/INFOMOV/

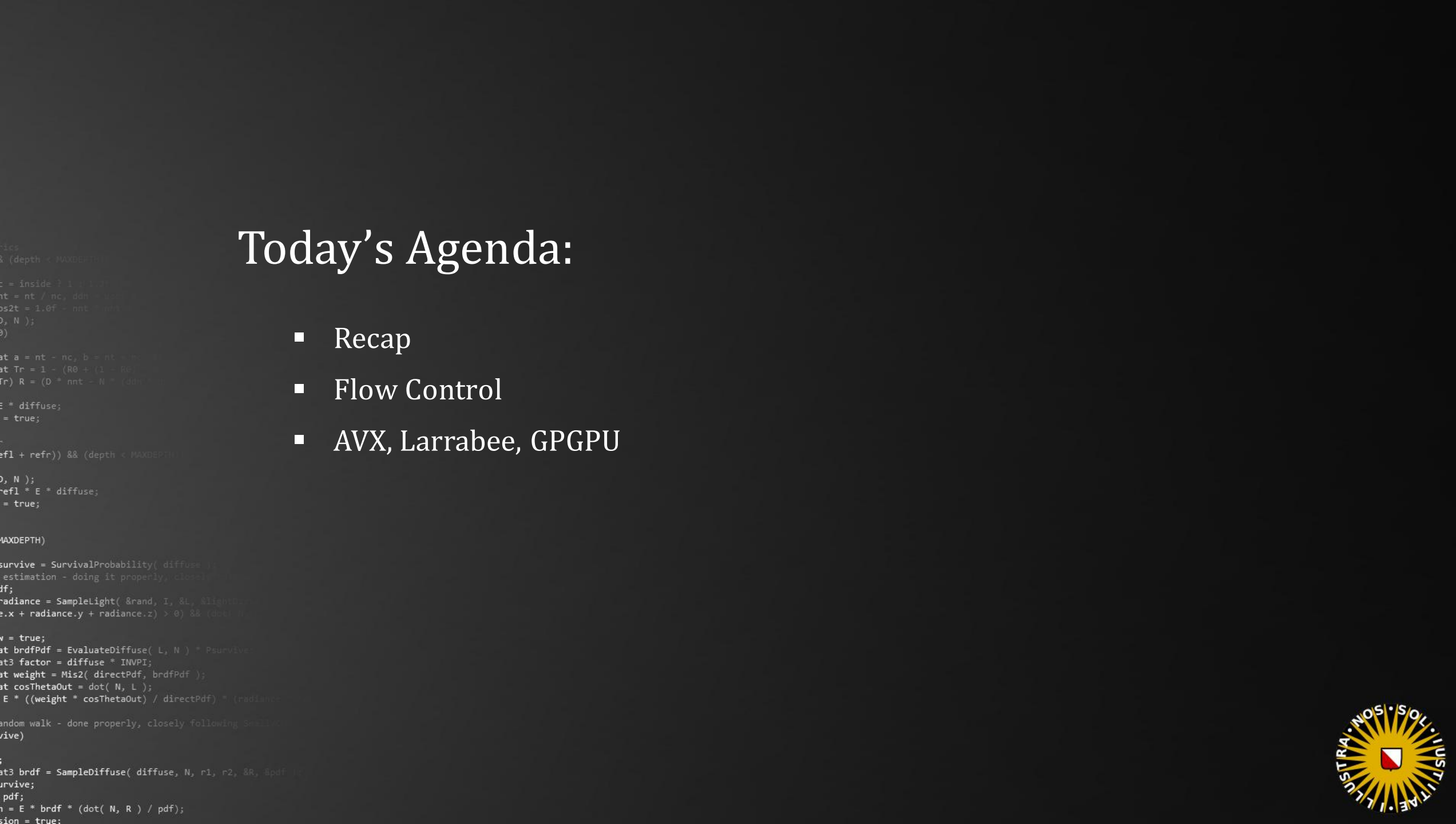
Optimization & Vectorization

J. Bikker - April - June 2024 - Lecture 7: “SIMD (2)”

Welcome!

Today’s Agenda:

- Recap
- Flow Control
- AVX, Larrabee, GPGPU



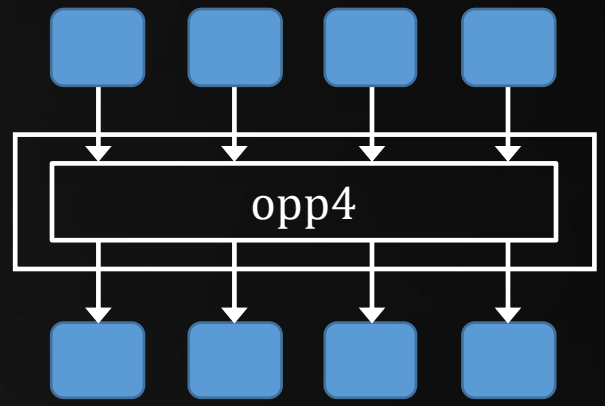
Recap

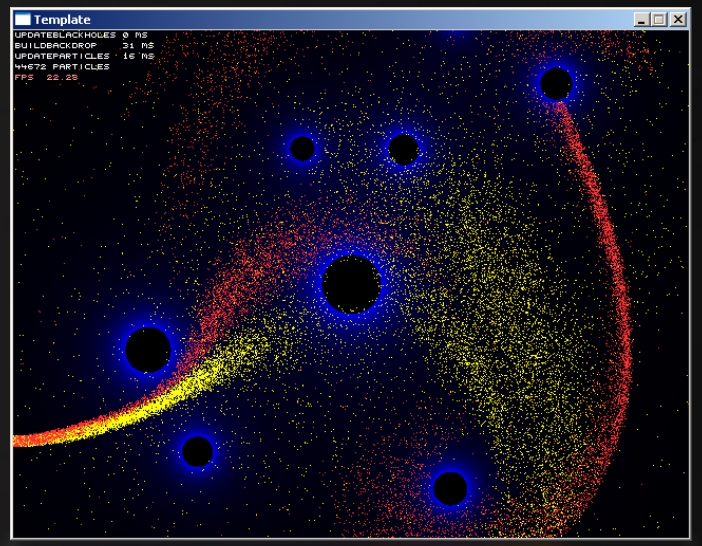
SSE: Four Floats

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

a4 = _mm_sub_ps( val1, val2 );
float sum = a[0] + a[1] + a[2] + a[3];

