dword ptr [rsp+10h],xmm1
0000000140002C46  mov         qword ptr [rsp+8],rcx
0000000140002C4B  push        rdi
0000000140002C4C  sub         rsp,90h
0000000140002C53  mov         rdi,rsp
0000000140002C56  mov         ecx,24h
0000000140002C5B  mov         eax,0CCCCCCCCh
0000000140002C60  rep stos    dword ptr [rdi]
0000000140002C62  mov         rcx,qword ptr [this]
    unsigned char a[4] = { 1, 2, 3, 4 };
0000000140002C6A  mov         byte ptr [a],1
0000000140002C6F  mov         byte ptr [rsp+35h],2
0000000140002C74  mov         byte ptr [rsp+36h],3
0000000140002C79  mov         byte ptr [rsp+37h],4
    unsigned char b[4] = { 5, 5, 5, 5 };
0000000140002C7E  mov         byte ptr [b],5
0000000140002C83  mov         byte ptr [rsp+55h],5
0000000140002C88  mov         byte ptr [rsp+56h],5
0000000140002C8D  mov         byte ptr [rsp+57h],5
    unsigned char c[4];
    *(uint*)c = *(uint*)a + *(uint*)b;
0000000140002C92  mov         eax,dword ptr [b]
0000000140002C96  mov         ecx,dword ptr [a]
0000000140002C9A  add         ecx,eax
0000000140002C9C  mov         eax,ecx
0000000140002C9E  mov         dword ptr [c],eax
```

out

same
, this
ter).

Examples:

```
union { uint a4; unsigned char a[4]; };
do
{
    GetFourRandomValues( a );
}
while (a4 != 0);
```

```
unsigned char a[4] = { 1, 2, 3, 4 };
unsigned char b[4] = { 5, 5, 5, 5 };
unsigned char c[4];
*(uint*)c = *(uint*)a + *(uint*)b;
// c is now { 6, 7, 8, 9 }.
```

```
void Game::Tick( float deltaTime )
{
0000000140002250  movss       dword ptr [rsp+10h],xmm1
0000000140002256  mov         qword ptr [rsp+8],rcx
000000014000225B  sub         rsp,38h
    unsigned char a[4] = { 1, 2, 3, 4 };
    unsigned char b[4] = { 5, 5, 5, 5 };
000000014000225F  mov         dword ptr [rsp+40h],5050505h
    unsigned char c[4];
    *(uint*)c = *(uint*)a + *(uint*)b;
0000000140002267  mov         edx,dword ptr [b]
000000014000226B  mov         dword ptr [rsp+48h],4030201h
0000000140002273  add         edx,dword ptr [a]
0000000140002277  mov         ecx,edx
0000000140002279  mov         eax,edx
```

ut

ame

this

allows us to do this in parallel (and thus: faster).

SIMD is also known as *instruction level parallelism*.

Examples:

```
union { uint a4; unsigned char a[4]; };
do
{
   GetFourRandomValues( a );
}
while (a4 != 0);
```

```
unsigned char a[4] = { 1, 2, 3, 4 };
unsigned char b[4] = { 5, 5, 5, 5 };
unsigned char c[4];
*(uint*)c = *(uint*)a + *(uint*)b;
// c is now { 6, 7, 8, 9 }.
```

uint = unsigned char[4]

Pinging google.com yields: 74.125.136.101
Each value is an unsigned 8-bit value (0..255).
Combing them in one 32-bit integer:

101 +
256 * 136 +
256 * 256 * 125 +
256 * 256 * 256 * 74 = 1249740901.

Browse to: http://1249740901 (works!)

Evil use of this:

We can specify a user name when visiting a website, but any username will be accepted by google. Like this:

http://infomov@google.com

Or:

http://www.ing.nl@1249740901

Replace the IP address used here by your own site which contains a copy of the ing.nl site to obtain passwords, and send the link to a 'friend'.

Example: color scaling

Assume we represent colors as 32-bit ARGB values using unsigned ints:

31 … 24	23 … 16	15 … 8	7 … 0

To scale this color by a specified percentage, we use the following code:

