Welcome!
Today's Agenda:

- Self-modifying code
- Multi-threading (1)
- Multi-threading (2)
- Madness
- Experiments
Fast Polygons on Limited Hardware

Typical span rendering code:

```c
for( int i = 0; i < len; i++ )
{
    *a++ = texture[u,v];
    u += du;
    v += dv;
}
```

How do we make this faster?
Every cycle counts…

- **Loop unrolling**
- **Two pixels at a time**
Fast Polygons on Limited Hardware

How about...

```c
switch (len)
{
    case 8: *a++ = tex[u,v]; u+=du; v+=dv;
    case 7: *a++ = tex[u,v]; u+=du; v+=dv;
    case 6: *a++ = tex[u,v]; u+=du; v+=dv;
    case 5: *a++ = tex[u,v]; u+=du; v+=dv;
    case 4: *a++ = tex[u,v]; u+=du; v+=dv;
    case 3: *a++ = tex[u,v]; u+=du; v+=dv;
    case 2: *a++ = tex[u,v]; u+=du; v+=dv;
    case 1: *a++ = tex[u,v]; u+=du; v+=dv;
}
```

(a.k.a. “Duff’s Device”)

INFOMOV – Lecture 13 – “Freestyle”

Self-modifying
Fast Polygons on Limited Hardware

What if a massive unroll isn’t an option, but we have only 4 registers?

```c
for ( int i = 0; i < len; i++ )
{
    *a++ = texture[u,v];
    u += du, v += dv;
}
```

Registers: { i, a, u, v, du, dv, len }.

Idea: just before entering the loop,

- replace ‘len’ by the correct constant \textit{in the code};
- replace du and dv by the correct constant.

Our code is now \textit{self-modifying}.
Self-modifying

Self-modifying Code

Good reasons for **not** writing SMC:

- the CPU pipeline (mind every potential (future) target)
- L1 instruction cache (handles reads only)
- code readability

Good reasons for writing SMC:

- code readability
- genetic code optimization
Self-modifying

Hardware Evolution*

Experiment:

- take 100 FPGA's, load them with random 'programs', max 100 logic gates
- test each chip's ability to differentiate between two audio tones
- use the best candidates to produce the next generation.

Outcome (generation 4000): one chip capable of the intended task.

Observations:

1. The chip used only 37 logic gates, of which 5 disconnected from the rest.
2. The 5 disconnected gates were vital to the function of the chip.
3. The program could not be transferred to another chip.


**: Evolved antenna, Wikipedia.
Self-modifying

Compiler Flags*

Experiment:

“...we propose a genetic algorithm to determine the combination of flags, that could be used, to generate efficient executable in terms of time. The input population to the genetic algorithm is the set of compiler flags that can be used to compile a program and the best chromosome corresponding to the best combination of flags is derived over generations, based on the time taken to compile and execute, as the fitness function.”

Self-modifying

Compiler Flags*
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A Brief History of Many Cores

Once upon a time... Everything was single-threaded.

Then, in 2005: Intel's Core 2 Duo *(April 22)*.
*(Also 2005: AMD Athlon 64 X2. April 21.)*

2007: Intel Core 2 Quad

2010: AMD Phenom II X6
A Brief History of Many Cores

Once upon a time...

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Today...
Multi-threading

A Brief History of Many Cores

Once upon a time...

Then, in 2005: Intel's Core 2 Duo *(April 22).*
*(Also 2005: AMD Athlon 64 X2. April 21.)*

**2007:** Intel Core 2 Quad

**2010:** AMD Phenom II X6

2017: Threadripper 1950X (16 cores, 32 threads)
2018: Threadripper 2950X
2019: Epyc 7742, 64 cores, 128 threads ($6,950)
Multi-threading

Threads / Scalability

Performance scaling in HWBOT Prime (Java)
Multi-threading

Optimizing for Multiple Cores

What we did before:

1. Profile.
2. Understand the hardware.
3. Trust No One.

Goal:

- It’s fast enough when it scales linearly with the number of cores.
- It’s fast enough when the parallelizable code scales linearly with the number of cores.
- It’s fast enough if there is no sequential code.
Multi-threading

Hardware Review

We have:

- Four physical cores
- Each running two threads
- L1 cache: 32Kb, 4 cycles latency
- L2 cache: 256Kb, 10 cycles latency
- A large shared L3 cache.

