Threading Game Engines

- QUAKE 4 & Enemy Territory QUAKE Wars

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Agenda

- Concurrency In Games Today
- Analysis of QUAKE 4
- Renderer Threading QUAKE 4 and ETQW
- AI & Mega texture Threading in ETQW
- Common Performance Issues & Workarounds
- Building Scalability into threading design

Concurrency In Games

- There has been a dramatic increase in compute power in consumer space in the last few years with multi-core
  - Game industry has started the move to adopt concurrent programming
- Most multithreaded games today still follow the first generation of parallelism i.e. threading based on functional decomposition.
- Game is broken up into various subsystems each of which run on their own thread typically rendering, and AI sometimes physics too


QUAKE 4

QUAKE 4 Analysis

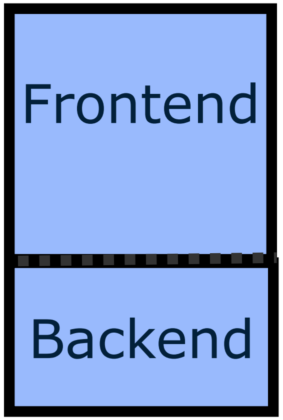
- As per the V-tune Analysis QUAKE 4 was
  - CPU bound
  - Predominantly Single threaded
  - Roughly equal amount is being spent in the driver and the engine 41% & 49% respectively
  - Each of the major hotspots consume 2-4% of CPU time.
- Peek into the source revealed
  - QUAKE 4 had a good separation between the renderer Front and Back end.
  - Most of the time spent in the OpenGL driver came from the Renderer Backend.

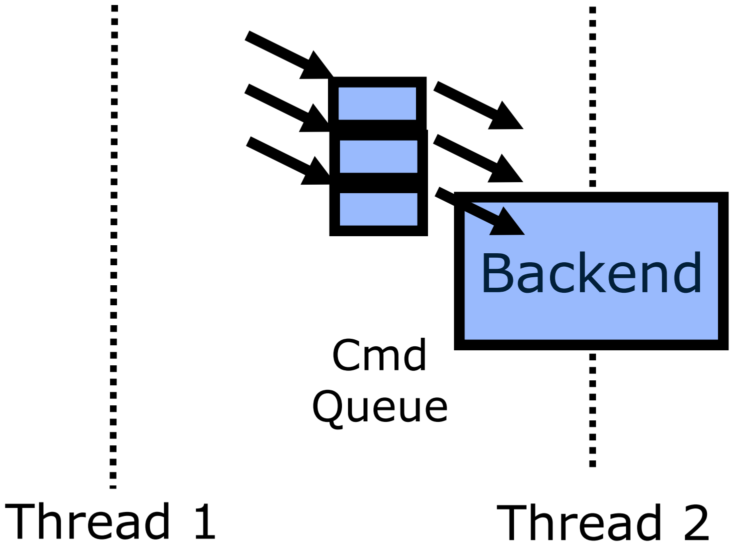
Constraints

– Threading an existing engine
– Time frame 4-6 months
– Target platform – P4 dual core (3.2 Ghz)
– Single core performance difference had to be less than 5%

Threading

- To get most performance in a constrained time decided to functionally decompose the 2 largest blocks.
- Split the render into front-end and back-end
- The backend was made to run on its own thread
- The front-end and back-end communicated through command queues and synchronization events

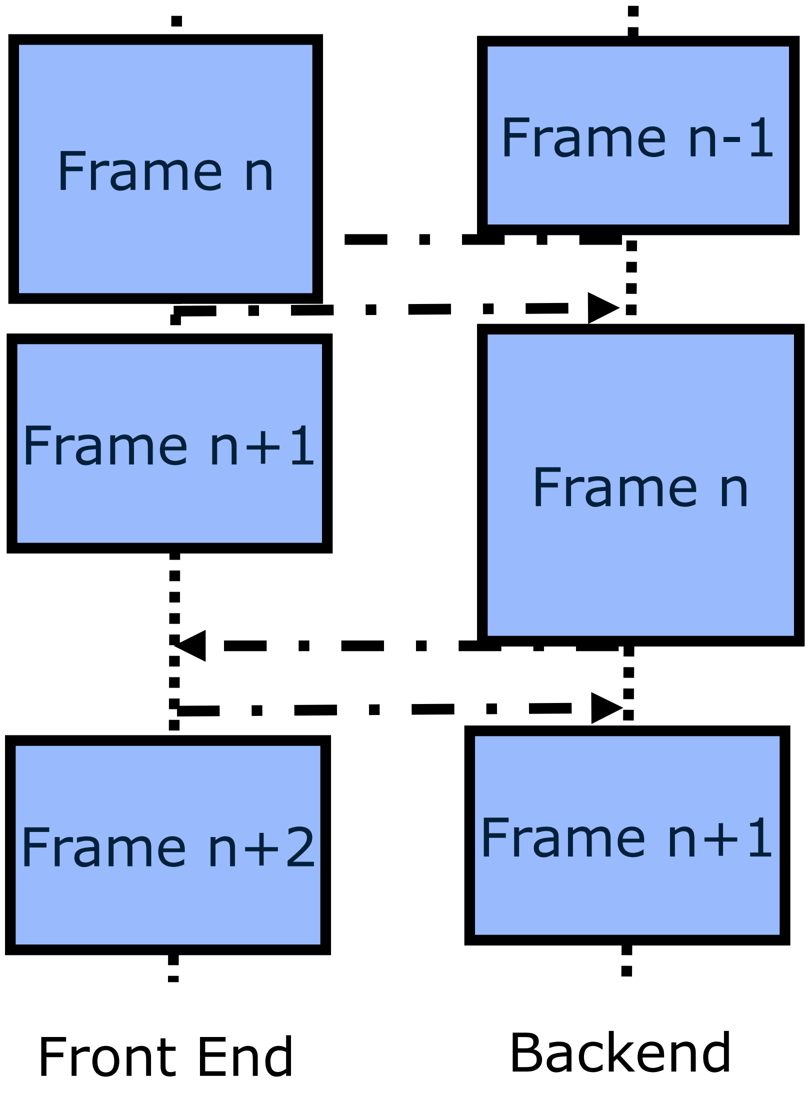




Threading

- The frame was prepared by the front end handed over to the back end while the front end prepared the next frame.
  - Data specific to a frame was double buffered
  - Data had to be allocated and freed safely.
  - Front end managed allocation & deallocation of shared data. Data to be freed was kept till the backend was done and cleared at the front end just before reuse.
  - Subsystems that were not thread safe had to be made thread safe models classes, animation, shadows, texture subsystems, deforms, loaders, writers, vertex caches, …

