Optimizing Games for AMD Athlon™ 64 Processors in 2006 and beyond

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Agenda

This talk is for PC Game Developers.
It's about maximizing game performance.

- Dual-core and multi-core CPUs: multi-threading
- SSE vectorization: fine-grained data parallelism
- 64-bit mode: more registers and large address space
- Threading recommendations from graphics experts
- Q & A

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Multi-threading

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Cores, cores, and more cores

- Dual-core CPUs.
- They’re everywhere.
- Typically twice as much CPU horsepower.
- And *multi*-core CPUs are expected.

- Games must be threaded or the CPU is wasted.
- Well-threaded games can get huge benefits.

- But how do you do it?

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How to multi-thread games

- Use existing threaded libraries, game engines, etc.
  - Why reinvent the wheel?
- Run DirectX on a separate thread
  - Relatively easy to do
  - Can achieve speed gains on dual-core
  - Doesn't scale beyond 2 cores
- Functional threading and producer/consumer have limits
  - Limited number of threads, may leave quad-core idle
  - Poor load balancing between threads
  - Stalling the producer also stalls the consumer
- Data parallel threading is the way to go

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Data-parallel threading

- Data parallel threading is a Really Good Thing
- Parallel algorithms
  - avoid restrictive data dependencies
- Large batch sizes
- Launch many threads: scalable!
- Threads run in parallel
  - Each thread can do the same stuff…
  - …but on different data

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OpenMP for easy data-parallel threading

- OpenMP lets you multi-thread a loop with a single pragma!
  - `#pragma omp parallel for`
  - also options for thread scheduling, synchronizing, sections, and more
- OpenMP is supported in Visual Studio® 2005
- Implements the “fork and join” programming model
  - There is a pool of sleeping threads
  - Execution is single-thread until a “fork” is reached
  - Then Multiple threads proceed in parallel
  - Once all threads complete, resume single-thread
- The main backbone of your game is single-thread!
  - Less chance for weird synchronization bugs

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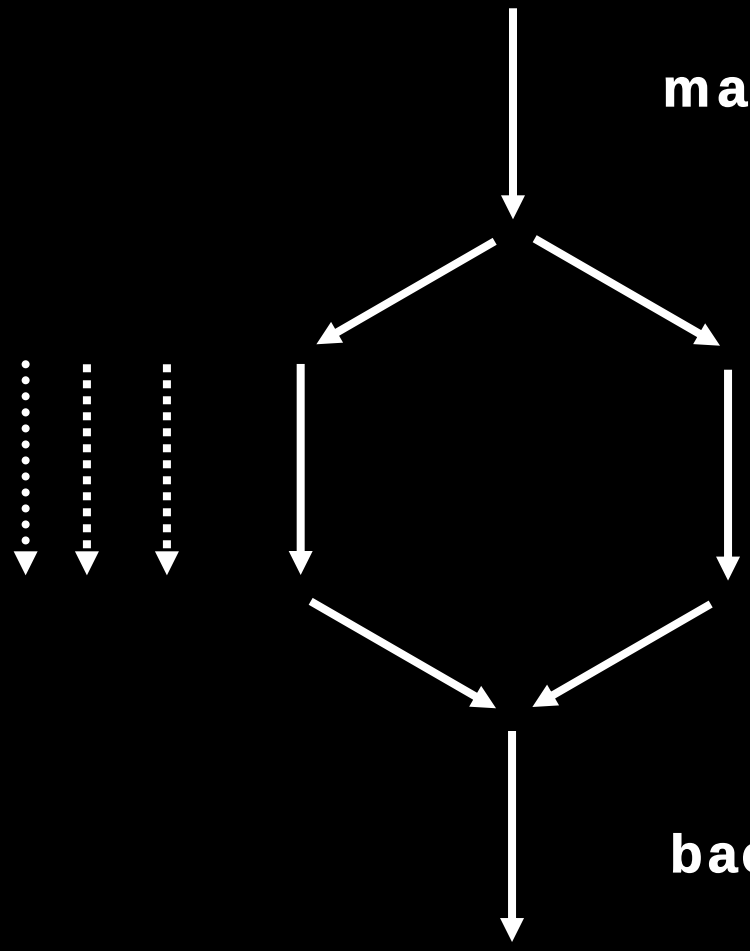
Fork and Join Programming Model



