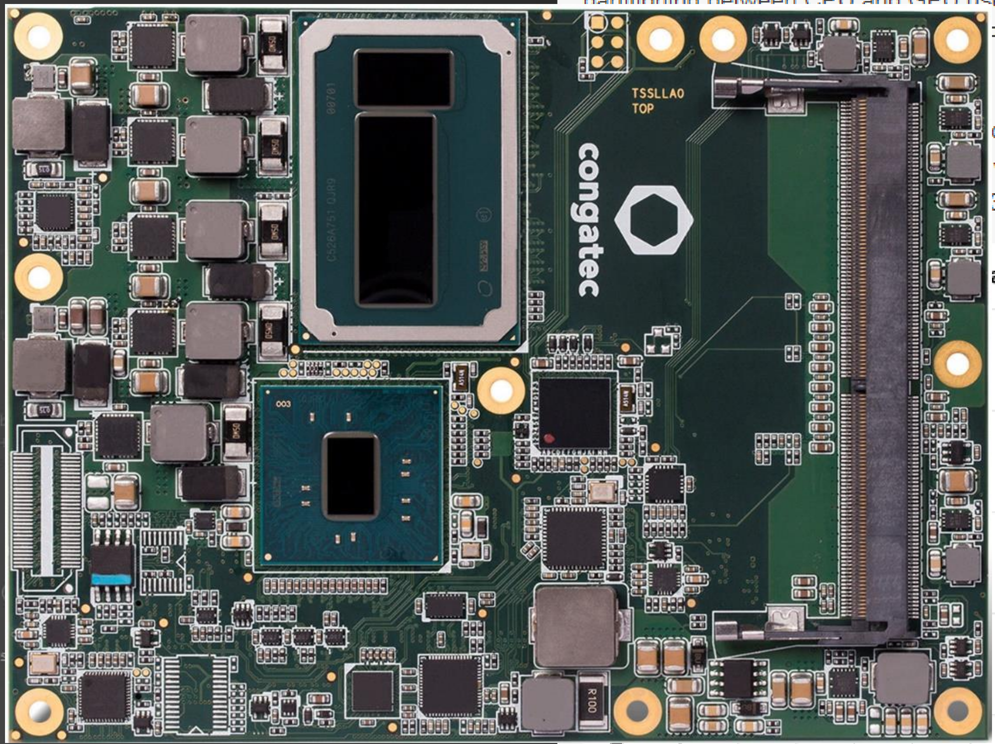
/INFOMOV/
Optimization & Vectorization

J. Bikker - Sep-Nov 2019 - Lecture 5: "SIMD (1)"

Welcome!