Synchronization

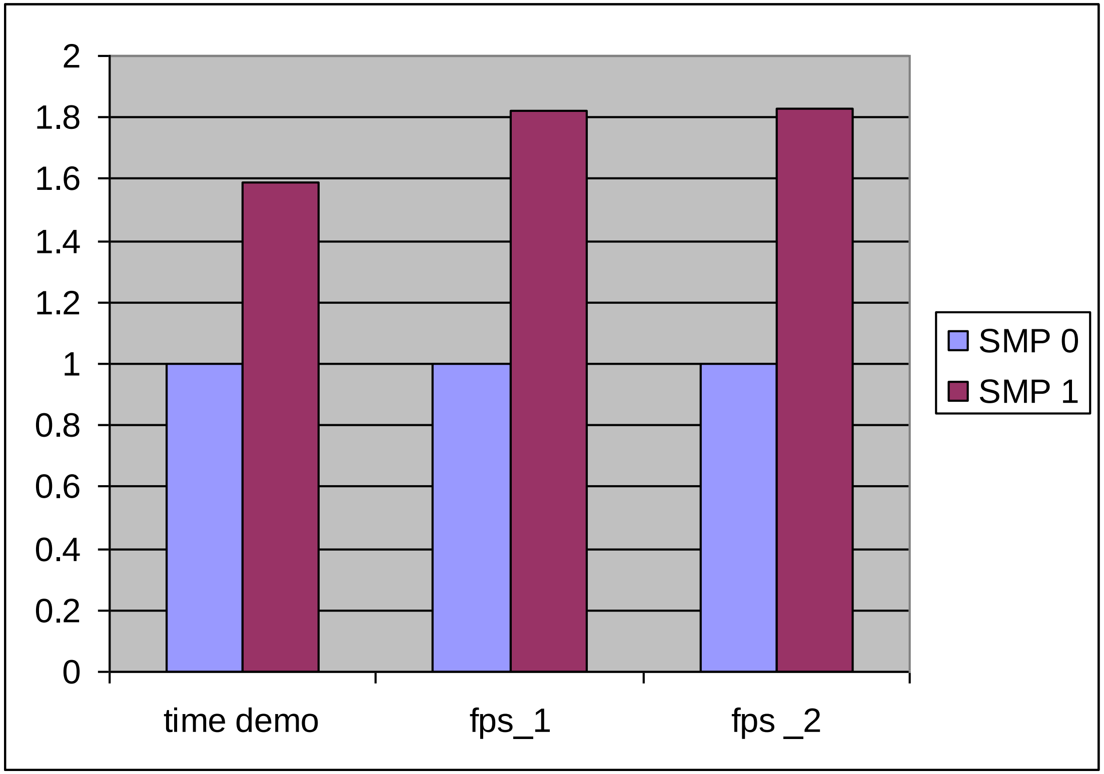


Issues with Threading

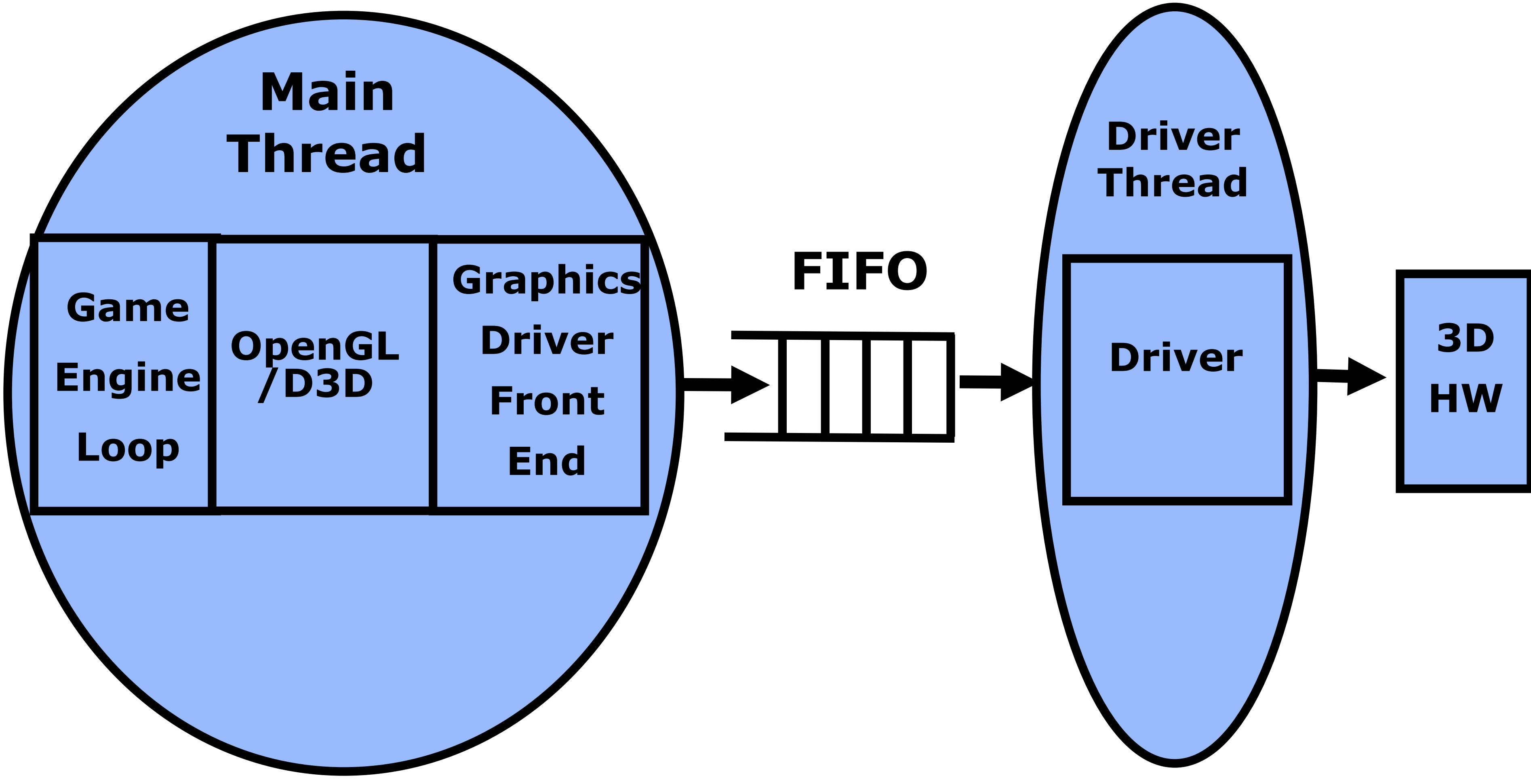
- Debugging The threaded code was the hardest
- Issues could be broadly categorized into 3 major types
  - Data Race Conditions
  - Object lifetime issues
  - OpenGL context issues
- Moved all the time critical OpenGL calls to the backend used a synch mechanism for others
- Added a realtime toggle capaility to turn threading on and off along with a lock step mode to the threaded code where the front end and back end would run on separate threads but run lock step
- Used Synchronization points to slowly & painfully eliminate Data Races
- Added lots of initialization and destruction code to deal with lifetime issues
- Needed to batch certain commands to improve performance