Observation:

If our code solely requires data from L1 and L2, this processor should do work split over four threads exactly four times faster.

(Is that true? Any conditions?)
Simultaneous Multi-Threading (SMT)

(Also known as hyperthreading)

Pipelines grow wider and deeper:

- **Wider:** to execute multiple instructions in parallel in a single cycle.
- **Deeper:** to reduce the complexity of each pipeline stage, which allows for a higher frequency.
Superscalar Pipeline

```
fldz
xor ecx, ecx
fld dword ptr [4520h]
mov edx, 28929227h
fld dword ptr [452Ch]
push esi
mov esi, 0C350h
add ecx, edx
mov eax, 91D2A969h
xor edx, 17737352h
shr ecx, 1
mul eax, edx
fld st(1)
faddp st(3), st
mov eax, 91D2A969h
shr edx, 0Eh
add ecx, edx
fmul st(1), st
xor edx, 17737352h
shr ecx, 1
mul eax, edx
shr edx, 0Eh
dec esi
jne tobetimed+1Fh
```
Multi-threading

Superscalar Pipeline

Nehalem (i7): six wide.

- Three memory operations
- Three calculations (float, int, vector)
Simultaneous Multi-Threading (SMT)
(Also known as hyperthreading)

Pipelines grow wider and deeper:
- Wider, to execute multiple instructions in parallel in a single cycle.
- Deeper, to reduce the complexity of each pipeline stage, which allows for a higher frequency.

However, parallel instructions must be independent, otherwise we get bubbles.

Observation: two threads provide twice as many independent instructions.

(Is that true? Any conditions?)
Multi-threading

Simultaneous Multi-Threading (SMT)

Nehalem (i7) pipeline: *six wide*.

- Three memory operations
- Three calculations (float, int, vector)

SMT: feeding the pipe from *two* threads.

All it really takes is an extra set of registers.

---

Simultaneous Multi-Threading (SMT)

Hyperthreading does mean that now two threads are using the same L1 and L2 cache.

- For the average case, this will reduce data locality.
- If both threads use the same data, data locality remains the same.
- One thread can also be used to fetch data that the other thread will need *.

Multi-threading

Multiple Processors: NUMA

Two physical processors on a single mainboard:

- Each CPU has its own memory
- Each CPU can access the memory of the other CPU.

The penalty for accessing ‘foreign’ memory is ~50%.
Multiple Processors: NUMA

Do we care?

- Most boards host 1 CPU.
- A quadcore still talks to memory via a single interface.

However:

Threadripper is a NUMA device.

Threadripper = 2x Zeppelin, with for each Zeppelin:

- L1, L2, L3 cache
- A link to memory

*This CPU behaves as two CPUs in a single socket.*
Multi-threading

Multiple Processors: NUMA

Threadripper & Windows:

- Threadripper hides NUMA from the OS
- Most software is not NUMA-aware.

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Windows

DWORD WINAPI myThread(LPVOID lpParameter)
{
    unsigned int& myCounter = *((unsigned int*)lpParameter);
    while(myCounter < 0xFFFFFFFF) ++myCounter;
    return 0;
}

int main(int argc, char* argv[])
{
    using namespace std;
    unsigned int myCounter = 0;
    DWORD myThreadID;
    HANDLE myHandle = CreateThread(0, 0, myThread, &myCounter, 0, &myThreadID);
    char myChar = ' '; 
    while(myChar != 'q') {
        cout << myCounter << endl;
        myChar = getchar();
    }
    CloseHandle(myHandle);
    return 0;
}
Boost

```cpp
#include <boost/thread.hpp>
#include <boost/chrono.hpp>
#include <iostream>

void wait(int seconds) {
    boost::this_thread::sleep_for(boost::chrono::seconds{seconds});
}

void thread() {
    for (int i = 0; i < 5; ++i) {
        wait(1);
        std::cout << i << 'n';
    }
}

int main() {
    boost::thread t{thread};
t.join();
}
```
Trust No One