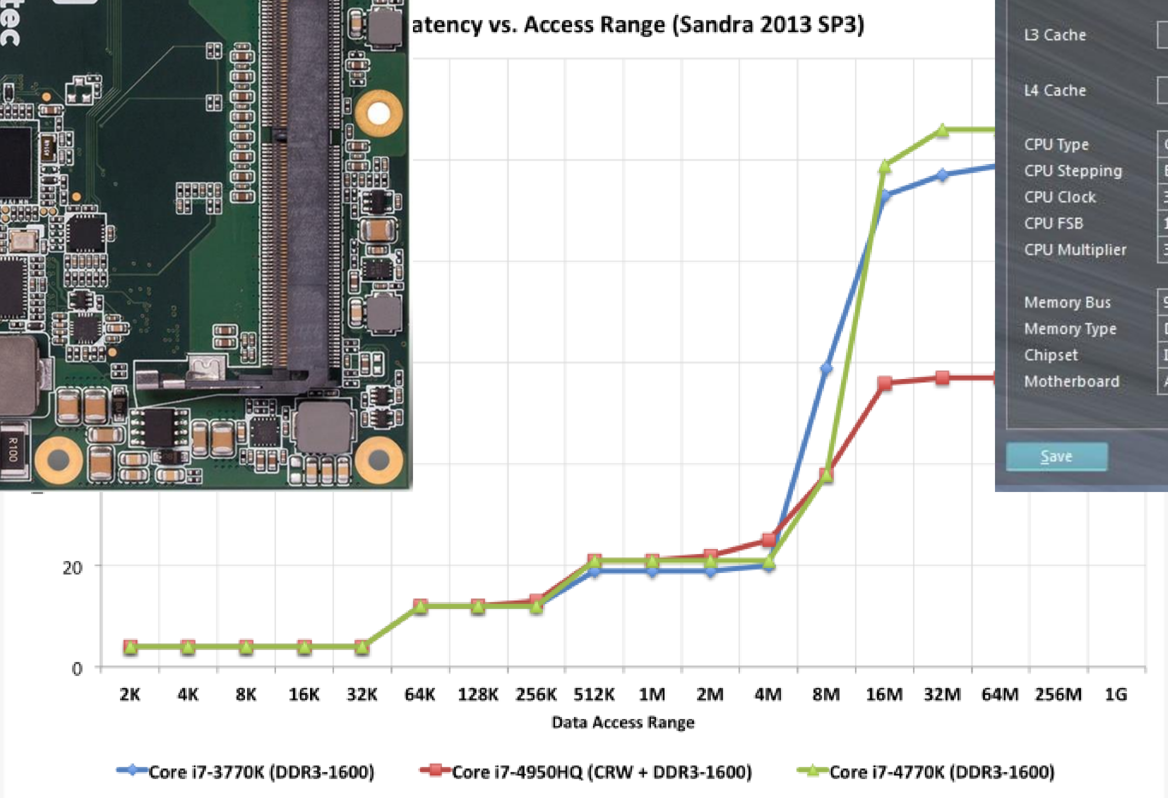
Meanwhile, on ars

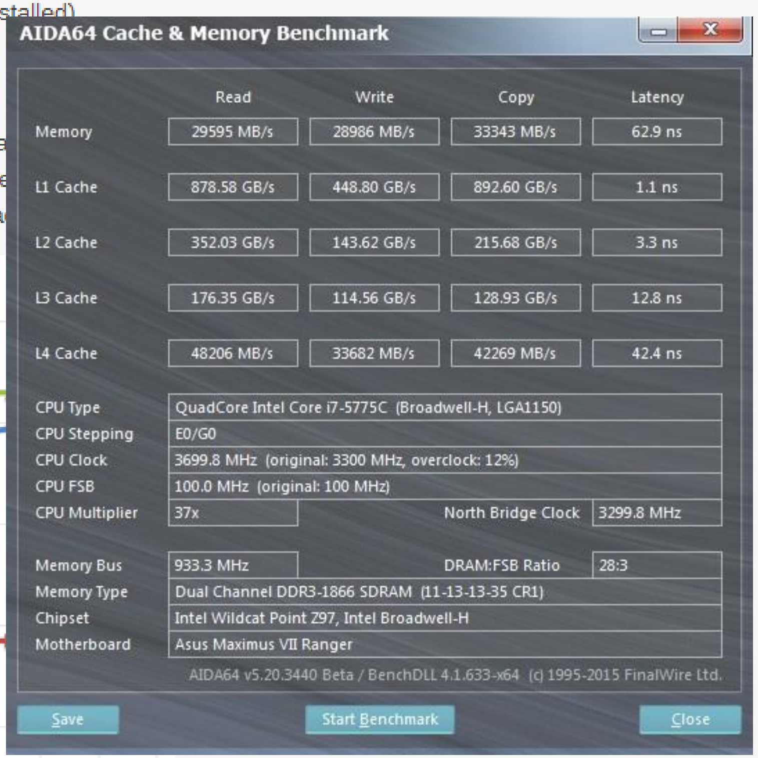


Crystalwell Architecture

Unlike previous eDRAM implementations in game consoles, Crystalwell is true 4th level cache in the memory hierarchy. It acts as a victim buffer to the L3 cache, meaning anything evicted from L3 cache immediately goes into the L4 cache. Both CPU and GPU requests are cached. The cache can dynamically allocate its partitioning between CPU and GPU use. If you don't use the GPU at all (e.g. discrete GPU installed)
…PU requests. That's right, Haswell CPUs equipped with

…connection to Crystalwell other than to say that it's a na…
…vering 50GB/s bi-directional bandwidth (100GB/s aggre…
…30 - 32ns, nicely in between an L3 and main memory a…





	Read	Write	Copy	Latency
Memory	29595 MB/s	28986 MB/s	33343 MB/s	62.9 ns
L1 Cache	878.58 GB/s	448.80 GB/s	892.60 GB/s	1.1 ns
L2 Cache	352.03 GB/s	143.62 GB/s	215.68 GB/s	3.3 ns
L3 Cache	176.35 GB/s	114.56 GB/s	128.93 GB/s	12.8 ns
L4 Cache	48206 MB/s	33682 MB/s	42269 MB/s	42.4 ns