__m128 b4 = _mm_sqrt_ps( a4 );
__m128 m4 = _mm_max_ps( a4, b4 );
```





Recap

SSE: Four Floats

```
_mm_add_ps
_mm_sub_ps
_mm_mul_ps
_mm_div_ps

_mm_sqrt_ps
_mm_rcp_ps
_mm_rsqrt_ps
```

```
_mm_add_epi32
_mm_sub_epi32
_mm_mul_epi32
_mm_div_epi32

_mm_sqrt_epi32
_mm_rcp_epi32
_mm_rsqrt_epi32

_mm_cvtps_epi32
_mm_cvtepi32_ps

_mm_slli_epi32
_mm_srai_epi32

_mm_cmpeq_epi32
```

```
_mm_add_epi16
_mm_sub_epi16

_mm_add_epu8
_mm_sub_epu8

_mm_mul_epu32

_mm_add_epi64
_mm_sub_epi64
```

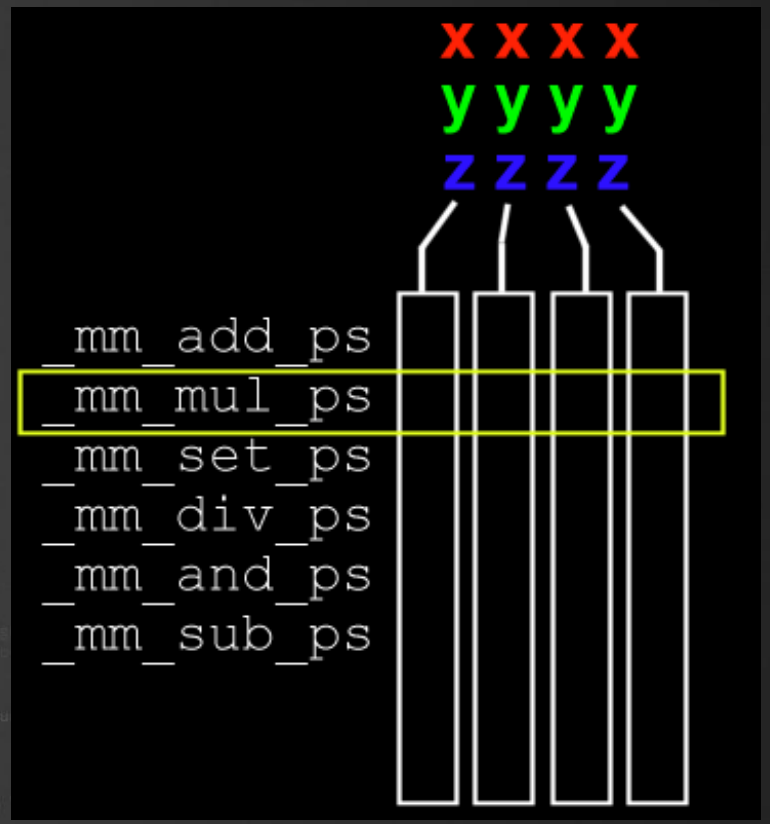
Actually…
_mm_mul_epi32 *does* exist. However, it produces 2 64-bit numbers, not 4 32-bit numbers.

Actually…
Intel’s ‘short vector math lib’ (SVML) has the _mm_div_epi32 instruction. However, as they note:

1. It’s a ‘sequence of instructions’;
2. “Many routines in the SVML are ‘more optimized’ for Intel CPUs.” **(read: are deliberately crippled for AMD)**

Recap

SSE: Four Floats



AOS

SOA

structure of arrays

Recap

SSE: Four Floats

```
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

Recap

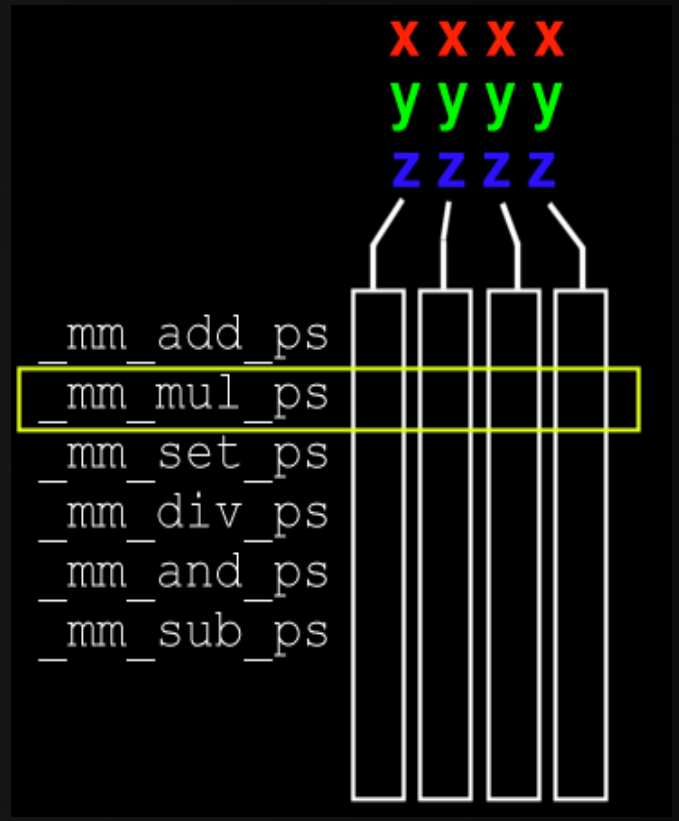
Vectorization:

“The Art of rewriting your algorithm so that it operates in four separate streams, rather than one.”

Note: compilers will apply SSE2/3/4 for you as well:

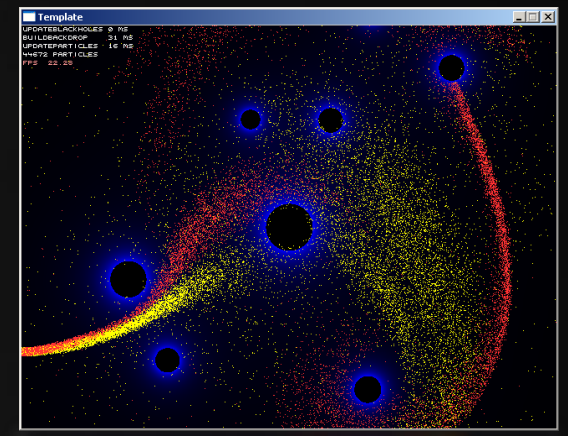
```
vector3f A = { 0, 1, 2 };
vector3f B = { 5, 5, 5 };
A += B;
```

This will marginally speed up *one line* of your code; manual vectorization is fundamental and requires data reordering.



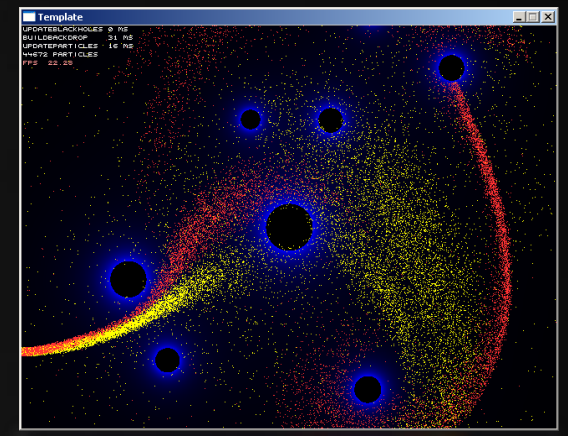
Recap

```
void Game::BuildBackdrop()
{
    Pixel* dst = m_Surface->GetBuffer();
    float fy = 0;
    for ( unsigned int y = 0; y < SCRHEIGHT; y++, fy++ )
    {
        float fx = 0;
        for ( unsigned int x = 0; x < SCRWIDTH; x++, fx++ )
        {
            float g = 0;
            for ( unsigned int i = 0; i < HOLES; i++ )
            {
                float dx = m_Hole[i]->x - fx, dy = m_Hole[i]->y - fy;
                float squareddist = ( dx * dx + dy * dy );
                g += (250.0f * m_Hole[i]->g) / squareddist;
            }
            if (g > 1) g = 0;
            *dst++ = (int)(g * 255.0f);
        }
        dst += m_Surface->GetPitch() - m_Surface->GetWidth();
    }
}
```



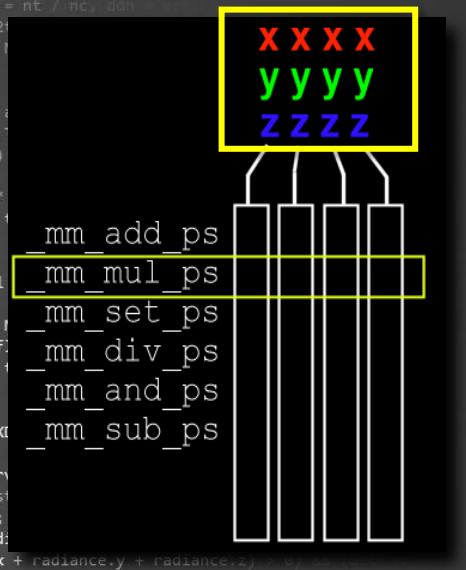
Recap

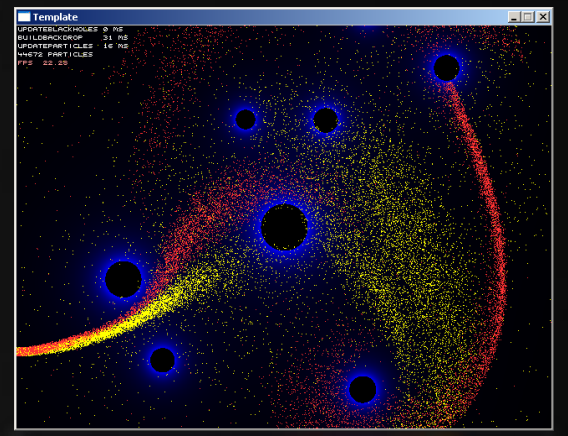
```
void Game::BuildBackdrop()
{
    Pixel* dst = m_Surface->GetBuffer();
    float fy = 0;
    for ( unsigned int y = 0; y < SCRHEIGHT; y++, fy++ )
    {
        float fx = 0;
        for ( unsigned int x = 0; x < SCRWIDTH; x++, fx++ )
        {
            float g = 0;
            for ( unsigned int i = 0; i < HOLES / 4; i++ )
            {
                float dx = m_Hole[i]->x - fx, dy = m_Hole[i]->y - fy;
                float squareddist = ( dx * dx + dy * dy );
                g += (250.0f * m_Hole[i]->g) / squareddist;
            }
            if (g > 1) g = 0;
            *dst++ = (int)(g * 255.0f);
        }
        dst += m_Surface->GetPitch() - m_Surface->GetWidth();
    }
}
```