```
uint ScaleColor( uint c, float x ) // x = 0..1
{
   uint red = (c >> 16) & 255;
   uint green = (c >> 8) & 255;
   uint blue = c & 255;
   red = red * x, green = green * x, blue = blue * x;
   return (red << 16) + (green << 8) + blue;
}
```

31 24	23 16	15 8	7 0

Example: color scaling

```
uint ScaleColor( uint c, float x ) // x = 0..1
{
    uint red = (c >> 16) & 255, green = (c >> 8) & 255, blue = c & 255;
    red = red * x, green = green * x, blue = blue * x;
    return (red << 16) + (green << 8) + blue;
}
```

Improved:

```
uint ScaleColor( uint c, uint x ) // x = 0..255
{
    uint red = (c >> 16) & 255, green = (c >> 8) & 255, blue = c & 255;
    red = (red * x) >> 8;
    green = (green * x) >> 8;
    blue = (blue * x) >> 8;
    return (red << 16) + (green << 8) + blue;
}
```

Example: color scaling

```
uint ScaleColor( uint c, uint x ) // x = 0..255
{
    uint red = (c >> 16) & 255, green = (c >> 8) & 255, blue = c & 255;
    red = (red * x) >> 8, green = (green * x) >> 8, blue = (blue * x) >> 8;
    return (red << 16) + (green << 8) + blue;
}
```

7 shifts, 3 ands, 3 muls, 2 adds

Improved:

```
uint ScaleColor( const uint c, const uint x ) // x = 0..255
{
    uint redblue = c & 0x00FF00FF;
    uint green   = c & 0x0000FF00;
    redblue = ((redblue * x) >> 8) & 0x00FF00FF;
    green = ((green * x) >> 8) & 0x0000FF00;
    return redblue + green;
}
```

2 shifts, 4 ands, 2 muls, 1 add

31 24	23 16	15 8	7 0
31 24	23 16	15 8	7

Example: color scaling

```
uint ScaleColor( uint c, uint x ) // x = 0..255
{
    uint red = (c >> 16) & 255, green = (c >> 8) & 255, blue = c & 255;
    red = (red * x) >> 8, green = (green * x) >> 8, blue = (blue * x) >> 8;
    return (red << 16) + (green << 8) + blue;
}
```

7 shifts, 3 ands, 3 muls, 2 adds (15 ops)

Further improved:

```
uint ScaleColor( const uint c, const uint x ) // x = 0..255
{
    uint redblue = c & 0x00FF00FF;
    uint green   = c & 0x0000FF00;
    redblue = (redblue * x) & 0xFF00FF00;
    green = (green * x) & 0x00FF0000;
    return (redblue + green) >> 8;
}
```

1 shift, 4 ands, 2 muls, 1 add (8 ops)

Other Examples

Rapid string comparison:

```
char a[] = “optimization skills rule”;
char b[] = “optimization is so nice!”;
bool equal = true;
int l = strlen( a );
for ( int i = 0; i < l; i++ )
{
  if (a[i] != b[i])
  {
    equal = false;
    break;
  }
}
```

```
char a[] = “optimization skills rule”;
char b[] = “optimization is so nice!”;
bool equal = true;
int q = strlen( a ) / 4;
for ( int i = 0; i < q; i++ )
{
  if (((int*)a)[i] != ((int*)b)[i])
  {
    equal = false;
    break;
  }
}
```

Likewise, we can copy byte arrays faster.

SIMD using 32-bit values - Limitations

Mapping four chars to an int value has a number of limitations:

{ 100, 100, 100, 100 } + { 1, 1, 1, 200 } = { 101, 101, 102, 44 }

{ 100, 100, 100, 100 } * { 2, 2, 2, 2 } = { ... }

{ 100, 100, 100, 200 } * 2 = { 200, 200, 201, 144 }

In general:

- Streams are not separated (prone to overflow into next stream);
- Limited to small unsigned integer values;
- Hard to do multiplication / division.

SIMD using 32-bit values - Limitations

Ideally, we would like to see:

- Isolated streams
- Support for more data types (char, short, uint, int, float, double)
- An easy to use approach

Meet SSE!

Agenda:

- Introduction
- SSE / AVX
- Streams
- Vectorization

A Brief History of SIMD

Early use of SIMD was in vector supercomputers such as the CDC Star-100 and TI ASC (image).

Intel's MMX extension to the x86 instruction set (1996) was the first use of SIMD in commodity hardware, followed by Motorola's AltiVec (1998), and Intel's SSE (P3, 1999).

SSE:

- 70 assembler instructions
- Operates on 128-bit registers
- Operates on vectors of 4 floats.

SIMD Basics

C++ supports a 128-bit vector data type: __m128
Henceforth, we will pronounce to this as ‘quadfloat’. ☺

__m128 literally is a small array of floats:

