Welcome!
Today's Agenda:

- Introduction
- Course Formalities
- High Level Overview
- Profiling
Introduction

Why?

Some problems require the supercomputer of the future.
Introduction

Why?

Some problems require the supercomputer of the future.

- Anything that depends on Moore’s Law and time to become feasible.
Introduction

Why?

*Games want to raise the bar:*

- More, better, faster. Also: be scalable.
Why?

Some software needs to run on pretty weak hardware.

- Limited CPU, limited RAM (limited controls).
Why?

Some software should not use 90% of your CPU.

- Leave room for other applications, be invisible.
Why?

*Sometimes the cheapest / lowest power CPU is the best.*

- What is the lowest end CPU this will still run on? Can we go lower?
Why?

*Waiting is annoying.*

- Turning on your digital camera
- Getting a train ticking at the vending machine
- Copying files to a USB stick
- Windows updates
- ...
- ...

---

**Working on updates**

11% complete

Don't turn off your computer
What is optimization?

Part of it is:

- INFOB3CC - Concurrency
- INFONW - Computerarchitectuur en netwerken
- INFOB3TC - Talen en compilers

And of course: any course that deals with improving existing algorithms.

Specific purpose of INFOMOV:

- To gain understanding of performance aspects of the hardware we use;
- To gain an intuition for what affects performance;
- To learn to apply a structured process to improve performance.
What is optimization?

**Think like a CPU**

- Instruction pipelines
- Latencies
- Dependencies
- Bandwidth
- Cycles
- Floating point versus integer
- SIMD
Introduction

What is optimization?

Work smarter, not harder: algorithm scalability

- Big O
- Research: not reinventing the wheel
- Data characteristics & algorithm choice
- STL, Boost: Trust No One
- As accurate as necessary (but not more)
- Balancing accuracy, speed and memory

- Instruction pipelines
- Latencies
- Dependencies
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- Floating point versus integer
- SIMD
Introduction

What is optimization?

Memory hierarchy: caches

- Cache architecture
- Cache lines
- Hits, misses and collisions
- Eviction policies
- Prefetching
- Cache-oblivious
- Data-centric programming

- Instruction pipelines
- Latencies
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- Big O
- Research: not reinventing the wheel
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Introduction

What is optimization?

Don’t assume, measure

- Profilers
- Interpreting profiling data
- Instrumentation
- Bottlenecks
- Steering optimization effort

- Instruction pipelines
- Latencies
- Dependencies
- Bandwidth
- Cycles
- Floating point versus integer
- SIMD

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- Cache architecture
- Cache lines
- Hits, misses and collisions
- Eviction policies
- Prefetching
- Cache-oblivious
- Data-centric programming
What is optimization? – Project Management

Keeping code maintainable

- Pareto principle / 80-20 rule: roughly 80% of the effects are caused by 20% of the causes.
- 1% of the code takes 99% of the time.

“The curse of premature optimization”

- Optimization, rule 1: “Don’t do it”.
- Rule 2 (for experts only!), “Don’t do it yet”.

Optimization as a deliberate process

- **Get predictable gains using a consistent approach.**
What is optimization?

“Perceived Performance”

1. Wait for user input
2. Respond to user input \textit{as quickly as possible}
3. Execute requested operation.
At the end of this course:

*You will know how to speed up critical code by a factor 2.5x to 25x (and more).*

- You will be able to do this to virtually any program*.
- Your understanding of higher-level optimization approaches will increase.
- You will be able to apply these principles to new / alien hardware.
- You will have a more intimate relationship with your computer.

In other words:

We will talk a lot about the ‘C’ in $O(N)$.

*disclaimer: ‘that has not been optimized by an expert’.
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Formalities

Lecturer

Jacco Bikker

j.bikker@uu.nl

Room 4.24 BBG
Course Layout

8 weeks + exam week:

- 2 lectures per week (for exceptions: see website)
- 1 guest lecture (I hope)
- Lectures start at 09:00...
- Working class PART 1 starts at 09:00, lecture at 10:00.
- Working class PART 2 starts at 12:00.