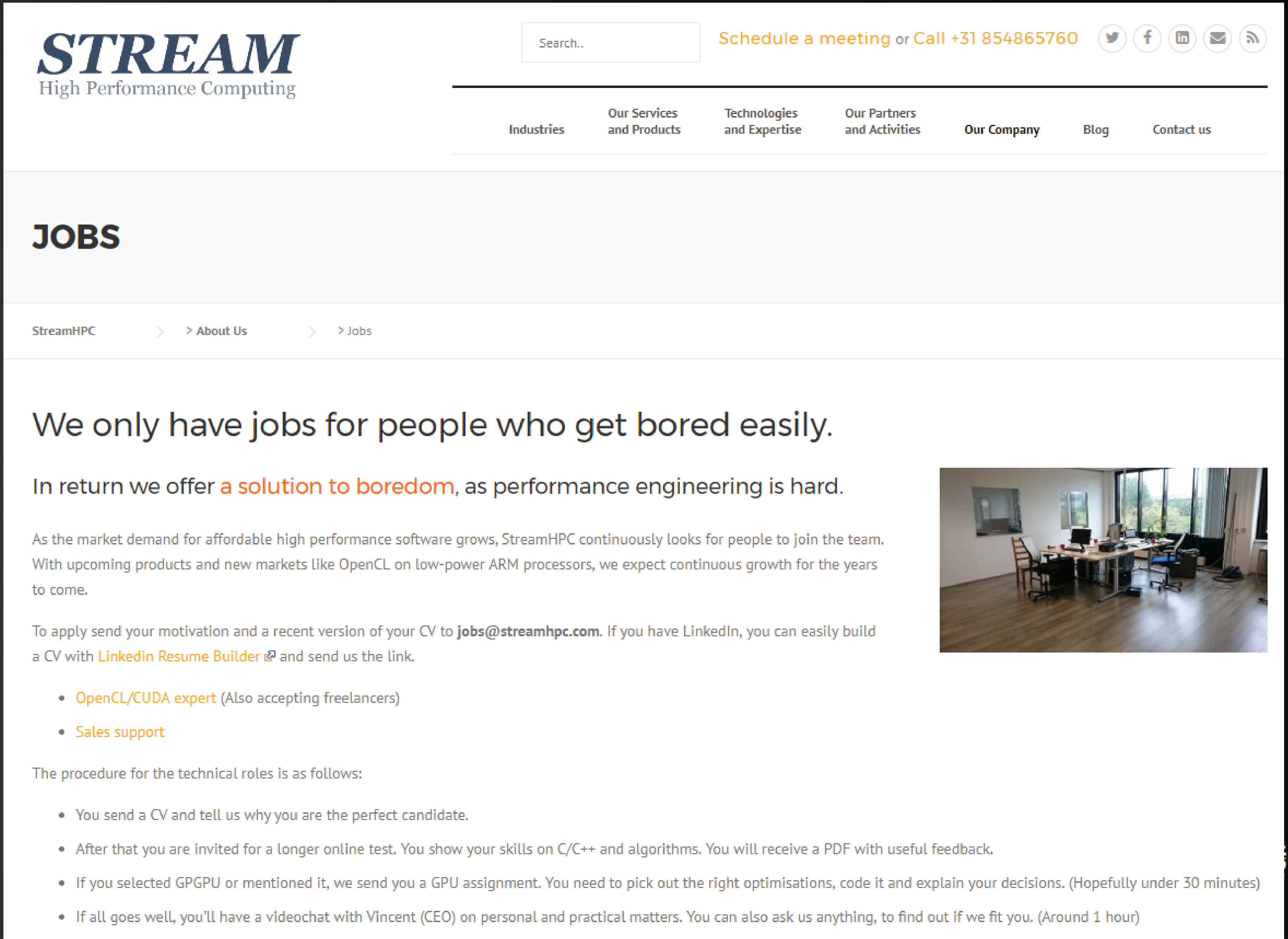
CPU Type	QuadCore Intel Core i7-5775C (Broadwell-H, LGA1150)
CPU Stepping	E0/G0
CPU Clock	3699.8 MHz (original: 3300 MHz, overclock: 12%)
CPU FSB	100.0 MHz (original: 100 MHz)
CPU Multiplier	37x — North Bridge Clock: 3299.8 MHz
Memory Bus	933.3 MHz — DRAM:FSB Ratio: 28:3
Memory Type	Dual Channel DDR3-1866 SDRAM (11-13-13-35 CR1)
Chipset	Intel Wildcat Point Z97, Intel Broadwell-H
Motherboard	Asus Maximus VII Ranger

AIDA64 v5.20.3440 Beta / BenchDLL 4.1.633-x64 (c) 1995-2015 FinalWire Ltd.

The eDRAM clock tops out at 1.6GHz.

There's only a single size of eDRAM offered this generation: 128MB. Since it's a cache and not a buffer (and a giant one at that), Intel found that hit rate rarely dropped below 95%. It turns out that for current workloads, Intel didn't see much benefit beyond a 32MB eDRAM however it wanted the design to be future proof. Intel

Meanwhile, the job market


STREAM
High Performance Computing

Search..

Schedule a meeting or Call +31 854865760

Industries | Our Services and Products | Technologies and Expertise | Our Partners and Activities | Our Company | Blog | Contact us

JOBS

StreamHPC > About Us > Jobs

We only have jobs for people who get bored easily.

In return we offer a solution to boredom, as performance engineering is hard.

As the market demand for affordable high performance software grows, StreamHPC continuously looks for people to join the team. With upcoming products and new markets like OpenCL on low-power ARM processors, we expect continuous growth for the years to come.

To apply send your motivation and a recent version of your CV to **jobs@streamhpc.com**. If you have LinkedIn, you can easily build a CV with Linkedin Resume Builder and send us the link.