**OpenMP**

```c
#pragma omp parallel for
def for( int n = 0; n < 10; ++n ) printf( " %d", n );

float a[8], b[8];
#pragma omp simd
for( int n = 0; n < 8; ++n) a[n] += b[n];

struct node { node *left, *right; }
extern void process(node* );
void postorder_traverse(node* p)
{
    if (p->left)
        #pragma omp task
        postorder_traverse(p->left);
    if (p->right)
        #pragma omp task
        postorder_traverse(p->right);
    #pragma omp taskwait
    process(p);
}
```
Trust No One

**Intel TBB**

```cpp
#include "tbb/task_group.h"

using namespace tbb;

int Fib( int n )
{
    if (n<2)
        return n;
    else
    {
        int x, y;
        task_group g;
        g.run( [&] { x = Fib( n - 1 ); } ); // spawn a task
        g.run( [&] { y = Fib( n - 2 ); } ); // spawn another task
        g.wait(); // wait for both tasks to complete
        return x + y;
    }
}
```
Trust No One

Considerations

When using external tools to manage your threads, ask yourself:

- What is the overhead of creating / destroying a thread?
- Do I even know when threads are created?
- Do I know on which cores threads execute?

What if... we handled everything ourselves?
**Trust No One**

- Worker threads never die
- Worker threads are pinned to a core
- Tasks are claimed by worker threads
- Execution of a task may depend on completion of other tasks
- Tasks can produce new tasks
Rules of Engagement

Multithreading & Performance

- **SMT / Hyperthreading: sharing L1 & L2 cache**
  - Problems similar to simply having more threads
  - However, without the extra threads we don’t benefit from SMT
  - Mitigate: have the threads work on the same data

- **Multiple cores**
  - Threads may travel from one core to the next (mind the caches)
  - Must share bandwidth
  - Mind false sharing

- **NUMA**
  - Thread assignment now depends on what memory is used
  - No longer a theoretical issue

- **Libraries**
  - Generally favor ease of use over performance
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Experiments

Trust No One

How fast does OpenMP make an ‘embarrassingly parallel’ application?

```cpp
class Game {
public:
  void Tick( float deltaTime ) {
    // draw one line of pixels
    static int xTiles = SCRWIDTH / TILESIZE, yTiles = SCRHEIGHT / TILESIZE;
    static int tileCount = xTiles * yTiles;
    for( int i = 0; i < tileCount; i++ ) // #pragma omp parallel for
    {
      int tx = i % xTiles;
      int ty = i / xTiles;
      drawtile( screen, tx * TILESIZE, ty * TILESIZE );
    }
  }
private:
  float deltaSeconds;
};
```
Experiments

Trust No One

How fast does OpenMP make an ‘embarrassingly parallel’ application?

Can we do better?

```c++
void Game::Tick( float deltaTime )
{
    // draw one line of pixels
    static int xtiles = SCRWIDTH / TILESIZE, ytiles = SCRHEIGHT / TILESIZE;
    static int tileCount = xtiles * ytiles;
    for( int i = 0; i < tileCount; i++ ) // #pragma omp parallel for
    {
        int tx = i % xtiles;
        int ty = i / xtiles;
        drawtile( screen, tx * TILESIZE, ty * TILESIZE );
    }
}
```
Worker Threads

```c
static DWORD threadId[THREADCOUNT];
static int params[THREADCOUNT];
static HANDLE worker[THREADCOUNT];

// spawn worker threads
for( int i = 0; i < 4; i++ )
{
    params[i] = i;
    worker[i] = CreateThread( NULL, 0, workerthread, &params[i], 0, &threadId[i] );
}
```
Experiments