main thread

fork to multiple threads

parallel execution of
heavy workload

join when all threads finish

back to main thread

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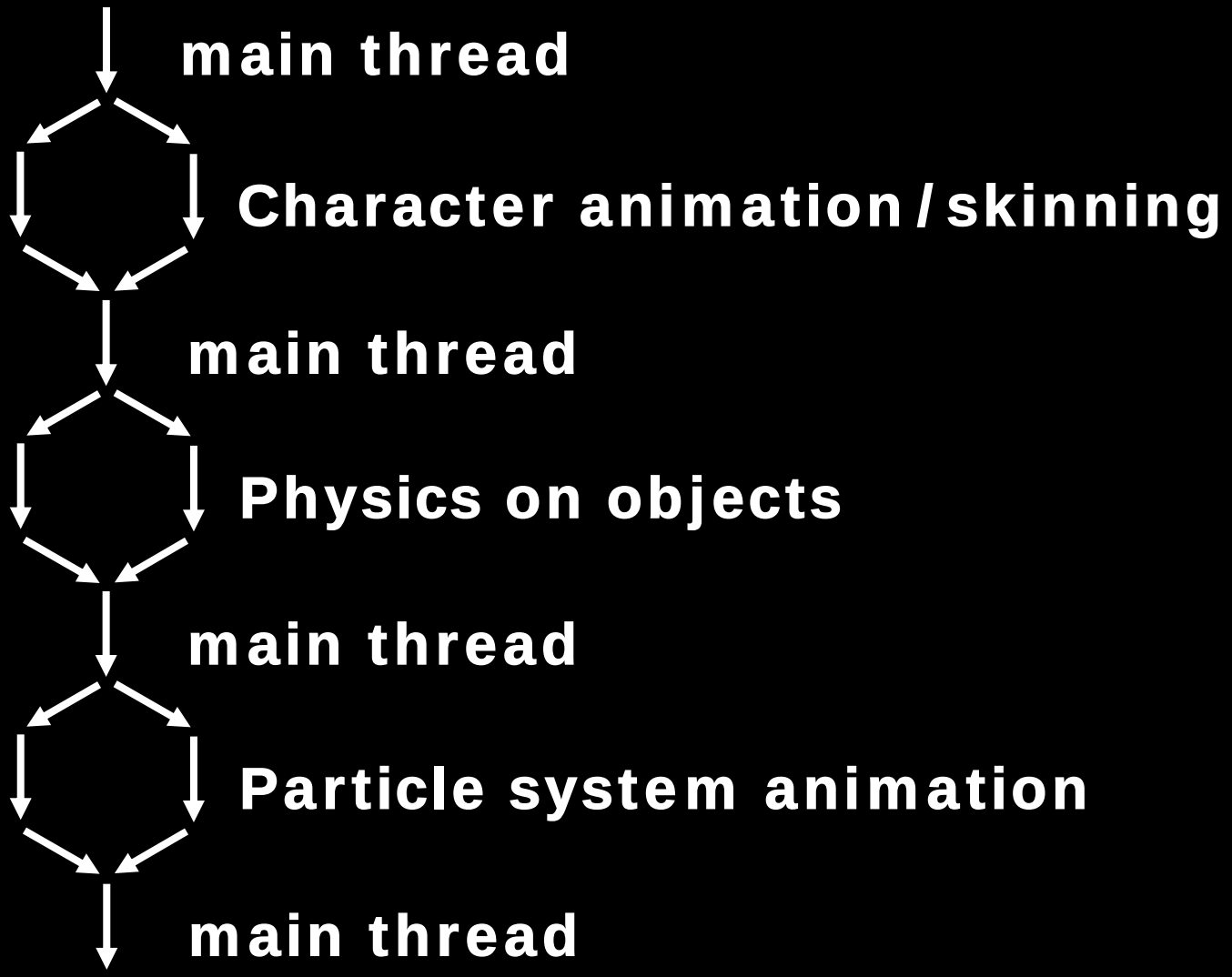
Thread Example: game pipeline