Recap

```
void Game::BuildBackdrop()
{
    Pixel* dst = m_Surface->GetBuffer();
    float fy = 0;
    for ( unsigned int y = 0; y < SCRHEIGHT; y++, fy++ )
    {
        float fx = 0;
        for ( unsigned int x = 0; x < SCRWIDTH; x++, fx++ )
        {
            float g = 0; __m128 g4 = _mm_setzero_ps();
            for ( unsigned int i = 0; i < HOLES / 4; i++ )
            {
                __m128 dx4 = _mm_sub_ps( bhx4[i], fx4 );
                __m128 dy4 = _mm_sub_ps( bhy4[i], fy4 );
                __m128 sq4 = _mm_add_ps( _mm_mul_ps( dx4, dx4 ), _mm_mul_ps( dy4, dy4 ) );
                __m128 mulresult4 = _mm_mul_ps( _mm_set1_ps( 250.0f ), bhg4[i] );
                g4 = _mm_add_ps( g4, _mm_div_ps( mulresult4, sq4 ) );
            }
            if (g > 1) g = 0;
            *dst++ = (int)(g * 255.0f);
        }
        dst += m_Surface->GetPitch() - m_Surface->GetWidth();
    }
}
```

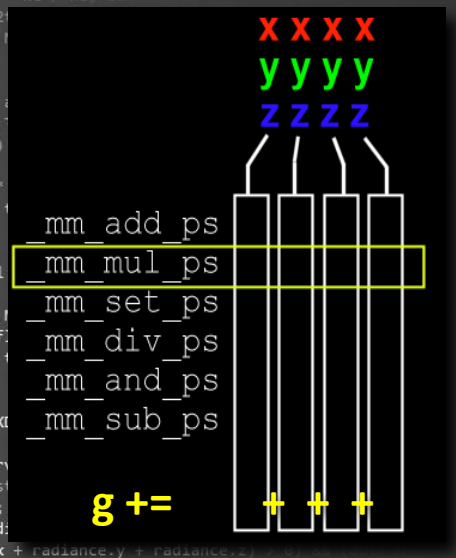


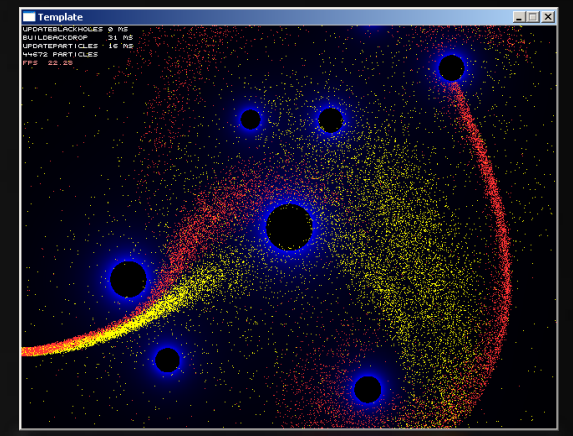


Recap

```
void Game::BuildBackdrop()
{
    Pixel* dst = m_Surface->GetBuffer();
    float fy = 0;
    for ( unsigned int y = 0; y < SCRHEIGHT; y++, fy++ )
    {
        float fx = 0;
        for ( unsigned int x = 0; x < SCRWIDTH; x++, fx++ )
        {
            float g = 0; __m128 g4 = _mm_setzero_ps();
            for ( unsigned int i = 0; i < HOLES / 4; i++ )
            {
                __m128 dx4 = _mm_sub_ps( bhx4[i], fx4 );
                __m128 dy4 = _mm_sub_ps( bhy4[i], fy4 );
                __m128 sq4 = _mm_add_ps( _mm_mul_ps( dx4, dx4 ), _mm_mul_ps( dy4, dy4 ) );
                __m128 mulresult4 = _mm_mul_ps( _mm_set1_ps( 250.0f ), bhg4[i] );
                g4 = _mm_add_ps( g4, _mm_div_ps( mulresult4, sq4 ) );
            }
            g += g_[0] + g_[1] + g_[2] + g_[3];
            if (g > 1) g = 0;
            *dst++ = (int)(g * 255.0f);
        }
        dst += m_Surface->GetPitch() - m_Surface->GetWidth();
    }
}
```

“Horizontal operation”





Today’s Agenda:

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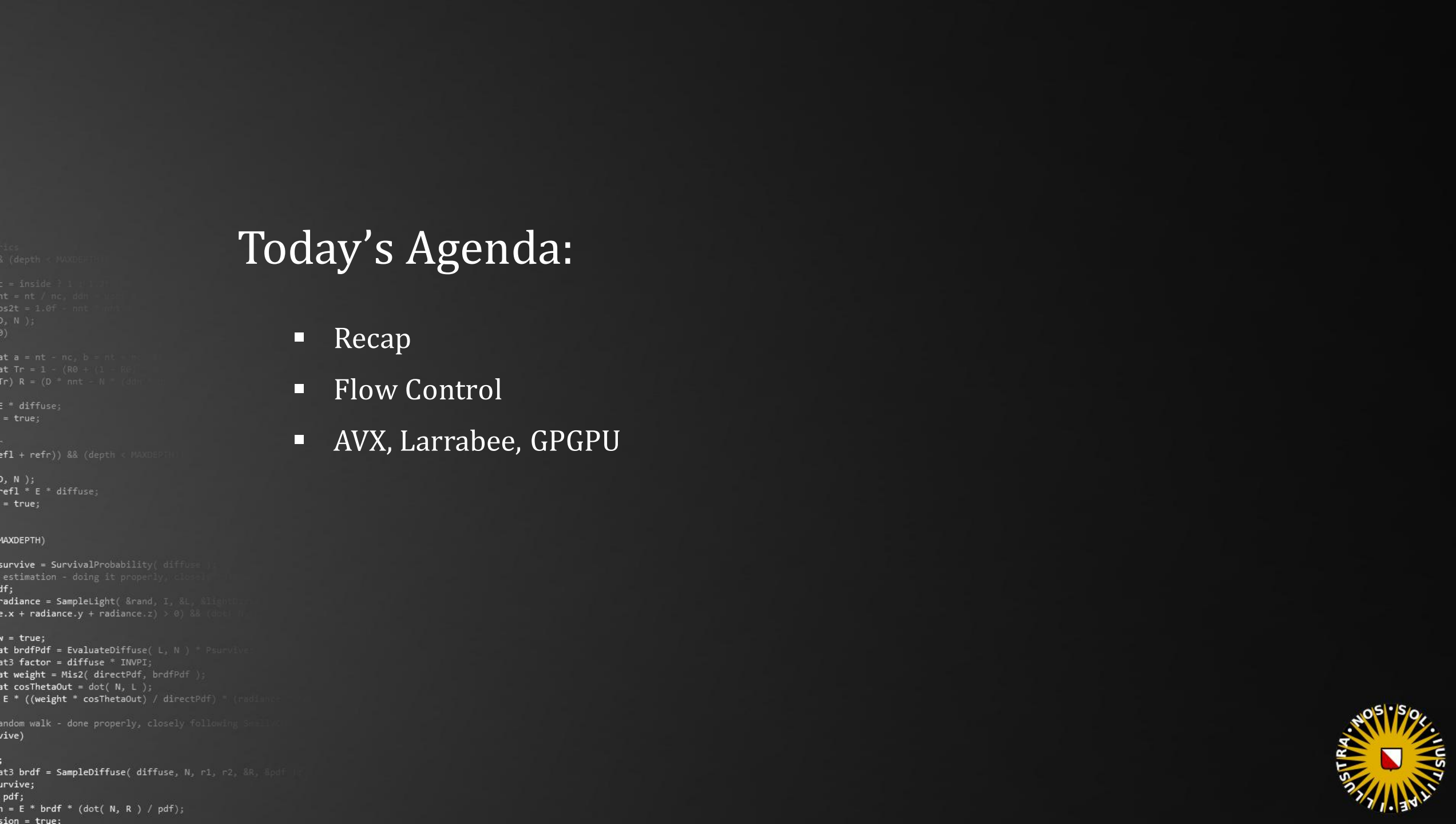