```
union { __m128 a4; float a[4]; };
```

Alternatively, you can use the integer variety __m128i:

```
union { __m128i a4; int a[4]; };
```

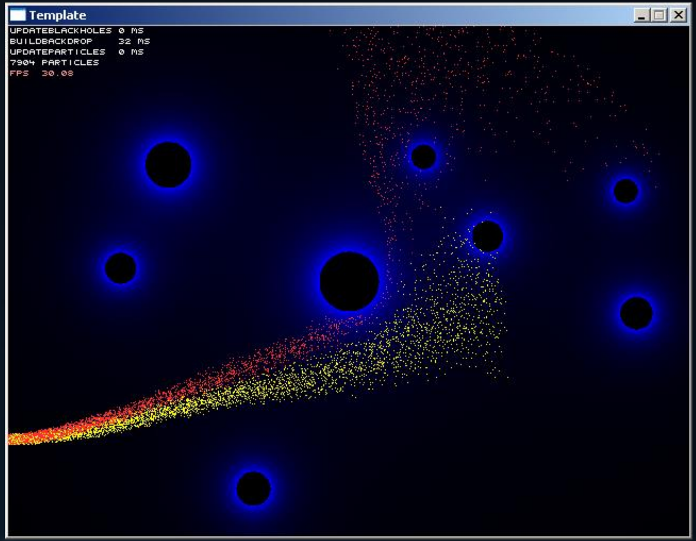
SIMD Basics

We operate on SSE data using *intrinsics*: in the case of SSE, these are keywords that translate to a single assembler instruction.

Examples:

```
__m128 a4 = _mm_set_ps( 1, 0, 3.141592f, 9.5f );
__m128 b4 = _mm_setzero_ps();
__m128 c4 = _mm_add_ps( a4, b4 ); // not: __m128 = a4 + b4;
__m128 d4 = _mm_sub_ps( b4, a4 );
```

Here, '_ps' stands for *packed scalar.*



SIMD Basics

Other instructions:

```
__m128 c4 = _mm_div_ps( a4, b4 ); // component-wise division
__m128 d4 = _mm_sqrt_ps( a4 );    // four square roots
__m128 d4 = _mm_rcp_ps( a4 );     // four reciprocals
__m128 d4 = _mm_rsqrt_ps( a4 );   // four reciprocal square roots (!)