Assessment:

- 2 assignments (25% each, individual or pairs);
- 1 final assignment (50%, individual or pairs);
- 1 final theory exam (individual).
Prerequisites

C++

English

Hardware / software

You'll need access to a computer with a CPU that supports SSE2 and OpenCL.

Obtaining VTune (Intel CPU) or CodeXL (AMD CPU) is beneficial (VTune is free for students).

We will use Visual Studio 2017/19 (community edition).

Other tools will (also) be free.
Formalities

Literature

No book!
But that doesn’t mean you won’t be reading.

Main documents:

(also see his website: http://agner.org)


You are encouraged to do research into specific topics of interest yourself, and to report on this in class.
New: overview of the lecture material, for some lectures (goal is a full set by next year).

These will become available on the website.
**Formalities**

**Audience**

Any computer science student
(with a slight bias towards games)

*Make sure you get as much as possible out of this course. This automatically includes a free pass.*
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Overview

Consistent Approach

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

(0.) Determine optimization requirements

- Target hardware (or range of hardware)
- Target performance
- Time available for optimization
- Constraints related to maintainability / portability
- ...

1. Profile: determine hotspots
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From here on, we will assume that:

- the code is ‘done’ (feature complete);
- a speed improvement is required;
- we have a finite amount of time for this.
Consistent Approach

0.) Determine optimization requirements
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5. Parallelize / use GPGPU
6. Profile again.
7. Apply low level optimizations to hotspots
   ▪ caching, data-centric programming,
   ▪ removing superfluous functionality and precision,
   ▪ aligning data to cache lines, vectorization,
   ▪ checking compiler output, fixed point arithmetic,
   ▪ ...
8. Repeat steps 6 and 7 until time runs out
Consistent Approach

(0.) Determine optimization requirements
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Assembler

In this course, we will not write assembler:

- It takes a pro to outperform the compiler
- You will be fighting the compiler
- You will have to redo the optimization for every target processor
- Maintainability will be zero.
"We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil. Yet we should not pass up our opportunities in that critical 3%.

(Donald Knuth)"
"A significant improvement in performance can often be achieved by solving only the actual problem and removing extraneous functionality." (Wikipedia)
"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)
“Dear Charles.

In almost every computation a great variety of arrangements for the succession of the processes is possible, and various considerations must influence the selection amongst them (...).

One essential object is to choose that arrangement which shall tend to reduce to a minimum the time necessary for completing the calculation.

Therefore, one should attend INFOMOV and learn from it.

Love, Ada.”
Today’s Agenda:

- Introduction
- Course Formalities
- High Level Overview
- Profiling
Never Assume

Consistent Approach

1. **Determine optimization requirements**
   - **Profile**: determine hotspots
   - **Analyze hotspots**: determine scalability
   - **Apply high level optimizations to hotspots**
   - **Profile again**
   - **Parallelize**
   - **Use GPGPU**
   - **Profile again**
   - **Apply low level optimizations to hotspots**
   - **Repeat steps 7 and 8 until time runs out**
   - **Report**.

Do you actually need to speed it up?
By how much?

Things to consider:

- You have a finite amount of time for this
- You don’t want to break anything
- You don’t want to reduce maintainability

⇒ Focus on ‘low hanging fruit’ – typically a small portion of the code.
Never Assume

Consistent Approach

1. **Profile: determine hotspots**
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**Don’t trust your intuition**

- Not even when optimizing your own code.
- *Especially* not when you are proficient at optimizing.

Blind changes may *reduce* the performance of the code.

Needless to say: *use version control.*
Profiling

Measuring application performance

- Using external tools
- Using timers in the code

Measurements:

- How much time is spent were? (inclusive / exclusive, cycles, percentage)
- How often is each function called?
- Low level behavior: stalls / latencies, branch mispredictions, occupation, ...
- Performance over time: lag, spikes, stutter
What if the goal is to have a 10x larger army in your RTS?

Don’t just measure performance, measure *scalability*. 
Profiling – getting accurate results

A profiler needs information about your code:
this is typically available in debug builds.

However:
Debug builds have very different performance characteristics,
for many reasons. We need to profile in release mode.