Flow

```
for ( uint i = 0; i < PARTICLES; i++ ) if (m_Particle[i]->alive)
{
    m_Particle[i]->x += m_Particle[i]->vx;
    m_Particle[i]->y += m_Particle[i]->vy;
    if (!((m_Particle[i]->x < (2 * SCRWIDTH)) && (m_Particle[i]->x > -SCRWIDTH) &&
          (m_Particle[i]->y < (2 * SCRHEIGHT)) && (m_Particle[i]->y > -SCRHEIGHT)))
    {
        SpawnParticle( i );
        continue;
    }
    for ( uint h = 0; h < HOLES; h++ )
    {
        float dx = m_Hole[h]->x - m_Particle[i]->x;
        float dy = m_Hole[h]->y - m_Particle[i]->y;
        float sd = dx * dx + dy * dy;
        float dist = 1.0f / sqrtf( sd );
        dx *= dist, dy *= dist;
        float g = (250.0f * m_Hole[h]->g * m_Particle[i]->m) / sd;
        if (g >= 1) { SpawnParticle( i ); break; }
        m_Particle[i]->vx += 0.5f * g * dx;
        m_Particle[i]->vy += 0.5f * g * dy;
    }
    int x = (int)m_Particle[i]->x, y = (int)m_Particle[i]->y;
    if ((x >= 0) && (x < SCRWIDTH) && (y >= 0) && (y < SCRHEIGHT))
        m_Surface->GetBuffer()[x + y * m_Surface->GetPitch()] = m_Particle[i]->c;
}
```

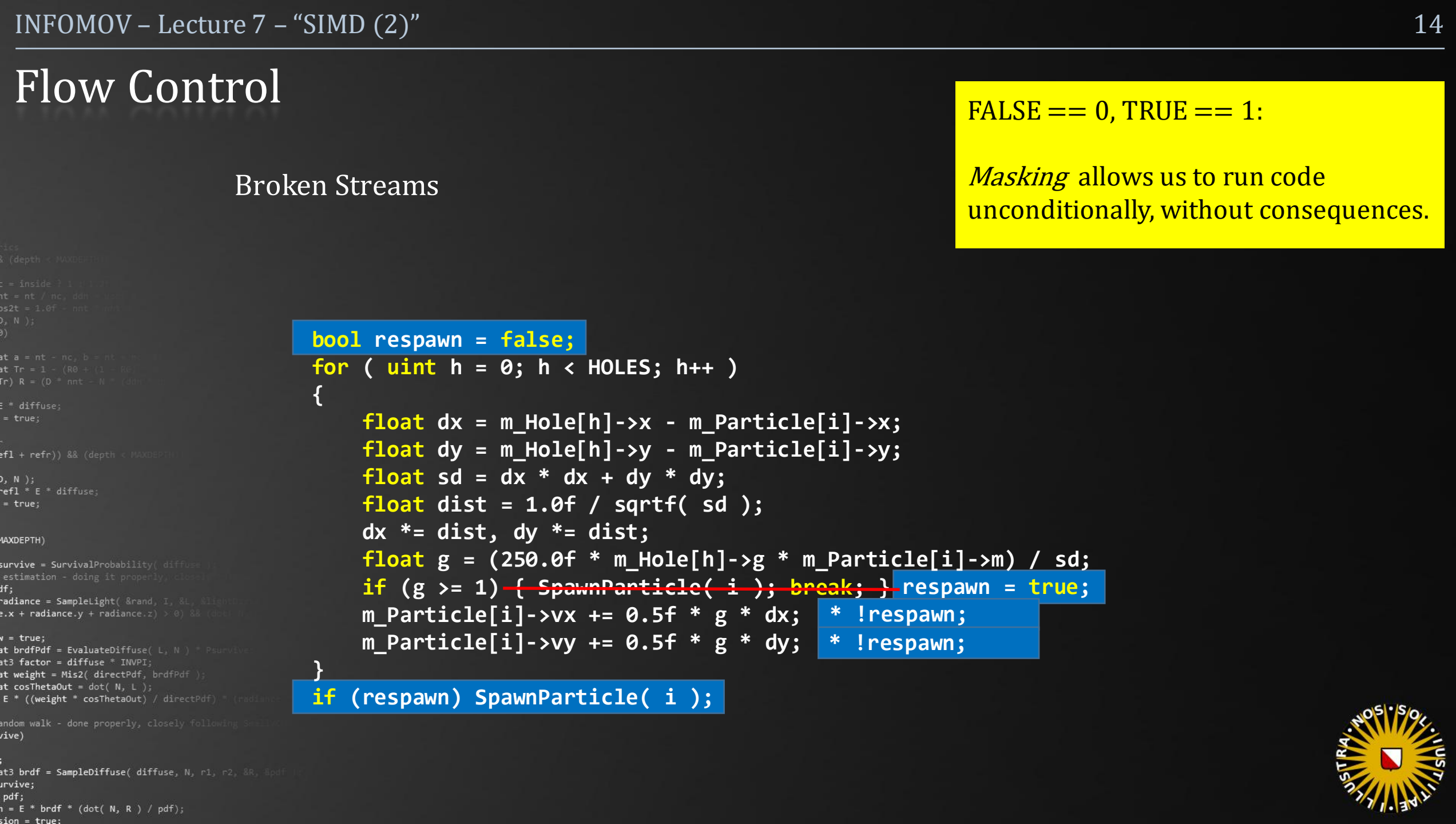
Flow Control

Broken Streams

```
bool respawn = false;
for ( uint h = 0; h < HOLES; h++ )
{
    float dx = m_Hole[h]->x - m_Particle[i]->x;
    float dy = m_Hole[h]->y - m_Particle[i]->y;
    float sd = dx * dx + dy * dy;
    float dist = 1.0f / sqrtf( sd );
    dx *= dist, dy *= dist;
    float g = (250.0f * m_Hole[h]->g * m_Particle[i]->m) / sd;
    if (g >= 1) { SpawnParticle( i ); break; } respawn = true;
    m_Particle[i]->vx += 0.5f * g * dx; * !respawn;
    m_Particle[i]->vy += 0.5f * g * dy; * !respawn;
}
if (respawn) SpawnParticle( i );
```

FALSE == 0, TRUE == 1:

Masking allows us to run code unconditionally, without consequences.



Flow Control

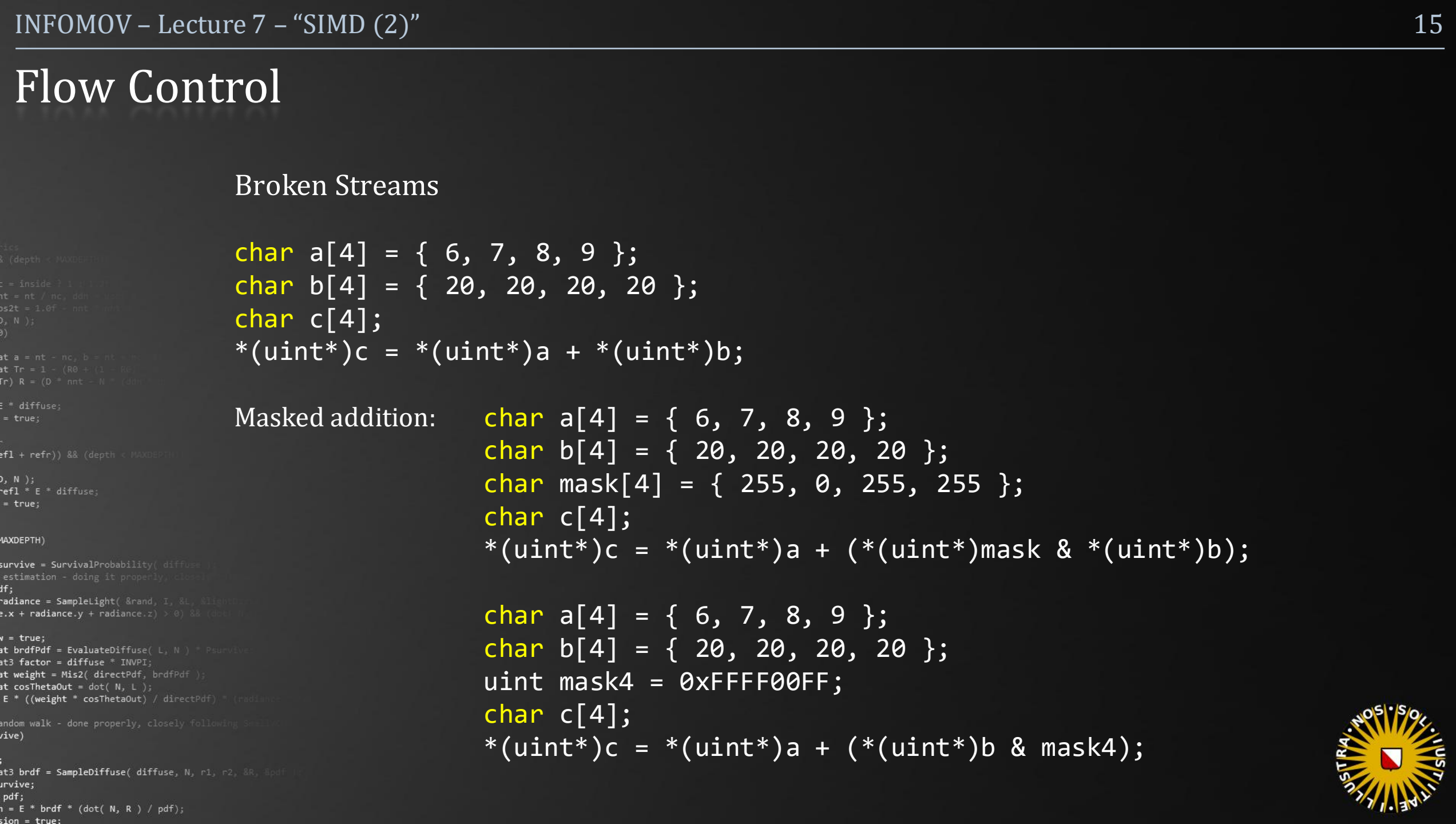
Broken Streams

```
char a[4] = { 6, 7, 8, 9 };
char b[4] = { 20, 20, 20, 20 };
char c[4];
*(uint*)c = *(uint*)a + *(uint*)b;
```