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OpenMP Rules of Thumb

- Thread your outer-most loop
  - Coarse-grained data parallelism
  - Minimum number of fork+join events
- Define local variables *inside* the loop
  - OpenMP will create a private copy for each thread
- Global variables
  - OK if the globals are *read only*
  - Writing to global variables will cause trouble
  - common but dangerous code:

```
*global++ = foo;   // danger! global pointer was modified
```

  - safe syntax:

```
*(global + local_offset++) = foo;
```

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OpenMP isn't the only way

- OpenMP is simple to use, but has limits
- Doesn't allow control of thread priority or affinity
  - but GetCurrentThread() gives you a Windows thread handle
- Load balancing is crucial
  - all threads must wait for the slowest thread!
  - dynamic scheduling option in OpenMP can help here
- Good for threading data-parallel loops
- Windows® thread APIs work great on multi-core
  - _beginthreadex(), WaitForMultipleObjects, etc.
  - Always trust the OS about how many processors, etc.
    Don't try and directly read the hardware
  - Some good MSDN white papers about threading
    synchronize threads using interlocks, and other good stuff

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A word about thread affinity

- The OS schedules threads and sets affinity for you
- Only the OS knows everything (in theory) about the execution environment
  - The PC is a general purpose multi-tasking device
  - New software and hardware can show up
- If you choose to manually set thread affinity, *be very careful*
- Test thoroughly on a variety of platforms
- Leave some secret way to adjust the behavior, just in case
- Other bits of code might be adjusting affinity too!
- DirectX can change your process affinity as a side effect:
  - IDirect3D9::CreateDevice
  - Direct3DDevice::Reset in D3D9
  - Be aware that the calling thread's affinity may get set

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Maximum cache performance

- Each core has its own L1 cache, and its own L2 cache
- Greater parallelism enables added performance:
  - L2 cache latency does not increase when another L2 is added
  - Total cache bandwidth scales up linearly with the number of cores
  - Threads cannot evict another thread's data from other L2

- Avoid "cache thrashing" between cores
  - Avoid multiple threads *writing* to the same variables
  - Also avoid one thread frequently writing what another is reading
    This is just a standard rule of threaded programming
  - Beware of **false sharing** which can cause thrashing:
    *Two threads modifying **different variables** which occupy the **same cache line***
    Can happen in heap data or in static (stack) variables
    One safe approach: _aligned_malloc for 64-byte aligned heap chunks
    Another handy trick: __declspec(align(64))
    See MSDN for complete details on managing alignment

- Use AMD CodeAnalyst profiler to examine threads and cache events
  - Thrashing would appear as excessive cache refill events
  - Just one way CodeAnalyst can help you build faster code

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Handy tips and tricks for threading

- Tricks for making a dual-core act like a single-core
  - Set process affinity in Task Manager to only one processor
  - Edit boot.ini file to include /numprocs=1 as alternate OS boot
- All system specs remain the same, except number of cores
- Benchmark and see the performance difference

- Don't use RDTSC instruction, use QueryPerformanceCounter
  - See Microsoft® application note about this in DX SDK

- Allow user tweaks to work around unexpected thread behavior
  - Who knows what other processes might be running
  - Offer some advanced control panel options?
    - *Adjust or limit number of threads*
    - *Set or disable thread affinity*

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SSE vectorization

Games do lots of heavy arithmetic

- Much heavy processing in games can be SSE vectorized
  - Physics, particles, collision detection
  - Animation and skinning
  - Image processing, scaling, synthesis
  - Audio synthesis

- SSE vectorization can accelerate all this processing…

- How to implement SSE optimization?