Performance Improvements

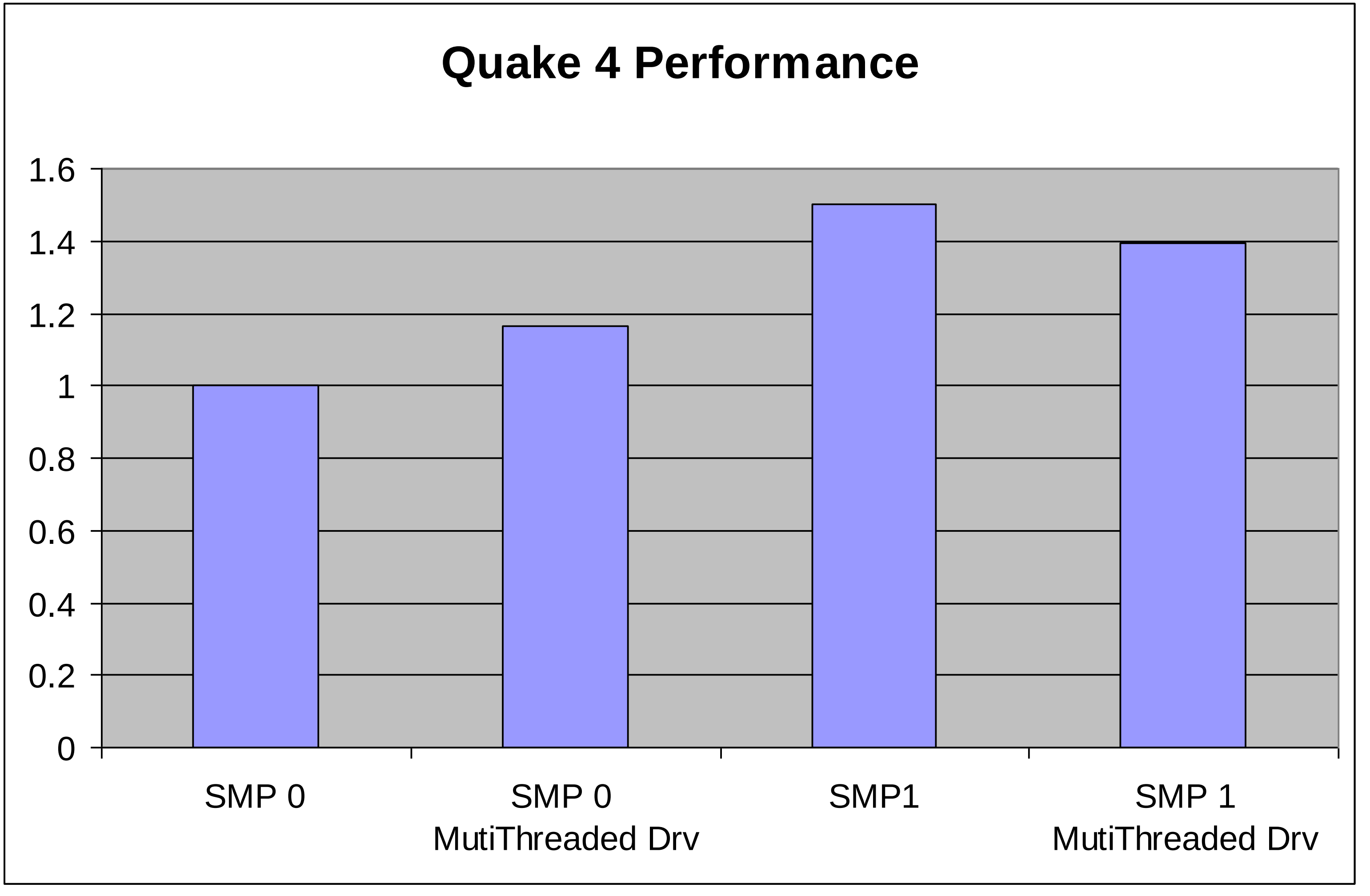
- Beta timeframe



Multi-Threaded Drivers



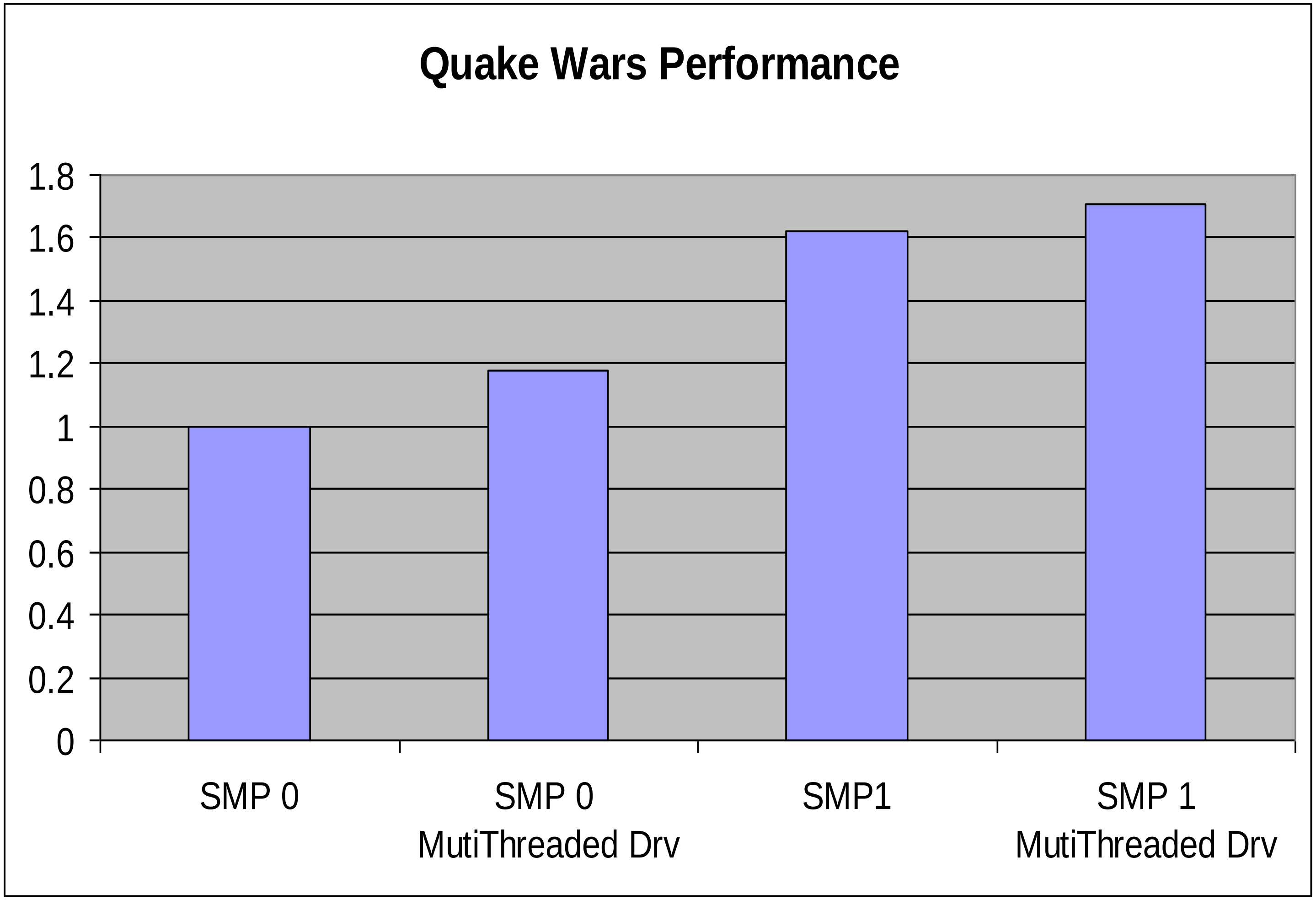
Current Performance



Renderer Threading with ETQW

- The whole renderer runs in a separate thread
- More work being done on the renderer thread
  - Culling and shadow volume construction
- Reduces amount of memory being buffered and shared between threads
  - Triangle meshes are not double buffered
- Better splitting of work on 2 cores
- Works better with multi-threaded drivers

ETQW



Quake Wars Performance
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
SMP 0
SMP 0 MutiThreaded Drv
SMP1
SMP 1 MutiThreaded Drv