- OpenCL/CUDA expert (Also accepting freelancers)
- Sales support

The procedure for the technical roles is as follows:

- You send a CV and tell us why you are the perfect candidate.
- After that you are invited for a longer online test. You show your skills on C/C++ and algorithms. You will receive a PDF with useful feedback.
- If you selected GPGPU or mentioned it, we send you a GPU assignment. You need to pick out the right optimisations, code it and explain your decisions. (Hopefully under 30 minutes)
- If all goes well, you'll have a videochat with Vincent (CEO) on personal and practical matters. You can also ask us anything, to find out if we fit you. (Around 1 hour)

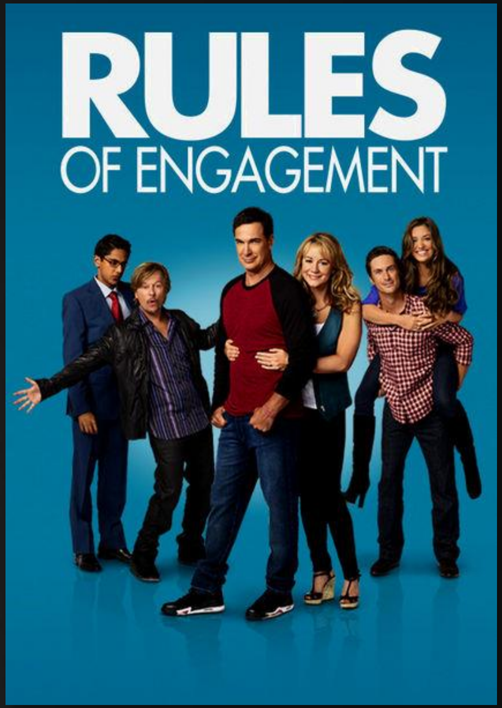
Today's Agenda:

- Introduction
- Intel: SSE
- Streams
- Vectorization

Introduction

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

Introduction

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
```

ut

ame
this
er).

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 }.
```

Introduction

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’.

Introduction

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;
}
```

Introduction

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;
}
```

Introduction

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;
}
```

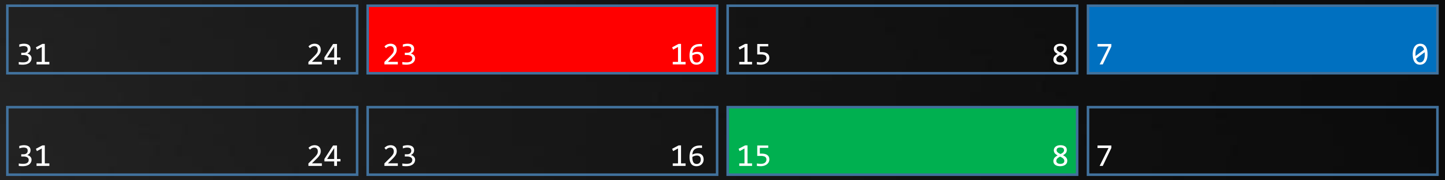
7 shifts, 3 ands, 3 muls, 2 adds

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

Introduction



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)

Introduction

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.

```
    for (int i = 0; i < q; i++)
00000001400022BD  movsxd      rdx,eax
00000001400022C0  test        eax,eax
00000001400022C2  jle         Tmpl8::Game::Tick+87h (01400022D7h)
00000001400022C4  xor         eax,eax
    {
        if (((int*)a)[i] != ((int*)b)[i])
00000001400022C6  mov         ecx,dword ptr b[rax*4]
00000001400022CA  cmp         dword ptr [rsp+rax*4],ecx
00000001400022CD  jne         Tmpl8::Game::Tick+87h (01400022D7h)
    for (int i = 0; i < q; i++)
00000001400022CF  inc         rax
00000001400022D2  cmp         rax,rdx
00000001400022D5  jl          Tmpl8::Game::Tick+76h (01400022C6h)
        {
            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;
  }
}
```

Introduction

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.

Introduction

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!

Today’s Agenda:

- Introduction
- Intel: SSE
- Streams
- Vectorization

SSE

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.

SSE

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]; };
```

SSE

SIMD Basics

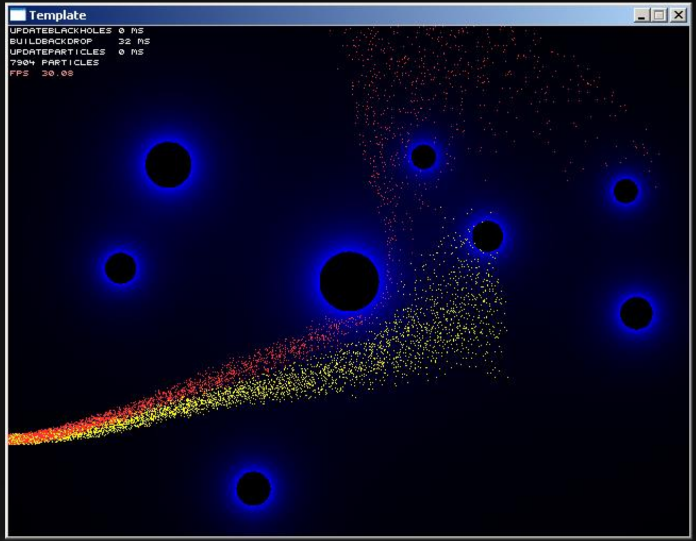
We operate on SSE data using *intrinsics*: in the case of SSE, these are keywords that translate to a single assembler instruction.