Enabling debug information in release mode in Visual Studio:

- Properties >> C/C++ >> General >> Debug information format
- Properties >> Linker >> Debugging >> Generate Debug Info

Differences between debug and release configurations

In debug:
- your code is not optimized
- debug info is added to the executable
- variables are initialized
- memory blocks are padded with guard bytes
- array bounds are checked

In release:
- code may be reordered

IMPORTANT:
It makes very little sense to optimize in debug mode.
Never Assume
Never Assume
INFOMOV – Lecture 1 – “Introduction”

Tools

Performance and Diagnostics

Recently Opened Sessions

- Solution temp84.00a_2013
  - GameItems
  - Performance1
  - Template
  - ExternalDepend
  - _readme.txt
- _game.cpp
- game.h
- surface.cpp
- surface.h
- template.cpp
- template.h
- threads.cpp
- threads.h

Analysis Target

Performance Wizard -- Page 1 of 3

Specify the profiling method

Profiling your application can help diagnose performance problems and identify options below.

**What method of profiling would you like to use?**

- **CPU sampling (recommended)**
  - Monitor CPU-bound applications with low overhead
- **Instrumentation**
  - Measure function call counts and timing
- **.NET memory allocation**
  - Track managed memory allocation
- **Resource contention data (concurrency)**
  - Detect threads waiting for other threads

```c
if (drop[1].pos.y > 20) drop[1].pos.y = 19.99f - drop[1].pos.z * 0.0001f;
if (drop[1].pos.x > 20) drop[1].pos.x = 19.99f - drop[1].pos.z * 0.0001f;
if (drop[1].pos.x < -20) drop[1].pos.x = 19.99f + drop[1].pos.z * 0.0001f;
if (drop[1].pos.z > 20) drop[1].pos.z = 19.99f - drop[1].pos.x * 0.0001f;
if (drop[1].pos.z < -20) drop[1].pos.z = 19.99f - drop[1].pos.x * 0.0001f;
```
Visual Studio Profiler
Tools

VerySleepy
Tools

Intel VTune
Tools

AMD CodeXL
Never Assume

Take-away:

Never assume. Profiling *always* steers optimization.

Optimize in release mode. Enable debug info during this process. Don’t forget to turn it off before distribution.
Profiler Output
Profiler Output

Profiling – Results

**Game::Simulate** 67.89% 67.89%
**Game::SmoothWater** 10.54% 10.54%
**Game::RenderZSprites** 7.18% 7.18%
**Game::Tick** 0.00% 76.32%

Running ~3 seconds, we spent 0.86s on this line:

```
float dist = length( drop[i].pos - drop[j].pos );
```

and 1.68s on this line:

```
if (dist < (DROPRADIUS * 2))
```
Profiling – finding hotspots

The profiler allows you to quickly find the parts of your program that take most time.

But:

- Mind debug versus release;
- The profiler doesn’t tell you why a function is costly;
- The profiler doesn’t report scalability;
- There is no ‘cost over time’ information.

➡ Scalability analysis requires running the program with different work sets (i.e., change \( N \) in \( O(N) \)).
➡ Determining why a section takes a lot of time requires more in-depth knowledge.
➡ Solving the performance issue requires even more in-depth knowledge.
Profiler Output
### Profiler Output

<table>
<thead>
<tr>
<th>Source</th>
<th>Clockticks</th>
<th>Instructions Retired</th>
<th>CPI Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Simulate: do Verlet physics simulation on the particles} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{for } i = 0 \rightarrow \text{DROPCOUNT-1} )</td>
<td></td>
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</tr>
<tr>
<td>( \text{if } i \text{ mod 2} = 1 )</td>
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</tr>
<tr>
<td>( \text{compute } \mathbf{a}_i \text{ by Verlet formula} )</td>
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<tr>
<td>( \text{compute } \mathbf{v}<em>i \text{ from } \mathbf{v}</em>{i-1}, \mathbf{a}_i )</td>
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<td>( \text{compute } \mathbf{x}<em>i \text{ from } \mathbf{x}</em>{i-1}, \mathbf{v}_{i-1} )</td>
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<tr>
<td>( \text{continue } )</td>
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<tr>
<td>( \text{for } j = 1 \rightarrow \text{DROPCOUNT-1} )</td>
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<td>( \text{compute } \mathbf{a}_{ij} \text{ by Verlet formula} )</td>
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<td>( \text{compute } \mathbf{v}<em>{ij} \text{ from } \mathbf{v}</em>{ij-1}, \mathbf{a}_{ij} )</td>
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<tr>
<td>( \text{continue } )</td>
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<tr>
<td>( \text{for } r = 1 \rightarrow \text{DROPCOUNT-1} )</td>
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<td>( \text{compute } \mathbf{a}_{ir} \text{ by Verlet formula} )</td>
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<td>( \text{compute } \mathbf{x}<em>{ir} \text{ from } \mathbf{x}</em>{ir-1}, \mathbf{v}_{ir-1} )</td>
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<tr>
<td>( \text{continue } )</td>
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</tr>
</tbody>
</table>