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Using vectorized SSE in your game

- Use existing libraries, engines, etc. which are SSE optimized
  - Why reinvent the wheel?
- Use the D3DX math functions in the DirectX SDK
  - Optimized for all popular CPUs
- Code your own algorithms directly using vectorized SSE
  - Data parallelism, logically much like data parallel threading
  - Use mask instructions to eliminate branch instructions
  - Floating point (SSE) and integer (SSE2) data types
  - Use CPU ID to detect current and future SSE capabilities

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Compiler intrinsics = portable SSE

- Use Visual Studio® 2005 compiler intrinsic functions!
  - It's like ASM code at the C/C++ source level
  - The compiler does register allocation and scheduling
  - Unlike ASM, it compiles for 32-bit mode and for 64-bit mode
  - 64-bit mode transparently offers 2x more SSE registers

```
__m128 a = _mm_mul_ps( z_real, z_real );
__m128 b = _mm_mul_ps( z_imag, z_imag );

__m128 t = _mm_add_ps( a, b );  // check magnitude of z
__m128 t_mask = _mm_cmpgt_ps( t, _mm_set1_ps( 4.0 ));  // 4 compares

   int m = _mm_movemask_ps(t_mask); // get a 4 bit int mask
   if(m & 1) { "do stuff here" }    // no shuffling is needed!
   if(m & 2) { "do other stuff" }
```

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MASM works fine for vectorized SSE

- Visual Studio® 2005 has 32-bit and 64-bit MASM
  - 64-bit ASM code is *not the same* as 32-bit
    same instruction set, but 64-bit pointers and more registers
  - VC2005 64-bit has no in-line ASM! Must use MASM 64 for ASM
  - New and improved calling convention for 64-bit Windows®
    args get passed in registers like fastcall

```
; random examples of 64-bit ASM code instructions
    movapd  xmm0, [rcx]
    movapd  xmm14, [rdx]
    xor     rax, rax
    mov     edx, 4
    shufpd    xmm15, xmm15, 1
    mov       r9, r8
    shl       r9, 32
    subpd     xmm4, xmm5
    addpd     xmm4, xmm14
```

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Summary: use both kinds of data parallelism

- Data-parallel threading for coarse-grained
- Vectorized SSE for fine-grained
- Each CPU core is a complete x86+SSE unit
- Ergo: use vectorization *and* threading

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64-bit mode

PC games need to keep raising the bar

- Gamers want more of everything
- Everything needs to be stored somewhere
- Windows® limits applications to 2GB address space
- And even graphic cards have 512MB now!

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Memory space is a good thing

- Large memory is an advantage of PC over consoles!
- Game PCs have 1GB – 2GB *physical* RAM
  - Approaching the size of the *virtual* address space!
- 32-bit Windows® has 2GB virtual space for a game
  - Virtual address space can get fragmented
  - You may not even be able to fully use 1GB of physical RAM!
- The time is ripe for 64-bit virtual address space
  - Even if the machine has less than 4GB physical memory
  - And certainly for the enthusiast who stuffs > 2GB

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64-bit mode: lots of benefits

- Large address space is not the only 64-bit benefit
- Bonus: twice as many registers
  - 16 GPR registers
  - 16 SSE registers (SSE and SSE2 instruction support guaranteed)
  - Register pressure was the biggest limit of x86… now it is fixed
- Visual Studio® 2005 x64 compiler uses all the registers
- Computationally intensive code can get a speed boost

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64-bit mode: wait, there's more!