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.*

SSE



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 );
```

Keep the assembler-like syntax in mind:

```
__m128 d4 = dx4 * dx4 + dy4 * dy4;   (crossed out)

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

CODING TIME

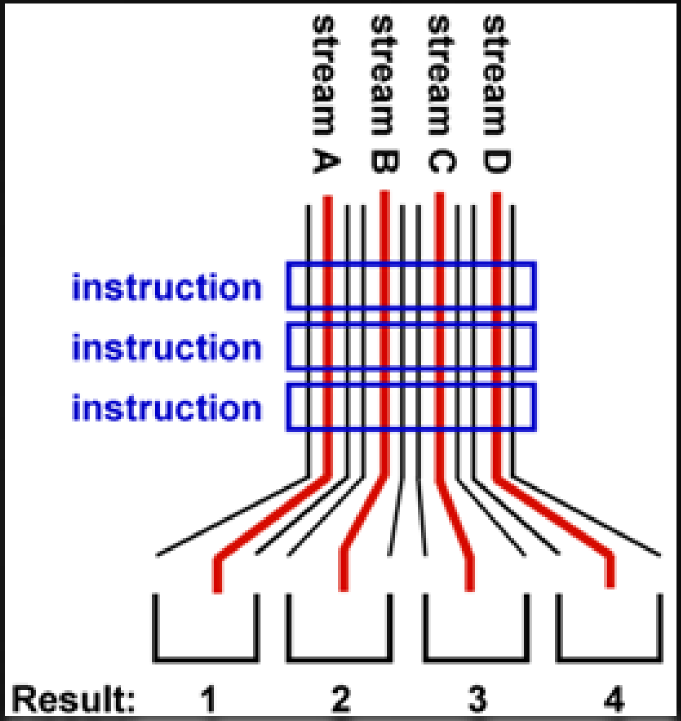
SSE

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…



Today’s Agenda:

- Introduction
- Intel: SSE
- Streams
- Vectorization

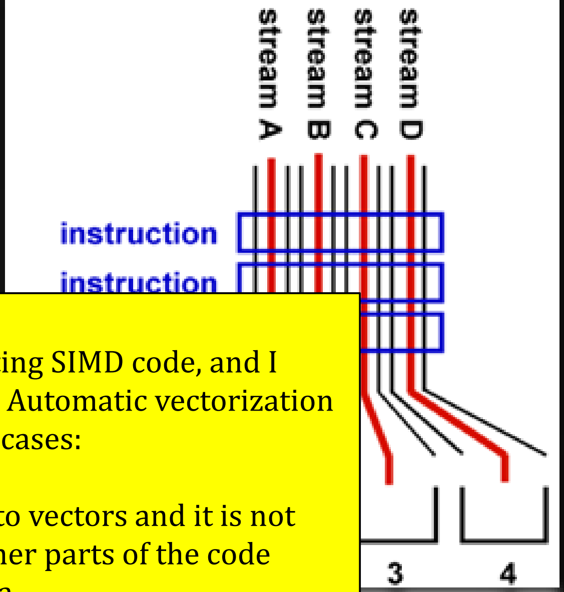
Streams

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 ope
vectors, and it will use SSE instructions
results in a modest speedup. Note that o

To get maximum throughput, we want fo
running in parallel.



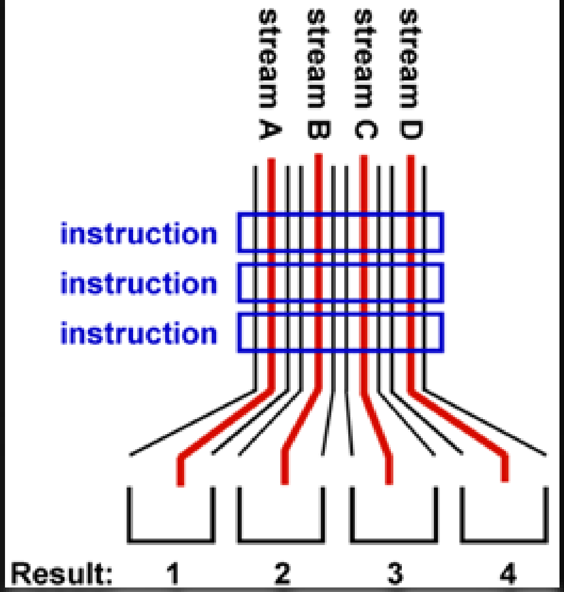
Agner Fog:
"Automatic vectorization is the easiest way of generating SIMD code, and I would recommend to use this method when it works. Automatic vectorization may fail or produce suboptimal code in the following cases:

- when the algorithm is too complex.
- when data have to be re-arranged in order to fit into vectors and it is not obvious to the compiler how to do this or when other parts of the code needs to be changed to handle the re-arranged data.
- when it is not known to the compiler which data sets are bigger or smaller than the vector size.
- when it is not known to the compiler whether the size of a data set is a multiple of the vector size or not.
- when the algorithm involves calls to functions that are defined elsewhere or cannot be inlined and which are not readily available in vector versions.
- when the algorithm involves many branches that are not easily vectorized.
- when floating point operations have to be reordered or transformed and it is not known to the compiler whether these transformations are permissible with respect to precision, overflow, etc.
- when functions are implemented with lookup tables.

Streams

SIMD According To Visual Studio

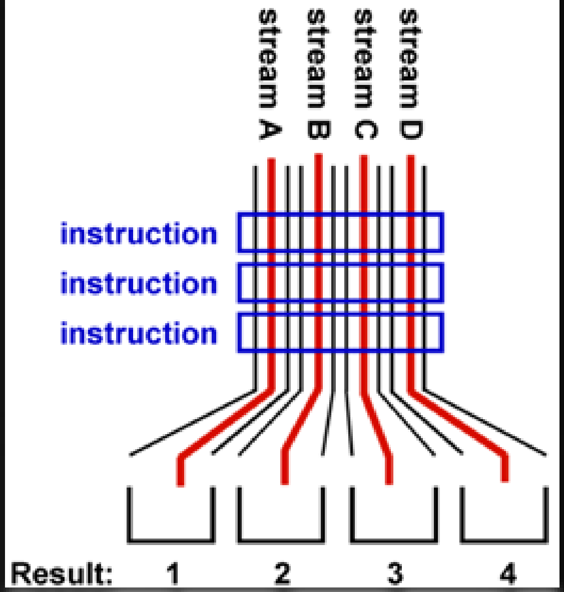
```
float Ax = 1, Ay = 0, Az = 0;
float Bx = 0, By = 1, Bz = 0;
float Cx = (Ax + Bx) * 0.1f;
float Cy = (Ay + By) * 0.1f;
float Cz = (Az + Bz) * 0.1f;
float l = sqrtf( Cx * Cx + Cy * Cy + Cz * Cz);
float Dx = Cx / l;
float Dy = Cy / l;
float Dz = Cz / l;
```



Streams

SIMD According To Visual Studio

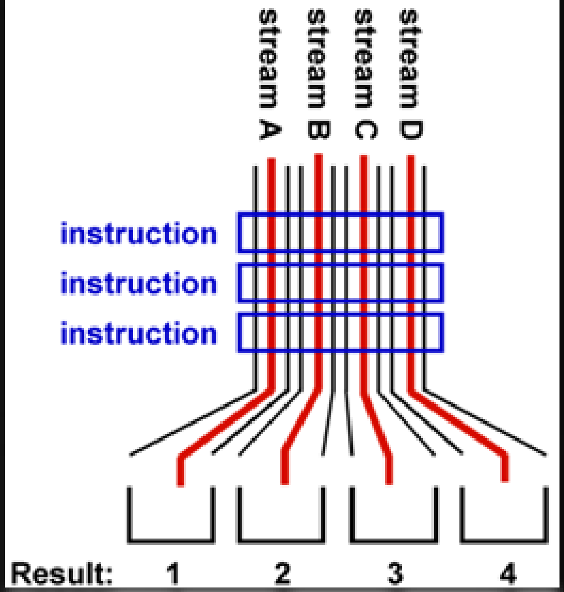
```
float Ax[4] = {…}, Ay[4] = {…}, Az[4] = {…};
float Bx[4] = {…}, By[4] = {…}, Bz[4] = {…};
float Cx[4] = …;
float Cy[4] = …;
float Cz[4] = …;
float l[4] = …;
float Dx[4] = …;
float Dy[4] = …;
float Dz[4] = …;
```