Worker Threads

```c
unsigned long __stdcall workerthread( LPVOID param )
{
    int threadId = *(int*)param;
    while (1)
    {
        WaitForSingleObject( goSignal[threadId], INFINITE );
        while (remaining > 0)
        {
            int task = (int)InterlockedDecrement( &remaining ) - 1;
            if (task >= 0)
            {
                int tx = task % xtiles, ty = task / xtiles;
                drawtile( theScreen, tx * TILESIZE, ty * TILESIZE );
            }
        }
        SetEvent( doneSignal[threadId] );
    }
}
```

`volatile` LONG remaining = 0;
goSignal[i] = CreateEvent( 0, 0, 0, 0 ),
doneSignal[i] = CreateEvent( 0, 0, 0, 0 );
Worker Threads

```
remaining = tileCount;
for ( int i = 0; i < 4; i++ ) SetEvent( goSignal[i] );
WaitForMultipleObjects( THREADCOUNT, doneSignal, true, INFINITE );
```
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DotCloud

Application breakdown, Tick:

```c
    t.reset(); Transform(); elapsed1 = t.elapsed();
    t.reset(); Sort();      elapsed2 = t.elapsed();
    t.reset(); Render();    elapsed3 = t.elapsed();
```

Transform:

```c
    for ( int i = 0; i < DOTS; i++ )
        m_Rotated[i] = m.Transform( m_Points[i] );
```

Sort:

```c
    for ( int i = 0; i < DOTS; i++ )
        for ( int j = 0; j < (DOTS - 1); j++ )
            if ( m_Rotated[j].z > m_Rotated[j + 1].z) Swap( j, j + 1 );
```

Render:

```c
    for ( int i = 0; i < DOTS; i++ )
        m_Dot->DrawScaled( (sx - size / 2), (sy - size / 2), size, size, screen );
```
Madness

DotCloud

Application breakdown:

Tick
Sort
Transform
Render

DrawScaled
Low Level Optimization of DrawScaled

```cpp
void Sprite::DrawScaled( float a_X, float a_Y, float a_Width, float a_Height, Surface* a_Target )
{
    Pixel* dest = a_Target->GetBuffer() + (int)a_X + (int)a_Y * a_Target->GetPitch();
    Pixel* src = GetBuffer() + m_CurrentFrame * m_Width;
    for ( int y = 0; y < (int)a_Height; y++ ) for ( int x = 0; x < (int)a_Width; x++ )
    {
        int v = (int)((y * m_Height) / a_Height);
        int u = (int)((x * m_Pitch) / a_Width);
        if (src[u + v * m_Pitch] & 0xffffff)
            *(dest + x + y * a_Target->GetWidth()) = src[u + v * m_Pitch];
    }
}
```

Functionality:
- for every pixel of the rectangular target image,
- find the corresponding source pixel,
- using interpolation,
- plot if it’s not black.
Low Level Optimization of DrawScaled

A few basic optimizations:

```cpp
void Sprite::DrawScaled( float a_X, float a_Y, float a_Width, float a_Height, Surface* a_Target )
{
    Pixel* dest = a_Target->GetBuffer() + (int)a_X + (int)a_Y * a_Target->GetPitch();
    Pixel* src = GetBuffer() + m_CurrentFrame * m_Width;
    for ( int y = 0; y < (int)a_Height; y++ )
    {
        int v = (int)((y * m_Height) / a_Height);
        for ( int x = 0; x < (int)a_Width; x++ )
        {
            int u = (int)((x * m_Pitch) / a_Width);
            Pixel color = src[u + v * m_Pitch] & 0xffffff;
            if (color) *(dest + x + y * a_Target->GetWidth()) = color;
        }
    }
}
```

- Loop hoisting (variable v is constant inside x loop)
- Reading source pixel only once

- ▪ Loop hoisting (variable v is constant inside x loop)
- ▪ Reading source pixel only once
Low Level Optimization of DrawScaled