Masked addition:

```
char a[4] = { 6, 7, 8, 9 };
char b[4] = { 20, 20, 20, 20 };
char mask[4] = { 255, 0, 255, 255 };
char c[4];
*(uint*)c = *(uint*)a + (*(uint*)mask & *(uint*)b);
```

```
char a[4] = { 6, 7, 8, 9 };
char b[4] = { 20, 20, 20, 20 };
uint mask4 = 0xFFFF00FF;
char c[4];
*(uint*)c = *(uint*)a + (*(uint*)b & mask4);
```



Flow Control

Broken Streams

```
_mm_cmpeq_ps        ==
_mm_cmplt_ps        <
_mm_cmpgt_ps        >
_mm_cmple_ps        <=
_mm_cmpge_ps        >=
_mm_cmpne_ps        !=
```

Flow Control

Broken Streams – Flow Divergence

Like other instructions, comparisons between vectors yield a *vector* of booleans.

```
__m128 mask = _mm_cmpeq_ps( v1, v2 );
```

The mask contains a bitfield: 32 x ‘1’ for each TRUE, 32 x ‘0’ for each FALSE.

The mask can be converted to a 4-bit integer using _mm_movemask_ps:

```
int result = _mm_movemask_ps( mask );
```

Now we can use regular conditionals:

```
if (result == 0)  { /* false for all streams */ }
if (result == 15) { /* true for all streams */ }
if (result < 15)  { /* not true for all streams */ }
if (result > 0)   { /* not false for all streams */ }
```

Flow Control

Streams – Masking

More powerful than ‘any’, ‘all’ or ‘none’ via movemask is *masking*.

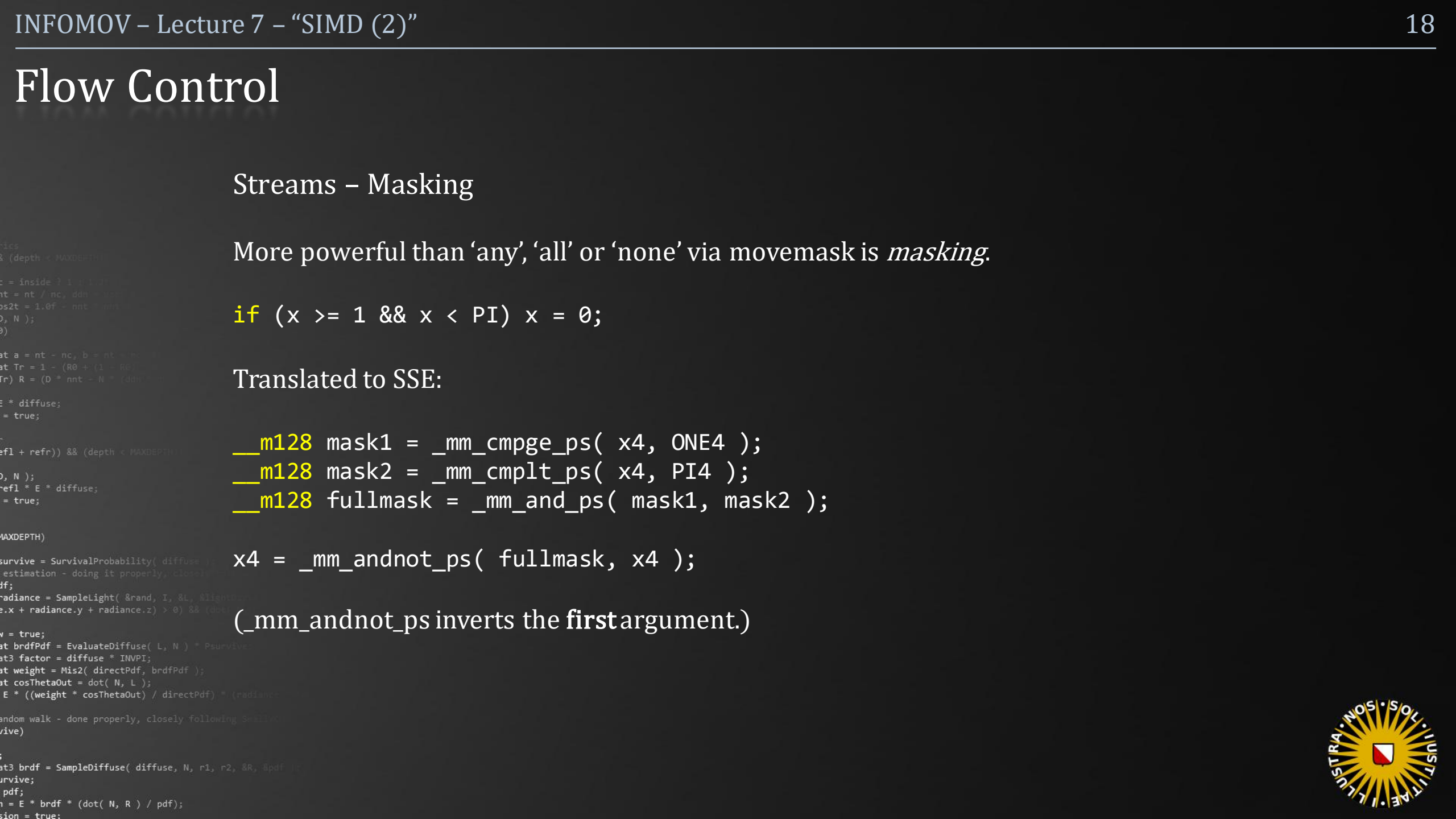
```
if (x >= 1 && x < PI) x = 0;
```

Translated to SSE:

```
__m128 mask1 = _mm_cmpge_ps( x4, ONE4 );
__m128 mask2 = _mm_cmplt_ps( x4, PI4 );
__m128 fullmask = _mm_and_ps( mask1, mask2 );

x4 = _mm_andnot_ps( fullmask, x4 );
```

(_mm_andnot_ps inverts the **first** argument.)