- Visual Studio® 2005 x64 compiler generates great code
  - Whole Program Optimization
  - Profile Guided Optimization
  - /fp:fast mode for improved floating point performance
  - _restrict keyword: hint to compiler about pointer aliasing
  - Intrinsic functions: data prefetch, streaming store, SSE, …
  - Optimized libc functions like memcpy, memset, strcmp, etc.
  - → Be sure to try /O1 minimize code size, especially for 64-bit
- DirectX and D3DX have optimized 64-bit code
- Graphics IHVs have significant investment in x64 performance

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A word about data bloat

- In 64-bit mode, pointers are 8 bytes instead of 4 bytes
- Data structures containing pointers will grow
- In some cases, data structures will grow a lot

- Games make heavy use of system memory
- System memory bandwidth may be pushing the limit
  - How many bytes of memory traffic happen per frame?
- Data bloat can adversely impact performance

- Reduce data bloat:
  - Use array[index] or *(base+offset), instead of *pointer
  - Re-order elements of a struct for better packing

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64-bit mode will soon be common

- Windows® Vista™ will offer both 32-bit and 64-bit flavors
  - 64-bit games for Vista are expected to get more attention
  - And 64-bit Windows XP Pro has been shipping since April 2005
- Competitive gaming CPUs all support 64-bit mode
- VS 2005 and DX SDK fully support 64-bit development
  - And so does AMD CodeAnalyst profiler
- Optimal scenario: design PC game for 64-bit from day #1
  - example: map your 10+ GB of resource files to virtual memory
- Caveat: all the code in the game must be native 64-bit
  - Cannot mix and match 32-bit and 64-bit
  - Can't use MMX in 64-bit code, use SSE2 which is always supported
  - Most game libraries, engines etc. are already 64-bit ported

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Putting it all together:

“The PC Game Layer Cake”

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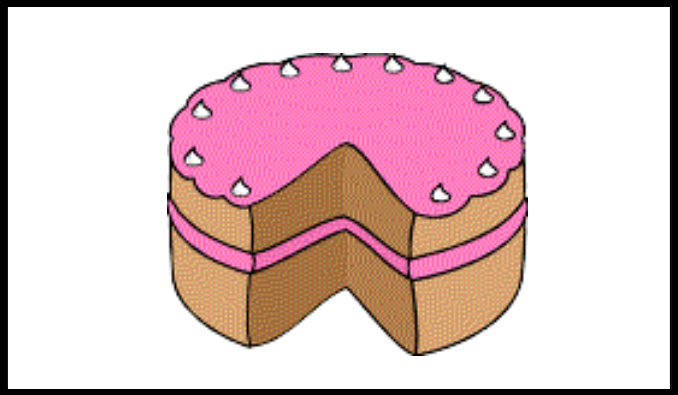
The PC Game Layer Cake



- The slices of cake are the many threads
  - Coarse-grained data parallelism, multi-threading
- The layers are the processing steps in each thread
  - Fine-grained data parallelism, opportunity for SSE
- 64-bit technology is frosting on the cake
  - Greater memory space and more registers to make it even better!

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Resources

- Go to developer.amd.com and get all the AMD docs
  - Optimization Guide, Programmer's Manuals, white papers, etc.
  - Download and use the CodeAnalyst profiler, for 32 and 64-bit code
  - Visual Studio® 2005 demo project and white paper: "Performance Optimization of 64-bit Windows® Applications using Visual Studio 2005, on AMD Athlon™ 64 and AMD Opteron™ Processors"
  - Other presentations, including TechEd and previous GDCs
- Sign up to use the AMD Developer Center in Sunnyvale, CA
  - Work on-site
  - Remote access by VPN to servers
- Also check out amd.com and especially the "gaming" link
  - Success stories, downloads

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More Resources

- Go to MSDN and get the Windows® x64 OS, Visual Studio® 2005
  - DirectX® for x64: already released in DirectX 9.0 SDK
- Go to MSDN and Microsoft.com for more docs
  - Search for 64-bit, AMD64, x64 or “64-bit Extended”
  - Read about new 64-bit compiler features, OpenMP, intrinsics, etc.
  - Read about threading and fast thread synchronization tricks
  - Especially read about VS2005 “Whidbey” performance optimization features
- OpenMP is simple and powerful www.openmp.org