Quake III Arena

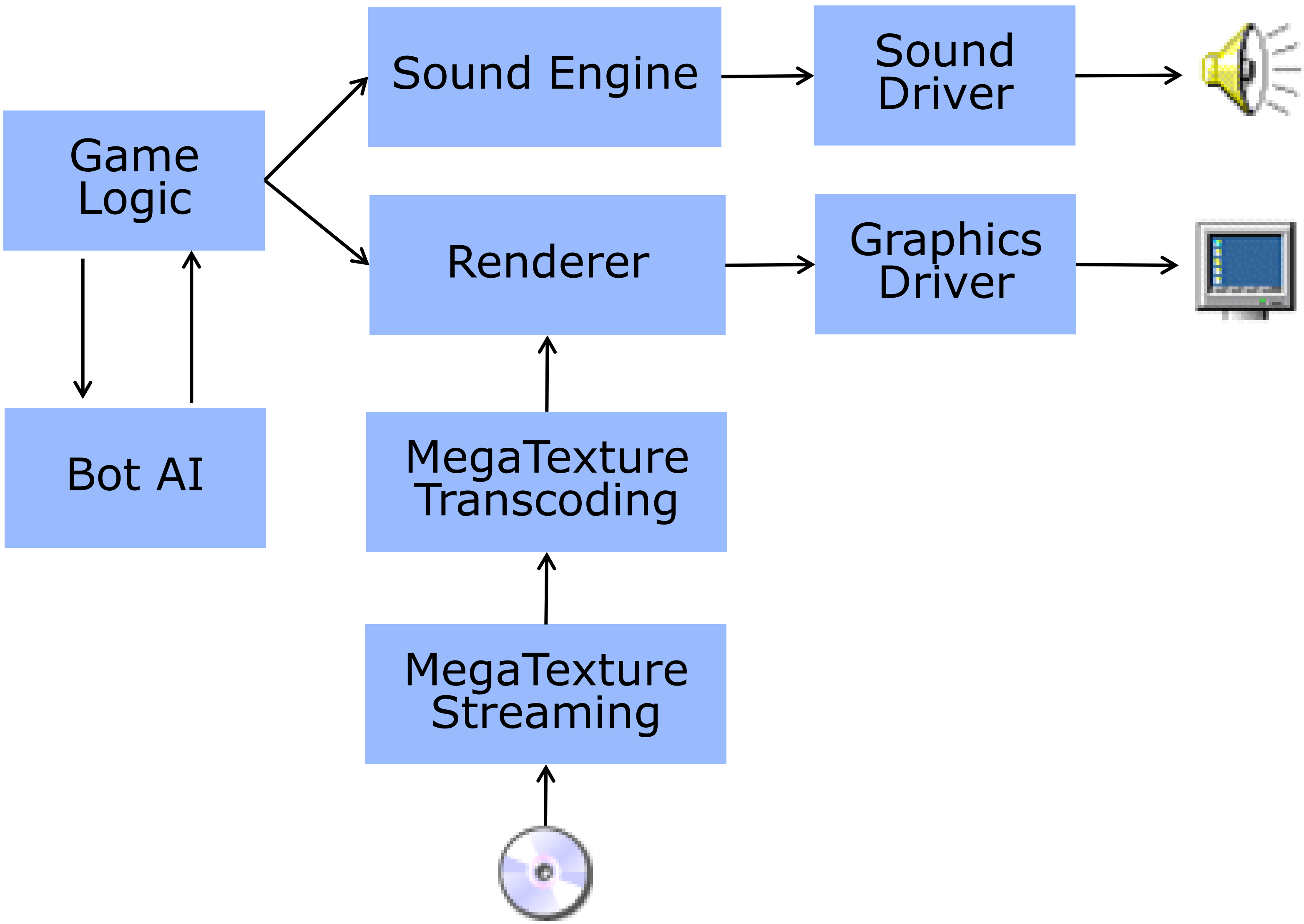
- Renderer back-end runs in a separate thread
- Very similar to QUAKE 4

DOOM III

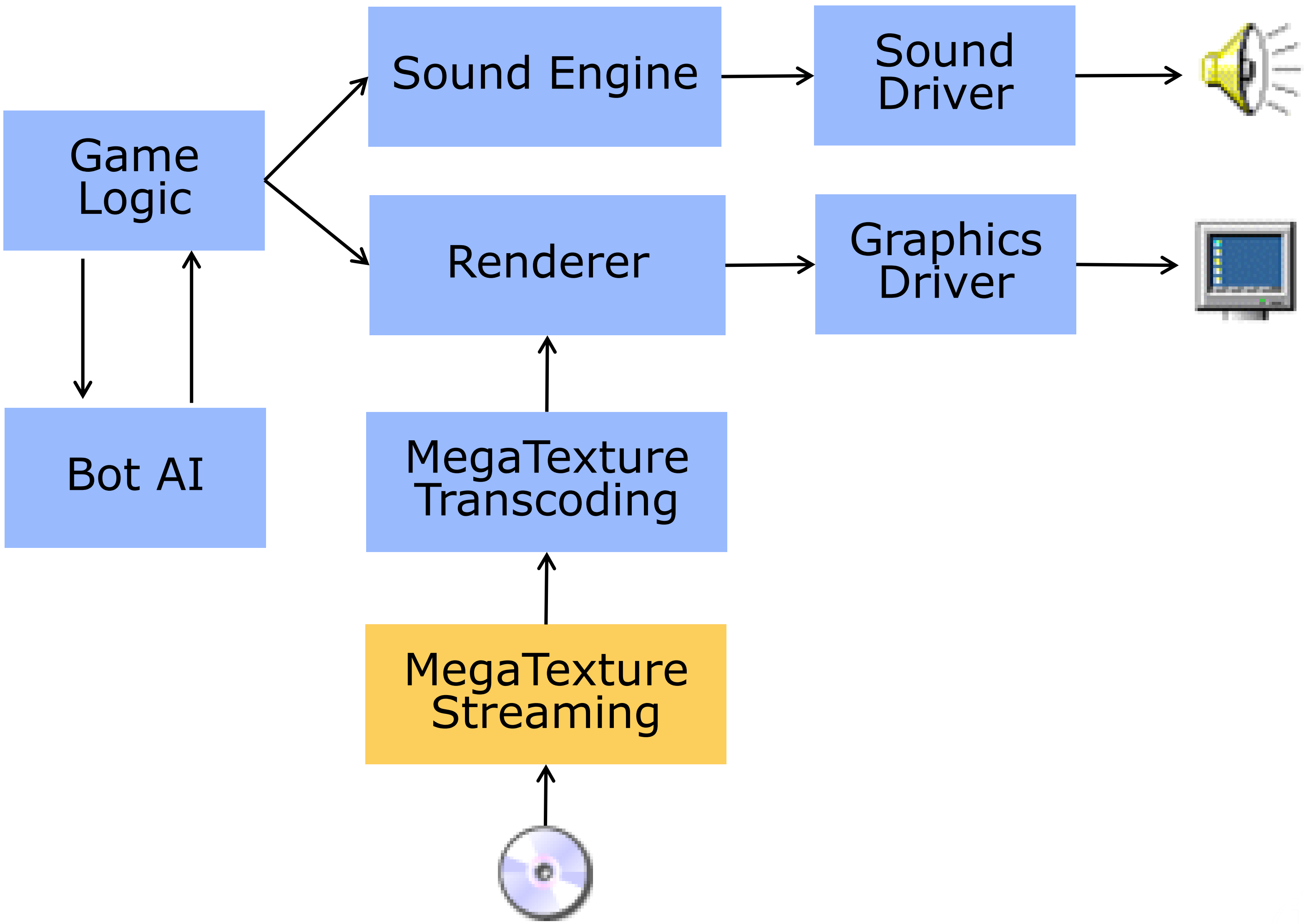
- Initially had the same threading as Quake III Arena
- Very much memory bound
- We actually removed the threading
- Instead SIMD optimized rendering pipeline
- The pipeline is optimized for cache usage