### Source Code

```cpp
// Simulate: do Verlet physics simulation on the particles
void Game::Simulate()
{
    for (int i = 0; i < DROPCOUNT-1; i++)
    {
        gravity = tan2i * sin( angle * PI / 180 );
        vec3 prev_pos = drop[i].prev_pos;
        drop[i].prev_pos = drop[i].pos;
        // simulation step 1 - move
        drop[i].pos = drop[i].pos - prev_pos;
        // simulation step 2 - apply gravity
        drop[i].pos = gravity * 0.25 *
        // simulation step 3 - satisfy constraints
        for (int step = 0; step < 3; step++)
        {
            float dist = length( drop[i].pos - drop[j].pos );
            if (dist < (DROPRADIUS + 2))
            {
                vec3 direction = normalize( drop[j].pos - drop[i].pos );
                if (drop[i].pos.y > 20) drop[i].pos.y = -19.999 - drop[i].pos.x = 0.001;
                if (drop[i].pos.x < -20) drop[i].pos.x = 19.999 + drop[i].pos.x = 0.001;
                if (drop[i].pos.z < -20) drop[i].pos.z = 19.999 + drop[i].pos.z = 0.001;
                if (drop[i].pos.z > 20) drop[i].pos.z = -19.999 - drop[i].pos.z = 0.001;
            }
        }
        leave(Simulate());
    }
}
```
Take-away:

Free, vendor-agnostic profilers tell you where time is spent in your program (but not why).

Vendor-specific tools provide a wealth of information, but generally require knowledge about the hardware processes.

Stalls are generally not vendor-specific and will be similar on similar hardware.

Just timing information is often sufficient to make an educated guess towards improvements.
Custom Profiling

Generic Profiler Downsides

- No ‘performance over time’ measurements
- Requires inclusion of debug information (including source code)
- Not real-time
- Not very intuitive

Using a custom in-app profiler we can drastically improve our profiling information.
Custom Profiling
Custom Profiling

UnrealEngine 3
Custom Profiling

StarCraft II
Custom Profiling
Custom Profiling

Take-away:

In-app profiling provides advantages over external profilers:

- You get real-time information, which is easily associated with what is going on in the app;
- You can measure statistics that are not available to the profiler;
- You can present the data in a form that is also useful to people not familiar with the intricacies of the profiler.
Custom timers: what to measure?

- Time spent in your code
- ‘Wall clock time’
- Cycles

This is what you can control
Including file I/O, library calls, ...
CPU-independent (but: rate may change)

In what quantities?

- A millisecond is a long time
- Averaged / smoothed values are easier to read
- Relative performance may be better

The impact of measurements:

- Especially relevant for brief snippets of code
- Logging is expensive!
Considerations

Consistent Approach

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7. Apply low level optimizations to hotspots
8. Repeat steps 6 and 7 until time runs out
And Finally:

Profiling:

Without it, no optimization – we need to know

How to profile: tools, custom timers, CPU + GPU

What to profile: realistically (release!), raw performance, scalability
(but also: cache misses, pipelining, branch prediction)

Keep in mind: profiling takes time too.

Repeated profiling: things change, if you’re doing it right. Stay informed.
END of “Introduction”

next lecture: “Low Level”