__m128 d4 = _mm_max_ps( a4, b4 );
__m128 d4 = _mm_min_ps( a4, b4 );
```

CODING TIME

Keep the assembler-like syntax in mind:

`__m128 d4 =` ~~`dx4 * dx4 + dy4 * dy4;`~~

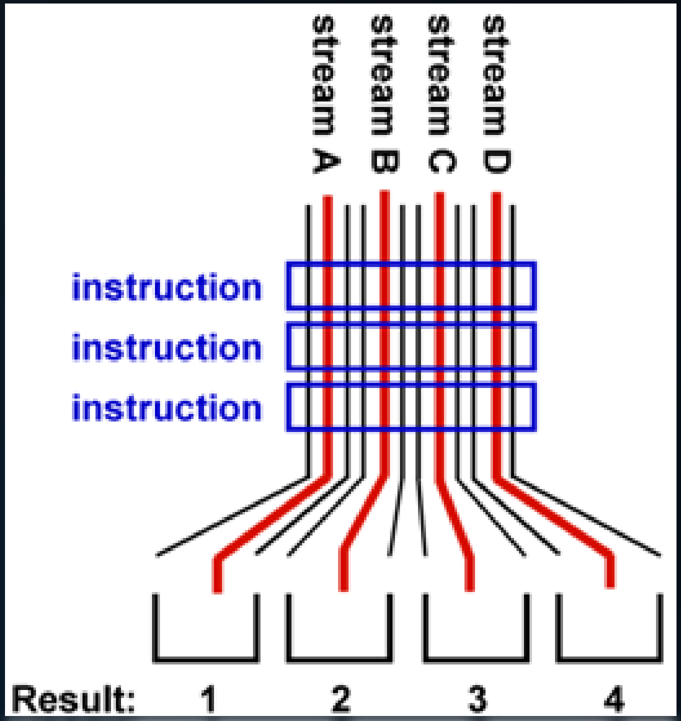
```
__m128 d4 = _mm_add_ps(
        _mm_mul_ps( dx4, dx4 ),
        _mm_mul_ps( dy4, dy4 )
    );
```

SIMD Basics

In short:

- Four times the work at the price of a single scalar operation (if you can feed the data fast enough)
- Potentially even better performance for min, max, sqrt, rsqrt
- Requires four independent streams.

And, with AVX we get __m256…



Agenda:

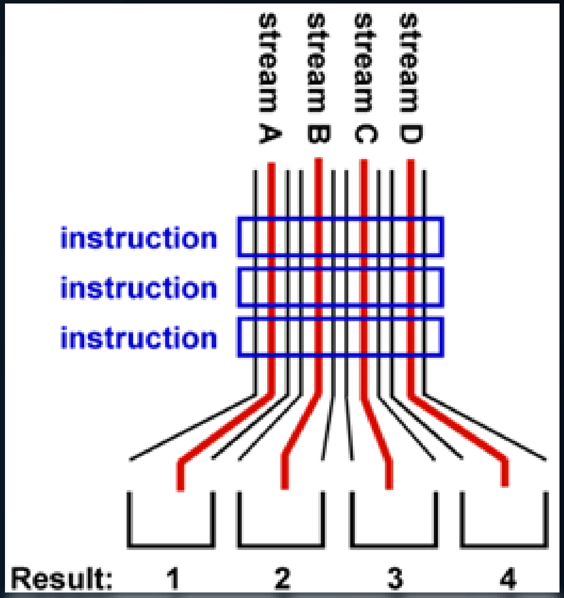
- Introduction
- SSE / AVX
- Streams
- Vectorization

SIMD According To Visual Studio

```
vec3 A( 1, 0, 0 );
vec3 B( 0, 1, 0 );
vec3 C = (A + B) * 0.1f;
vec3 D = normalize( C );
```

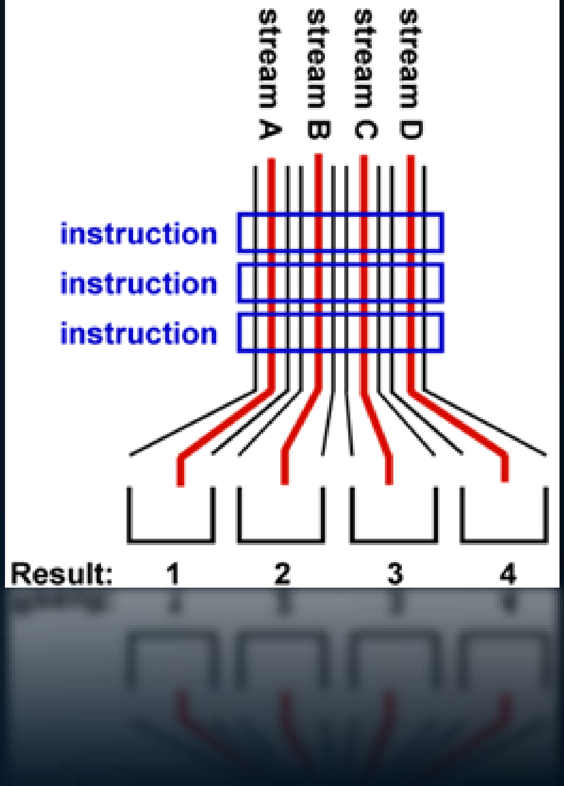
The compiler will notice that we are operating on 3-component vectors, and it will use SSE instructions to speed up the code. This results in a modest speedup. Note that one lane is never used at all.

To get maximum throughput, we want four independent streams, running in parallel.



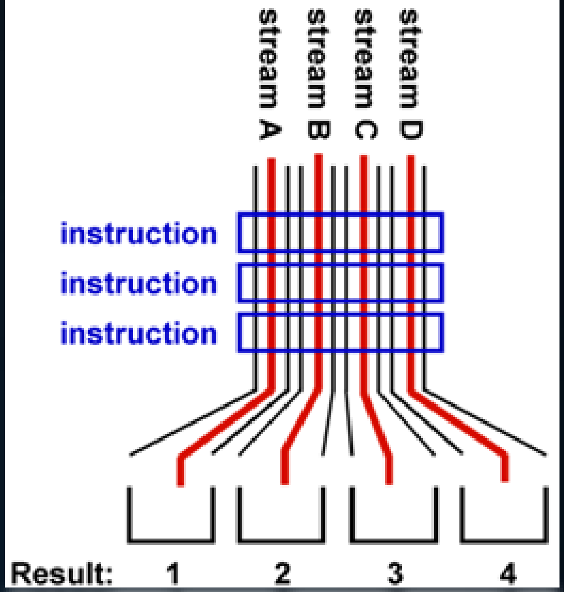
SIMD According To Visual Studio