http://softwarecommunity.intel.com/articles/eng/2773.htm

ETQW Threading overview



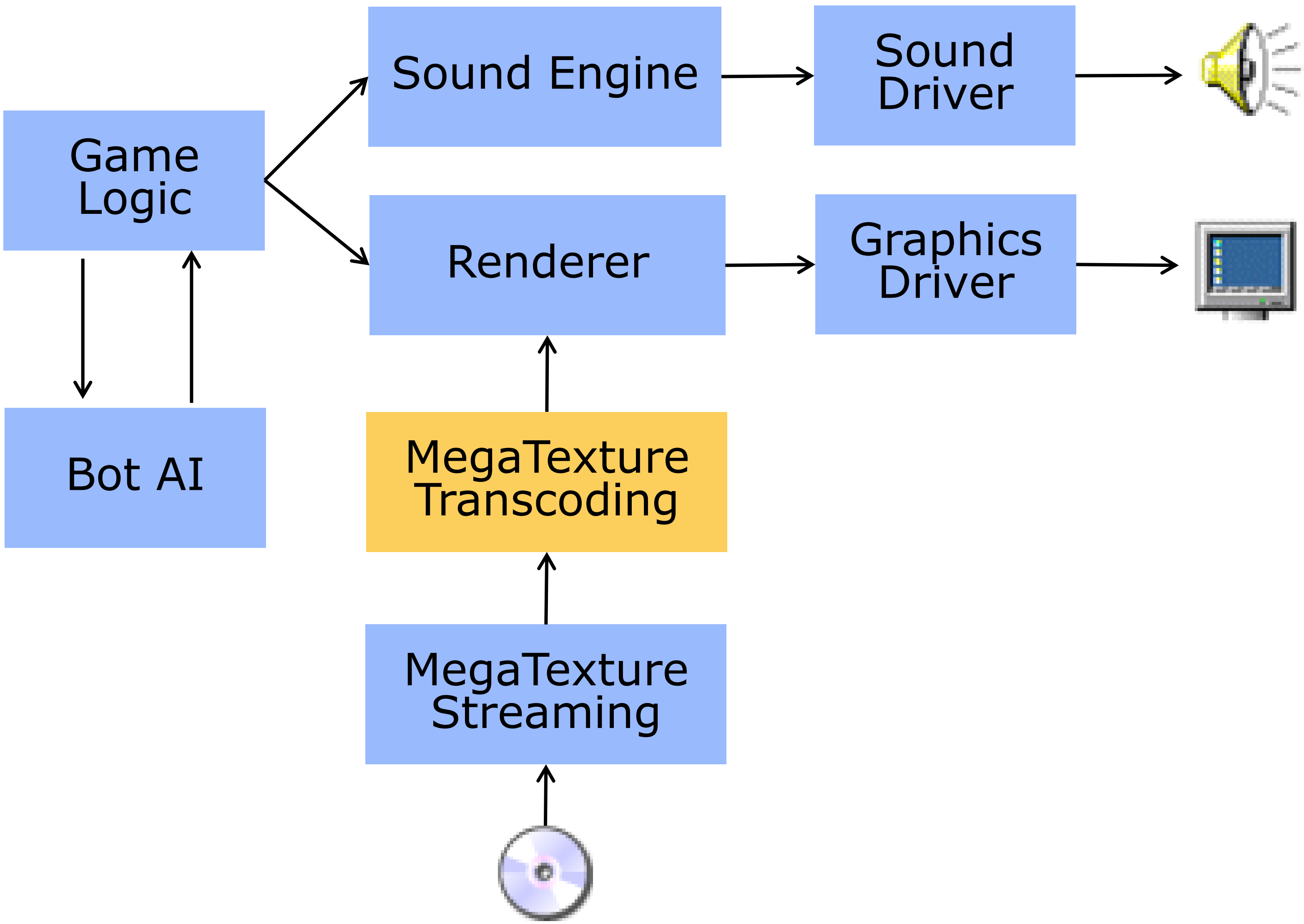
Mega Texture Streaming



Mega Texture Streaming

- The Mega Texture streaming thread dynamically sorts tile read requests.
- This thread is not doing any significant amount of work and mostly waits in place while data is being read from disk.
- The streaming is optimized using a texture database with an optimized layout to minimize seek times.
- The streaming thread reads 128 kB non-cached sector aligned blocks of data for optimal streaming from a DVD without polluting file system caches.