Streams

SIMD According To Visual Studio

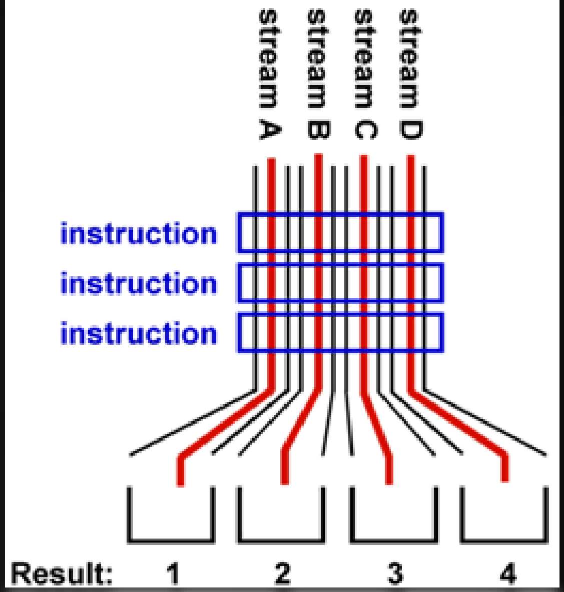
```
__m128 Ax4 = {…}, Ay4 = {…}, Az4 = {…};
__m128 Bx4 = {…}, By4 = {…}, Bz4 = {…};
__m128 Cx4 = …;
__m128 Cy4 = …;
__m128 Cz4 = …;
__m128 l4 = …;
__m128 Dx4 = …;
__m128 Dy4 = …;
__m128 Dz4 = …;
```



Streams

SIMD According To Visual Studio

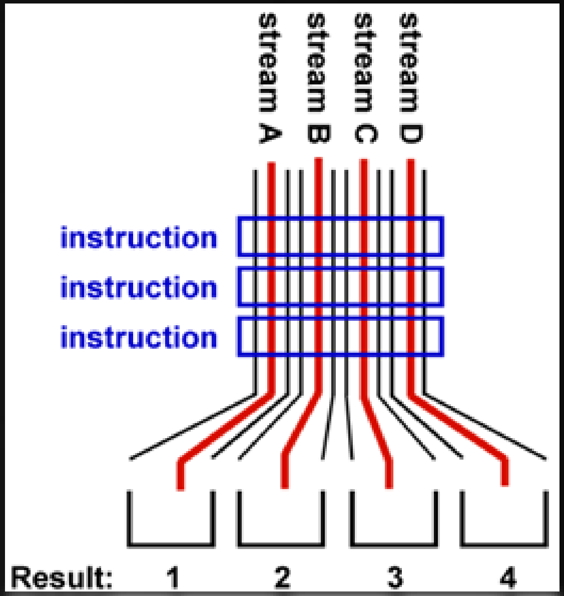
```
__m128 Ax4 = {…}, Ay4 = {…}, Az4 = {…};
__m128 Bx4 = {…}, By4 = {…}, Bz4 = {…};
__m128 X4 = _mm_set1_ps( 0.1f );
__m128 Cx4 = _mm_mul_ps( _mm_add_ps( Ax4, Bx4 ), X4 );
__m128 Cy4 = _mm_mul_ps( _mm_add_ps( Ay4, By4 ), X4 );
__m128 Cz4 = _mm_mul_ps( _mm_add_ps( Az4, Bz4 ), X4 );
__m128 l4 = …;
__m128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



Streams

SIMD According To Visual Studio

```
__m128 Ax4 = _mm_set_ps( Ax[0], Ax[1], Ax[2], Ax[3] );
__m128 Ay4 = _mm_set_ps( Ay[0], Ay[1], Ay[2], Ay[3] };
__m128 Az4 = _mm_set_ps( Az[0], Az[1], Az[2], Az[3] };
__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 = …;
```



Streams

SIMD Friendly Data Layout

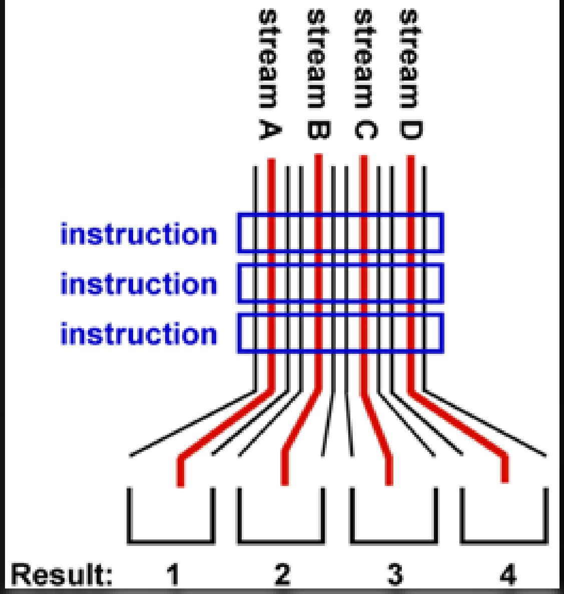
Consider the following data structure:

```
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



Streams

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.