```
float Ax = 1, Ay = 0, Az = 0;
float Bx = 0, By = 1, Bz = 0;
float Cx = (Ax + Bx) * 0.1f;
float Cy = (Ay + By) * 0.1f;
float Cz = (Az + Bz) * 0.1f;
float l = sqrtf( Cx * Cx + Cy * Cy + Cz * Cz);
float Dx = Cx / l;
float Dy = Cy / l;
float Dz = Cz / l;
```



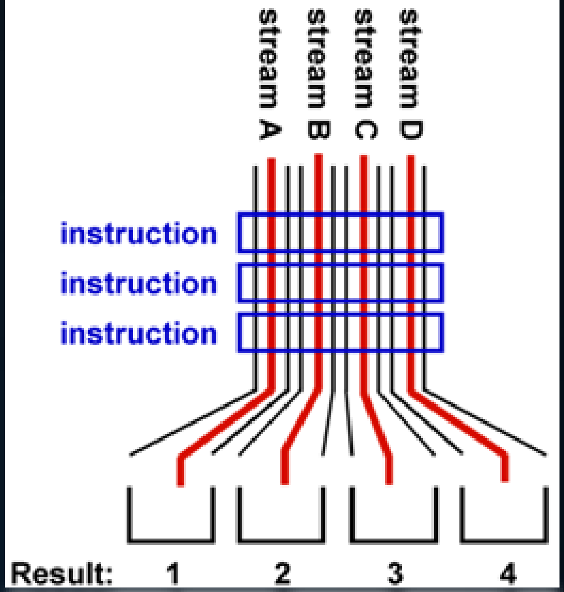
SIMD According To Visual Studio

```
float Ax[4] = {…}, Ay[4] = {…}, Az[4] = {…};
float Bx[4] = {…}, By[4] = {…}, Bz[4] = {…};
float Cx[4] = …;
float Cy[4] = …;
float Cz[4] = …;
float l[4] = …;
float Dx[4] = …;
float Dy[4] = …;
float Dz[4] = …;
```



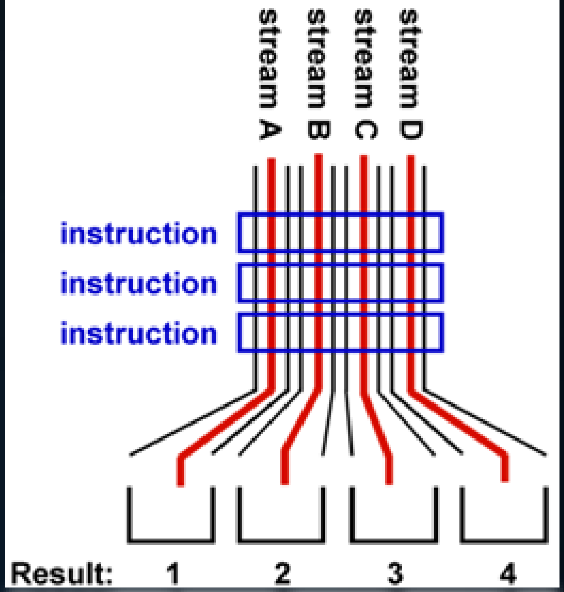
SIMD According To Visual Studio