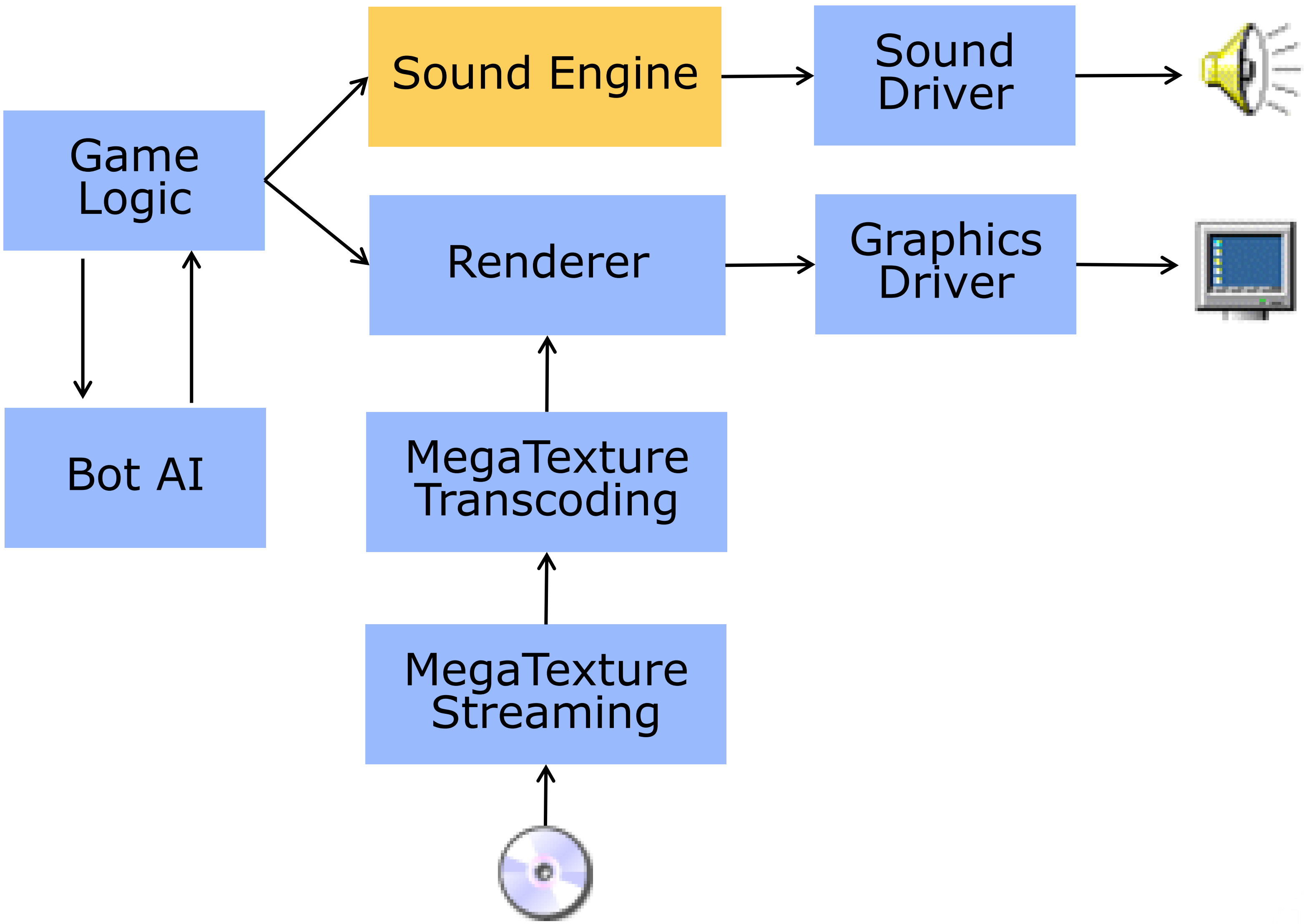
Mega Texture Transcoding



Mega Texture Transcoding

- Real-Time conversion from JPEG-like format to DXT.
- The transcoding uses highly optimized SIMD code and as such this thread does not consume a whole lot of CPU time.
- On systems based on the Core 2 microarchitecture the mega texture transcoding thread typically consumes less than 15% CPU time.
- Real-Time Texture Streaming & Decompression
  http://softwarecommunity.intel.com/articles/eng/1221.htm
- Real-Time DXT Compression
  http://www.intel.com/cd/ids/developer/asmo-na/eng/324337.htm