Flow Control

Streams – Masking

```
float a[4] = { 1, -5, 3.14f, 0 };
if (a[0] < 0) a[0] = 999;
if (a[1] < 0) a[1] = 999;
if (a[2] < 0) a[2] = 999;
if (a[3] < 0) a[3] = 999;
```

in SSE:

```
__m128 a4 = _mm_set_ps( 1, -5, 3.14f, 0 );
__m128 nine4 = _mm_set_ps1( 999 );
__m128 zero4 = _mm_setzero_ps();
__m128 mask = _mm_cmplt_ps( a4, zero4 );
```

00000000000000000000000000000001111111111111111111111111111100000000000000000000000000000000000000000000000000000000000000000000

Flow Control

Streams – Masking

```
__m128 a4 = _mm_set_ps( 1, -5, 3.14f, 0 );
__m128 nine4 = _mm_set_ps1( 999 );
__m128 zero4 = _mm_setzero_ps();
__m128 mask = _mm_cmplt_ps( a4, zero4 );
```

00000000000000000000000000000001111111111111111111111111111110000000000000000000000000000000000000000000000000000000000000000

```
__m128 part1 = _mm_and_ps( mask, nine4 );
// yields: { 0, 999, 0, 0 }

__m128 part2 = _mm_andnot_ps( mask, a4 );
// yields: { 1, 0, 3.14, 0 }

a4 = _mm_or_ps( part1, part2 );
// yields: { 1, 999, 3.14, 0 }
```

…or simply: `a4 = _mm_blendv_ps( a4, nine4, mask );` ☺

Flow Control

Streams – Masking

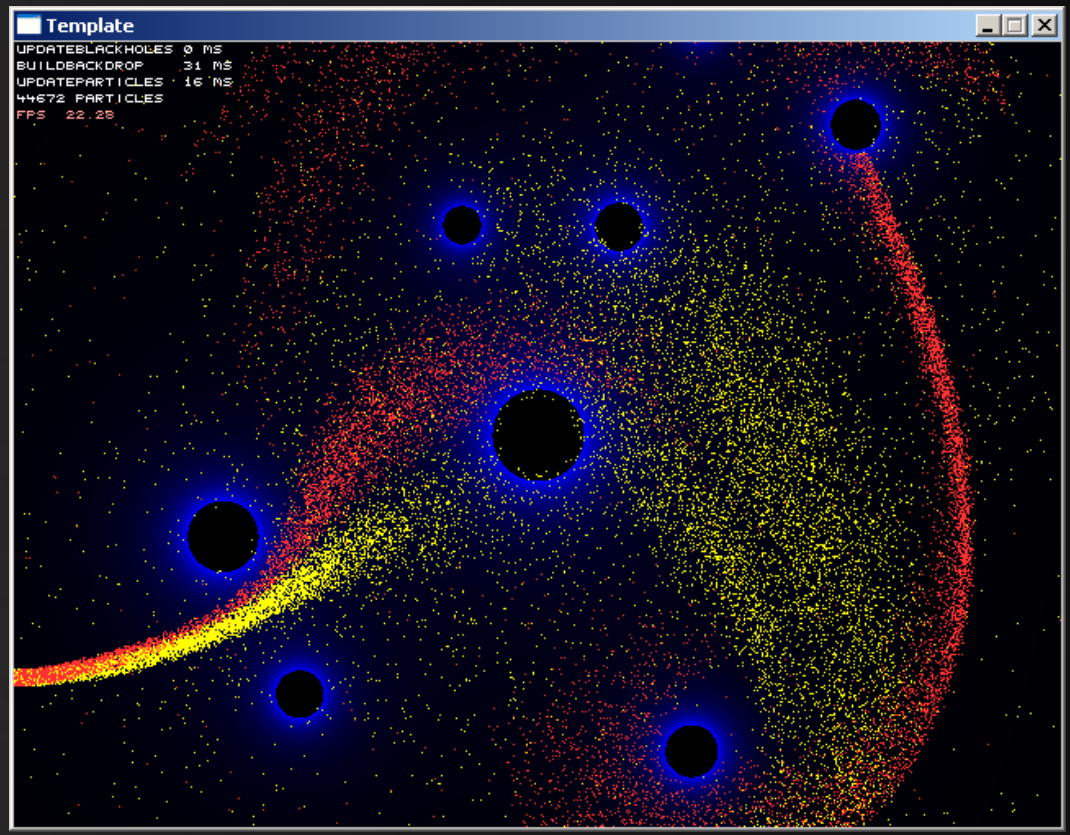
Take-away:

- In vectorized code, stream divergence is not possible.
- We solve this by keeping all lanes alive.
- ‘Inactive lanes’ use *masking* to nullify actions.

This approach is used in SSE/AVX, as well as on GPUs.

Flow Control

Streams – Masking

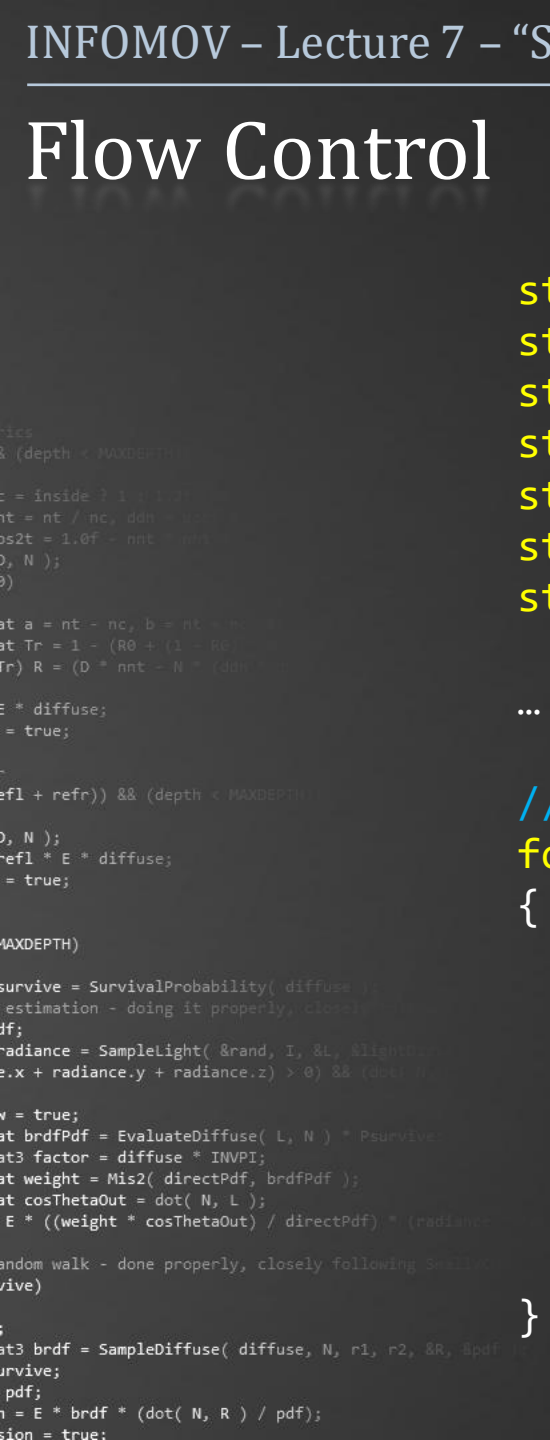


Flow Control

```
static union { float px[PARTICLES]; __m128 px4[PARTICLES / 4]; };
static union { float py[PARTICLES]; __m128 py4[PARTICLES / 4]; };
static union { float pvx[PARTICLES]; __m128 pvx4[PARTICLES / 4]; };
static union { float pvy[PARTICLES]; __m128 pvy4[PARTICLES / 4]; };
static union { float pm[PARTICLES]; __m128 pm4[PARTICLES / 4]; };
static bool pa[PARTICLES];
static union { uint pc[PARTICLES]; __m128i pc4[PARTICLES / 4]; };

…

// convert to SoA
for( int i = 0; i < PARTICLES; i++ )
{
     px[i] = m_Particle[i]->x;
     py[i] = m_Particle[i]->y;
     pvx[i] = m_Particle[i]->vx;
     pvy[i] = m_Particle[i]->vy;
     pa[i] = m_Particle[i]->alive;
     pc[i] = m_Particle[i]->c;
     pm[i] = m_Particle[i]->m;
}
```