```
__m128 Ax4 = {…}, Ay4 = {…}, Az4 = {…};
__m128 Bx4 = {…}, By4 = {…}, Bz4 = {…};
__m128 Cx4 = …;
__m128 Cy4 = …;
__m128 Cz4 = …;
__m128 l4 = …;
__m128 Dx4 = …;
__m128 Dy4 = …;
__m128 Dz4 = …;
```



SIMD According To Visual Studio

```
__m128 Ax4 = {…}, Ay4 = {…}, Az4 = {…};
__m128 Bx4 = {…}, By4 = {…}, Bz4 = {…};
__m128 X4 = _mm_set1_ps( 0.1f );
__m128 Cx4 = _mm_mul_ps( _mm_add_ps( Ax4, Bx4 ), X4 );
__m128 Cy4 = _mm_mul_ps( _mm_add_ps( Ay4, By4 ), X4 );
__m128 Cz4 = _mm_mul_ps( _mm_add_ps( Az4, Bz4 ), X4 );
__m128 l4 = …;
__m128 Dx4 = …;
__m128 Dy4 = …;
__m128 Dz4 = …;
```



SIMD Friendly Data Layout

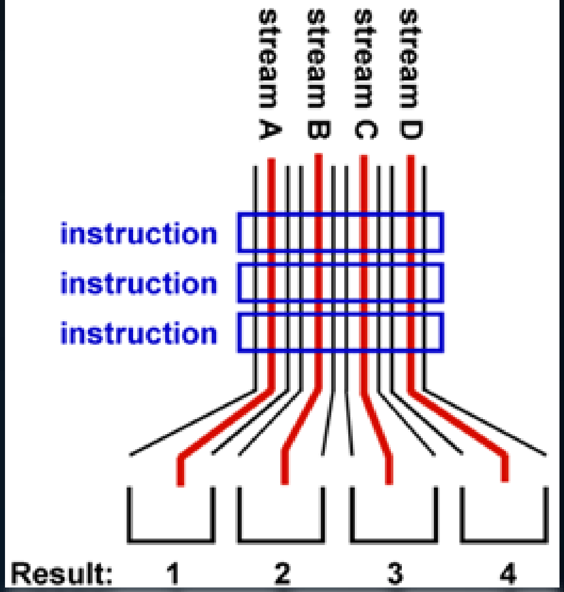
Consider the following data structure:

```
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



SIMD Data Naming Conventions

```
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]; };
```

Notice that SoA is breaking our OO...

Consider adding the struct name to the variables:

```
float particle_x[512];
```

Or put an amount of particles in a struct.

Also note the convention of adding ‘4’ to any SSE variable.

Agenda:

- Introduction
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- Streams
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Converting your Code

1. Locate a significant bottleneck in your code
   (converting is going to be labor-intensive, be sure it's worth it)
2. Keep a copy of the original code (use #ifdef)
   (you may want to compile on some other platform later)
3. Prepare the scalar code
   (add a 'for(int stream = 0; stream < 4; stream++)' loop)
4. Reorganize the data
   (make sure you don't have to convert all the time)
5. Union with floats
6. Convert one line at a time, verifying functionality as you go
7. Check MSDN for exotic SSE instructions
   (some odd instructions exist that may help your problem)

Take some time to speed up your ray tracer.

SIMD:

Easy: create four (or eight) primary rays at once, then switch to regular code.
Easy: convert four pixels to integer.
Higher gain: intersect 4 rays with 1 sphere, or 1 ray with 4 spheres.

Advanced SIMD:

Conditional code with SIMD is done with *masking:*

```
__m128 mask = _mm_cmple_ps( a4, b4 );
__m128 result = _mm_add_ps( total4, _mm_and_ps( a4, mask ) );
```

End of PART 4.