More basic optimizations:

```cpp
void Sprite::DrawScaled( float a_X, float a_Y, float a_Width, float a_Height, Surface* a_Target )
{
    Pixel* dest = a_Target->GetBuffer() + (int)a_X + (int)a_Y * a_Target->GetPitch();
    Pixel* src = GetBuffer() + m_CurrentFrame * m_Width;
    float rw = (float)m_Width / a_Width;
    float rh = (float)m_Height / a_Height;
    int iw = (int)a_Width, ih = (int)a_Height;
    for ( int y = 0; y < ih; y++ )
    {
        int v = (int)(y * rh);
        Pixel* line = dest + y * a_Target->GetWidth();
        for ( int x = 0; x < iw; x++ )
        {
            int u = (int)(x * rw);
            Pixel color = src[u + v * m_Width] & 0xffffff;
            if (color) line[x] = color;
        }
    }
}
```

- Precalculate \( m_{Height} / a_{Height} \), \( m_{Width} / a_{Width} \)
- Calculate target address once per line; index using \( x \)
Low Level Optimization of DrawScaled

Fixed point optimization:

```cpp
void Sprite::DrawScaled( int a_X, int a_Y, int a_Width, int a_Height, Surface* a_Target )
{
    const int rh = (m_Height << 10) / a_Height,
        rw = (m_Width << 10) / a_Width;
    Pixel* line = a_Target->GetBuffer() + a_X + a_Y * a_Target->GetPitch();
    for ( int y = 0; y < a_Height; y++,
        line += a_Target->GetPitch() )
    {
        const int v = (y * rh) >> 10;
        for ( int x = 0; x < a_Width; x++ )
        {
            const int u = (x * rw) >> 10;
            const Pixel color = GetBuffer()[(u + v * m_Pitch)];
            if (color & 0xffffff) line[x] = color;
        }
    }
}
```

- Fixed point works really well here... but doesn't improve performance.
- Seems we reached the end here...
Low Level Optimization of DrawScaled

Now what?

- Plot multiple pixels at a time?
- ...

How many different ball sizes do we encounter?

...Why don’t we simply precalculate those frames?
Blind Stupidity

“More computing sins are committed in the name of efficiency (without necessarily achieving it) than for any other single reason – including blind stupidity.” (W.A. Wulff)
Low Level Optimization of Sprite::Draw

Pre-scaled sprites are faster than on-the-fly scaling.

But, we still have loops, and if-statements, and look-ups. I wonder...
Low Level Optimization of Sprite::Draw

**Extreme Optimization:**

- We simply generate a function that plots every pixel, without the need for a loop.

**Side effect:**

L1 data cache is now used for the screen buffer; L1 instruction cache is used for the sprite data. 😊

```c
void Sprite::DrawBall( int x, int y, int size, Surface* target )
{
    uint* a = target->GetBuffer() + x + y * SCRWIDTH;
    switch( size )
    {
    case 1:
        break;
    case 2:
        a[1]=1052688;
        a[800]=1052688;
        a[801]=15724527;
        break;
    case 3:
        a[801]=9737364;
        a[802]=8684676;
        a[1601]=8684676;
        a[1602]=8092539;
        break;
    case 4:
        a[2]=1052688;
        a[801]=6513507;
        a[802]=9737364;
        a[803]=4868682;
        a[1600]=1052688;
        a[1601]=9737364;
        a[1602]=15724527;
        a[1603]=7566195;
        a[2401]=4868682;
        a[2402]=7566195;
        a[2403]=3223857;
        break;
    ```
Low Level Optimization of Sprite::Draw

**Extreme Optimization:**

- We simply generate a function that plots every pixel, without the need for a loop.

```c
FILE* f = fopen( "drawfunc.h", "w" );
fprintf( f, "void Sprite::DrawBall( int x, int y, int size, Surface* target )\n" );
fprintf( f, "\n{\nswitch( size )\n\n{\n\n\nfor( int i = 0; i < 64; i++ )\n{\n...\n\n\nif ( scaled[i]-GetBuffer()[x + y * size] & 0xffffffff )\n    fprintf( f, "a[%i]=%i;\n", a, scaled[i]-GetBuffer()[x + y * size] & 0xffffffff );\n}\n\nfprintf( f, "\n" );\n```

(Continues with additional code)
| a[2405] = 9211020; |
“Madness!? This is INFOMOV’22!”
END of “Snippets”
next lecture: “Exam Practice”