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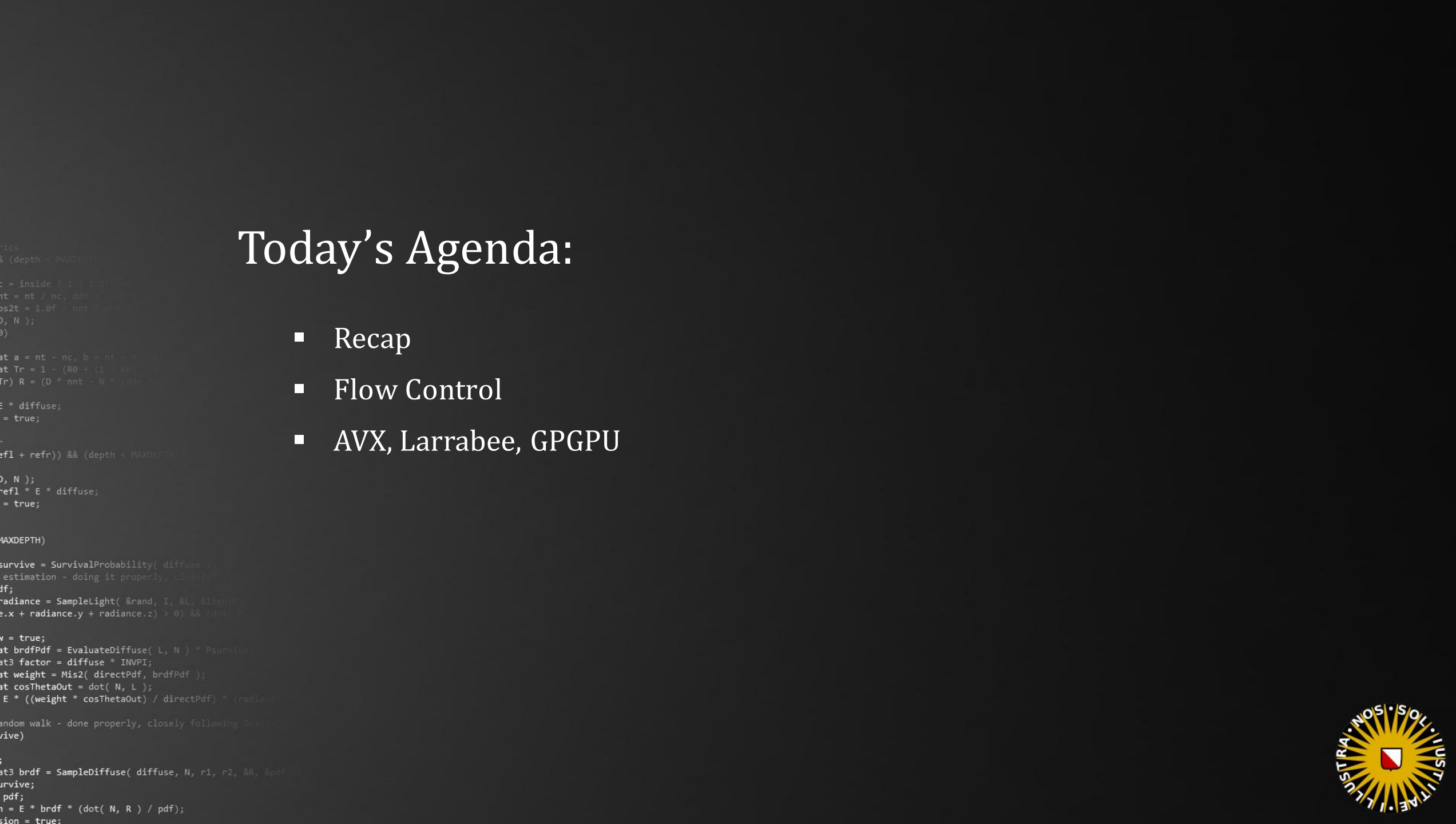
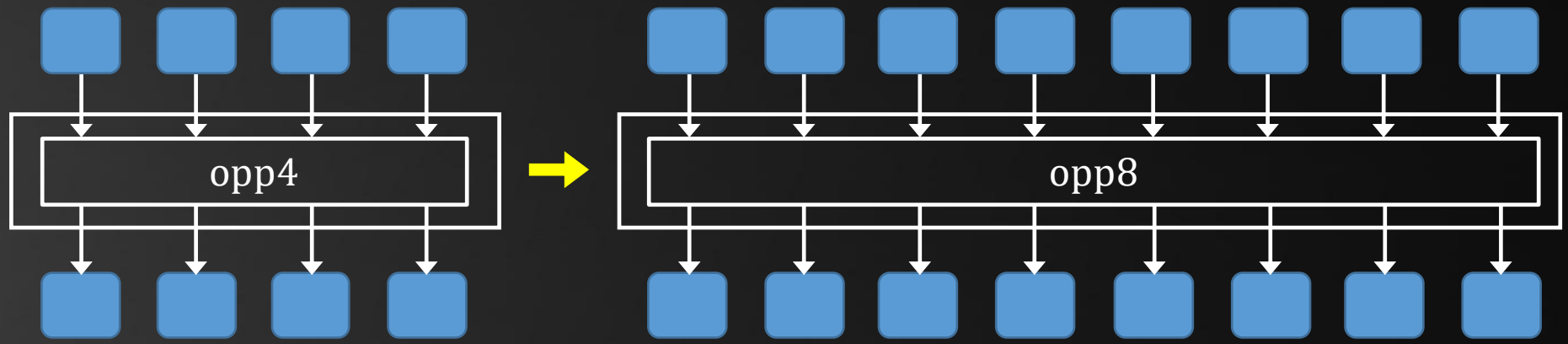


Beyond SSE

AVX*




```
__m256          _mm256_add_ps
                _mm256_sqrt_ps
                ...etc.
```

*: On: ‘Sandy Bridge’ (Intel, 2011), ‘Bulldozer’ (AMD, 2011).

Beyond SSE

AVX2*

Extension to AVX: adds broader __mm256i support, and FMA:

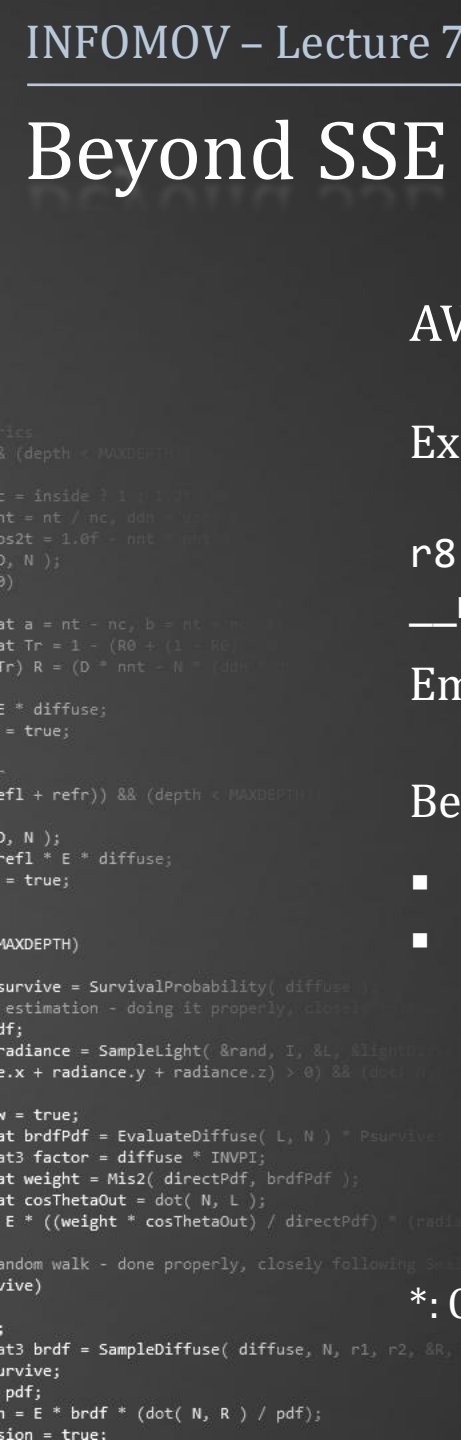
```
r8 = (a8*b8)+c8
__m256 r8 = _mm256_fmadd_ps( a8, b8, c8 );
```

Emulate on AVX: `r8 = _mm256_add_ps( _mm256_mul_ps( a8, b8 ), c8 );`

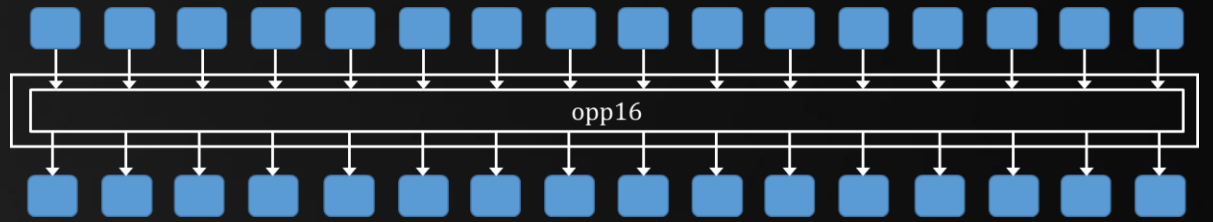
Benefits of *fused multiply and add*:

- Even more work done for a single ‘fetch-decode’
- Better precision: rounding doesn’t happen between multiply and add

*: On: ‘Haswell’ (Intel, 2013), ‘Carrizo’ and ‘Zen’ (AMD, 2015, 2017).