Today's Agenda:

- Introduction
- Intel: SSE
- Streams
- Vectorization

Vectorization

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)

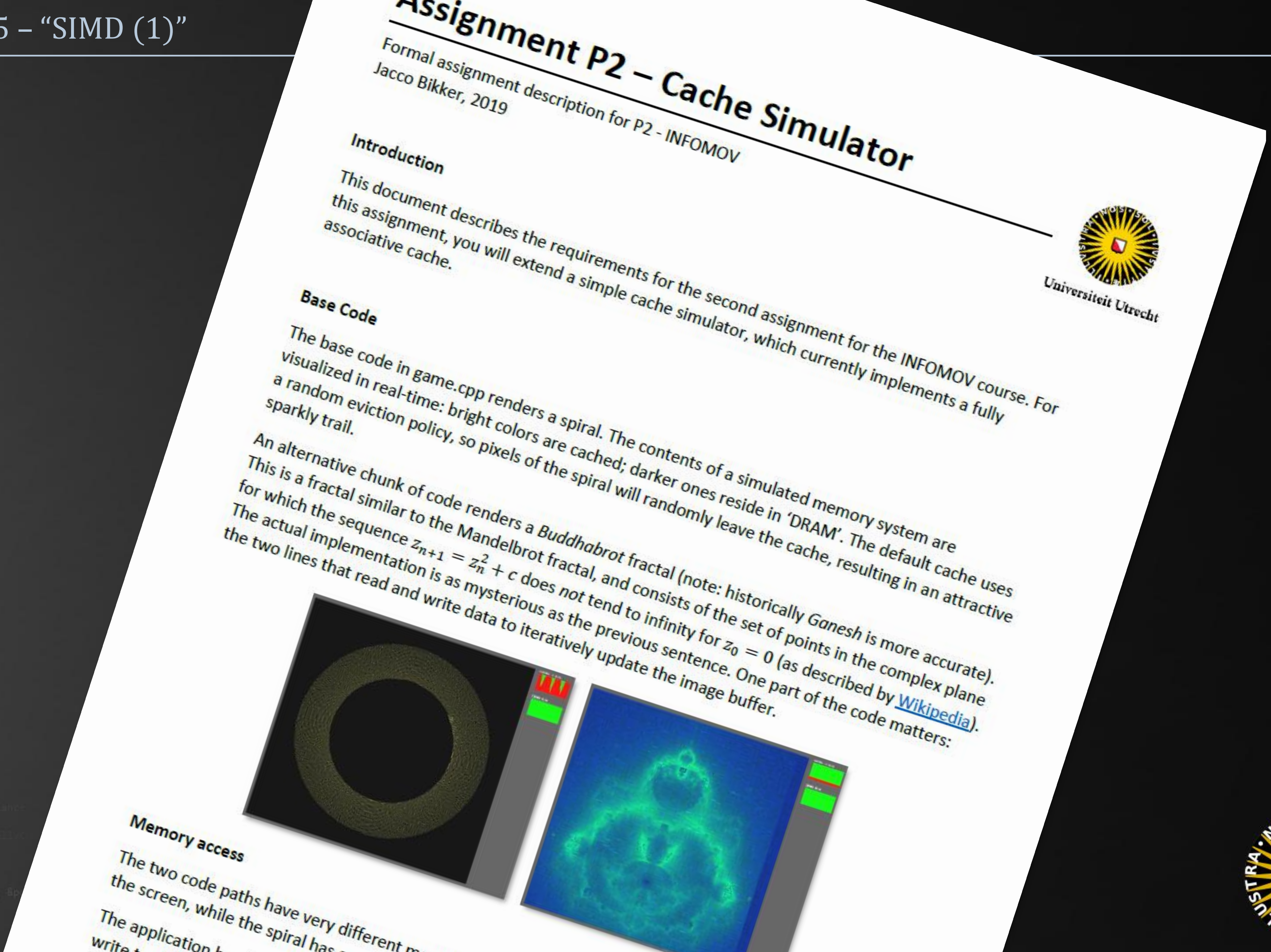
/INFOMOV/

END of "SIMD (1)"

next lecture: "SIMD (2)"

/PRACTICAL/

P2



Assignment P2 – Cache Simulator

Formal assignment description for P2 - INFOMOV

Jacco Bikker, 2019

Universiteit Utrecht

Introduction

This document describes the requirements for the second assignment for the INFOMOV course. For this assignment, you will extend a simple cache simulator, which currently implements a fully associative cache.

Base Code

The base code in game.cpp renders a spiral. The contents of a simulated memory system are visualized in real-time: bright colors are cached; darker ones reside in ‘DRAM’. The default cache uses a random eviction policy, so pixels of the spiral will randomly leave the cache, resulting in an attractive sparkly trail.

An alternative chunk of code renders a *Buddhabrot* fractal (note: historically *Ganesh* is more accurate). This is a fractal similar to the Mandelbrot fractal, and consists of the set of points in the complex plane for which the sequence $z_{n+1} = z_n^2 + c$ does *not* tend to infinity for $z_0 = 0$ (as described by Wikipedia). The actual implementation is as mysterious as the previous sentence. One part of the code matters: the two lines that read and write data to iteratively update the image buffer.

Memory access

The two code paths have very different m…

the screen, while the spiral has …

The application h…

write t…

/END OF PRACTICAL/