Beyond SSE



AVX512*

16-wide SIMD, with 32 512-bit registers (__m512, __m512i).

Most AVX512 instructions can be masked:

```
__m512 _mm512_maskz_add_ps( __mmask16 k, __m512 a, __m512 b )
```

“Add packed single-precision (32-bit) floating-point elements in a and b, and store the results in dst using zeromask k (elements are zeroed out when the corresponding mask bit is not set).”

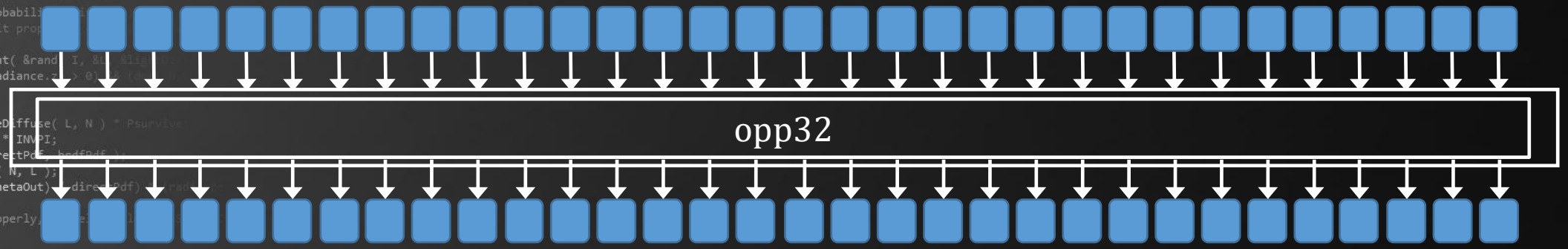
For a full list of instructions, see:
https://software.intel.com/sites/landingpage/IntrinsicsGuide

*: On: ‘Skylake-X’ (Intel, 2013), ‘Carrizo’ and ‘Zen’ (AMD, 2015, 2017).

Beyond SSE

GPU Model

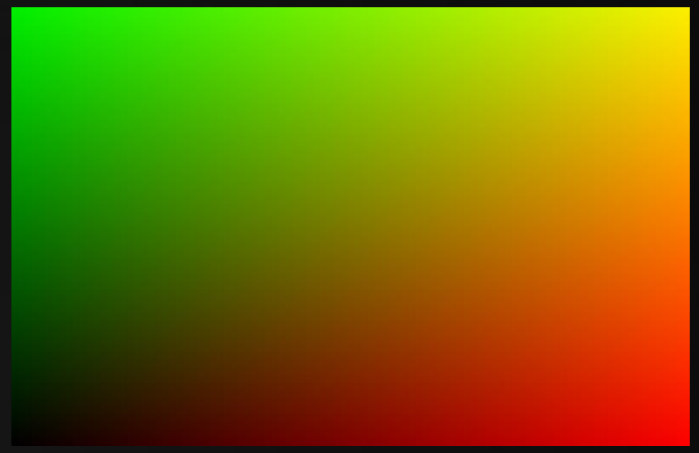
```
__kernel void main( write_only image2d_t outimg )
{
    int column = get_global_id( 0 );
    int line = get_global_id( 1 );
    float red = column / 800.;
    float green = line / 480.;
    float4 color = { red, green, 0, 1 };
    write_imagef( outimg, (int2)(column, line), color );
}
```



Beyond SSE

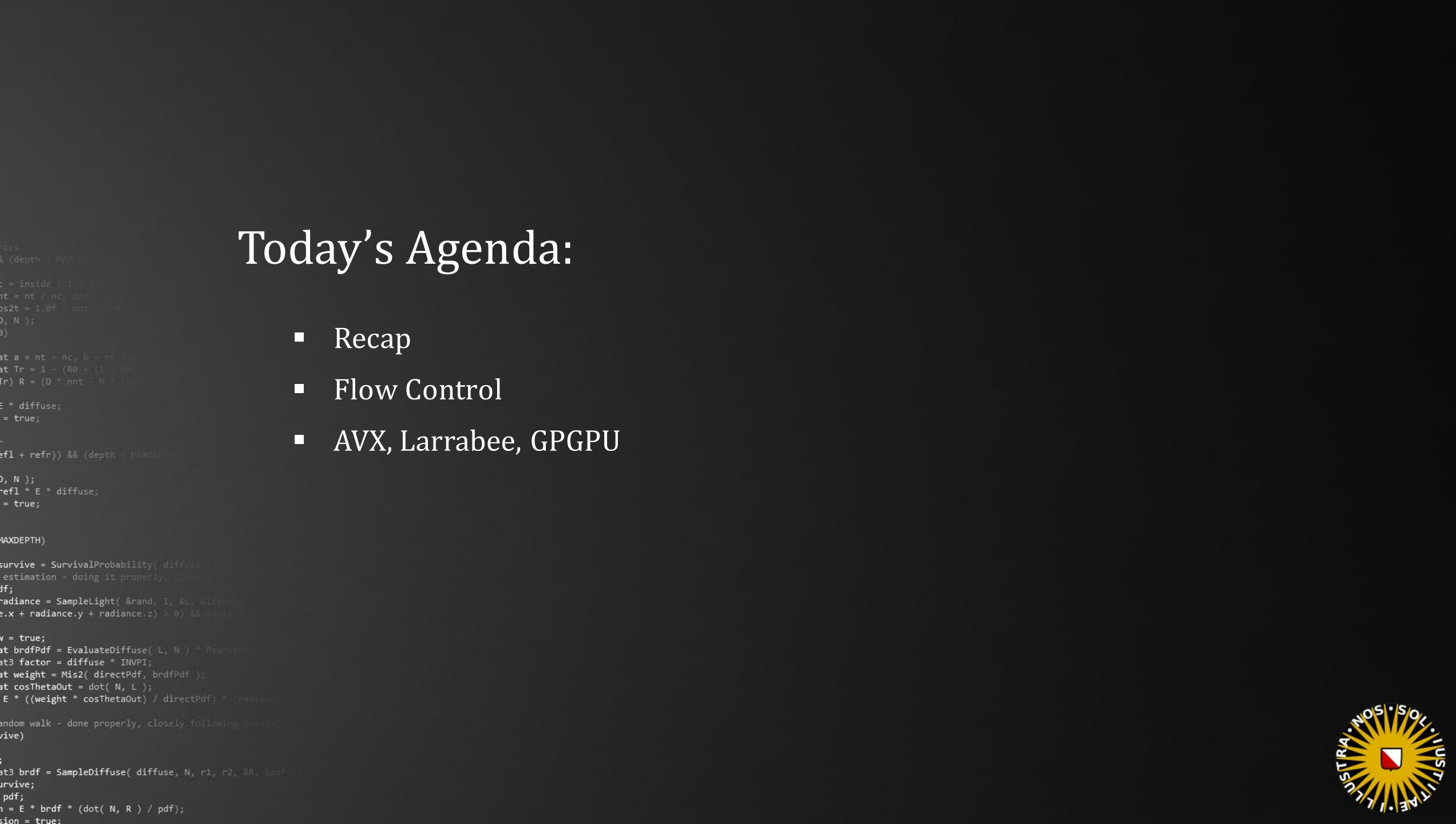
GPU Model

```
__kernel void main( write_only image2d_t outimg )
{
    int column = get_global_id( 0 );
    int line = get_global_id( 1 );
    float red, green, blue;
    if (column & 1)
    {
        red = column / 800.;
        green = line / 480.;
        color = { red, green, 0, 1 };
    }
    else
    {
        red = green = blue = 0;
    }
    write_imagef( outimg, (int2)(column, line), color );
}
```



Today’s Agenda:

- Recap
- Flow Control
- AVX, Larrabee, GPGPU



/INFOMOV/

END of “SIMD (2)”

next lecture: “GPGPU (1)”