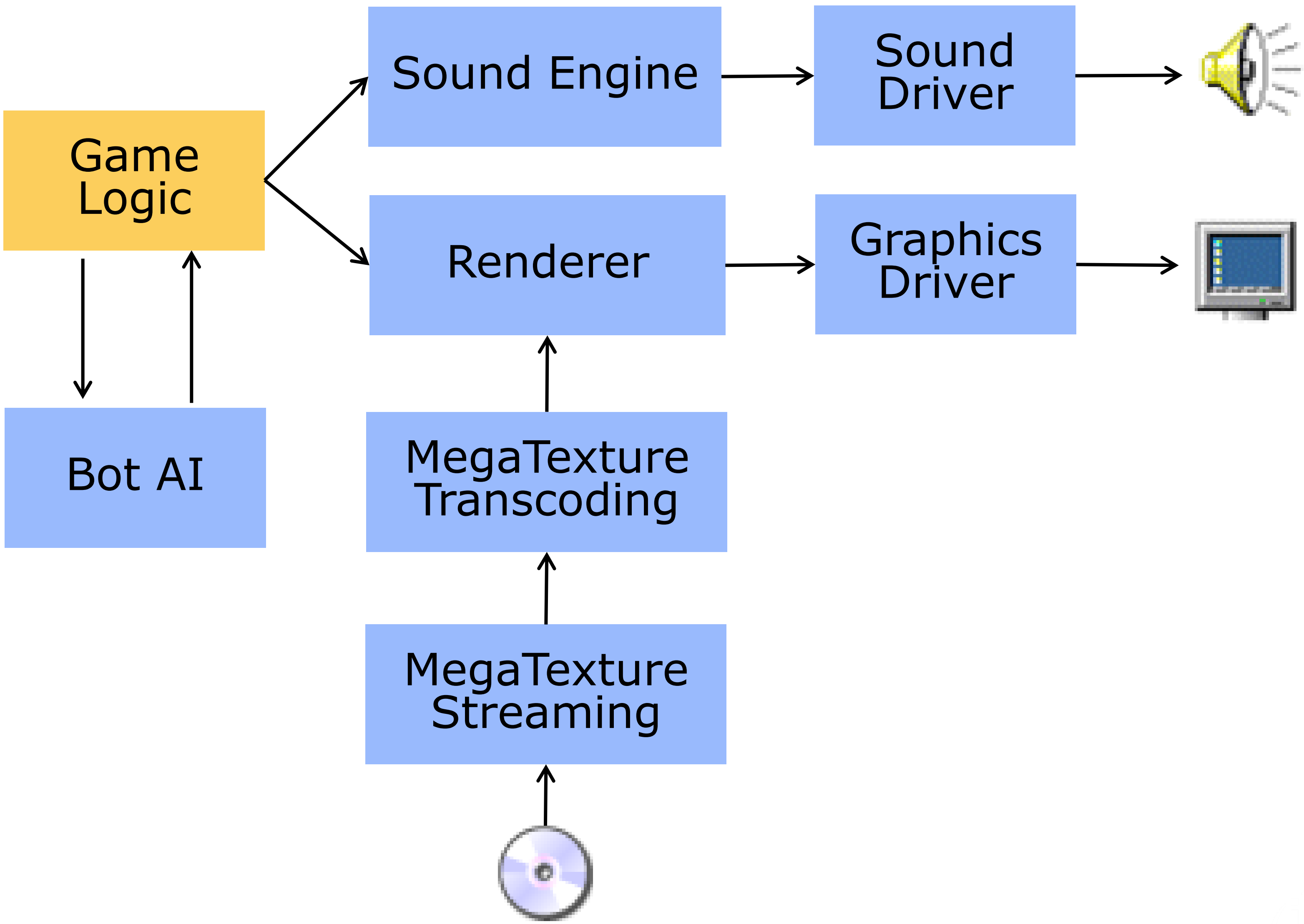
Sound Engine



Sound Engine

- The sound system performs spatialization.
- Decompresses OGG sounds in real-time.
- The sound thread does not consume a whole lot of CPU (typically < 5% on a Core 2).

Game Logic

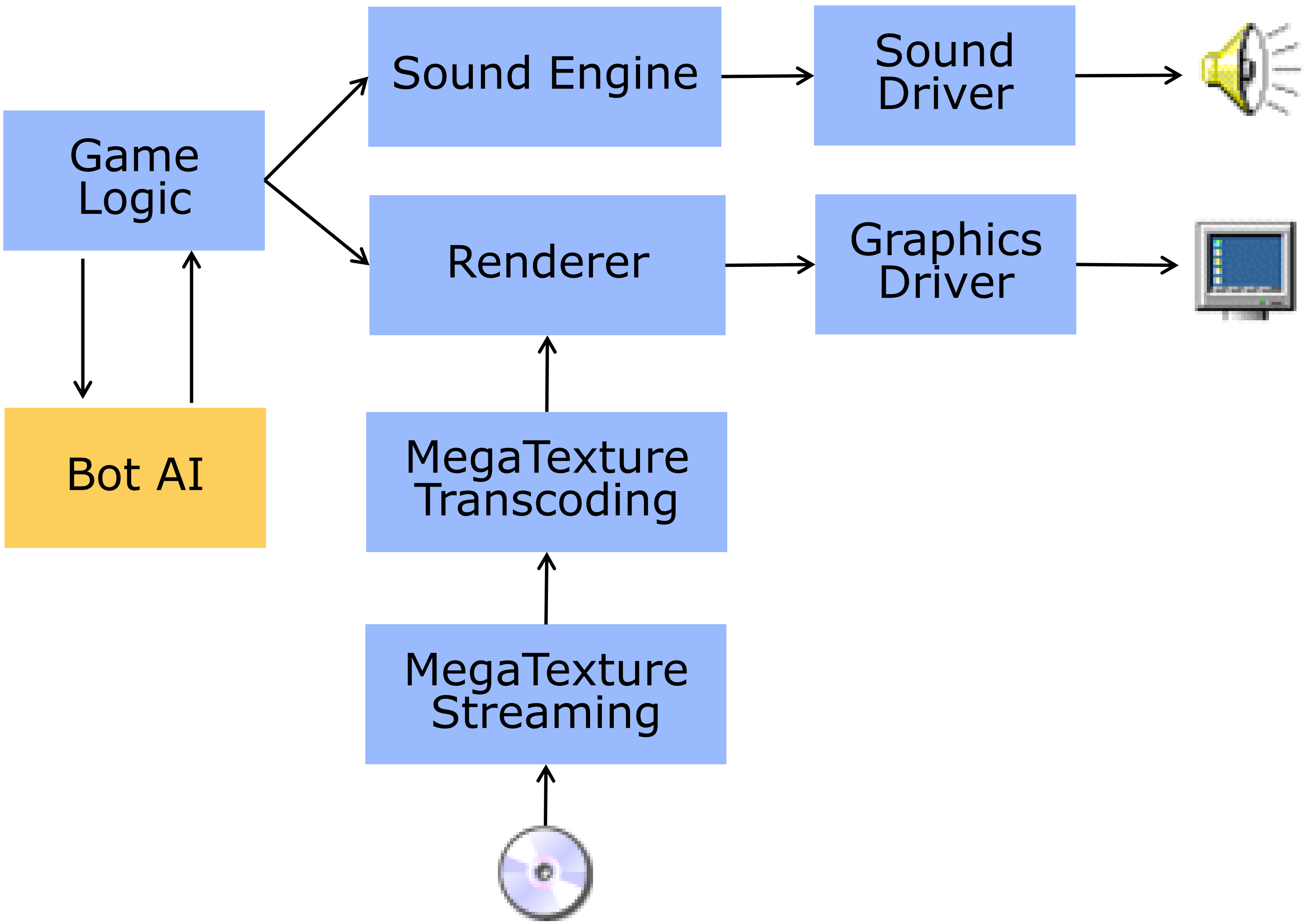


Game Logic
Sound Engine
Sound Driver
Renderer
Graphics Driver
Bot AI
MegaTexture Transcoding
MegaTexture Streaming

Game Logic

- The game logic runs at a fixed 30 Hz.
- The game code consumes quite a bit of CPU.
- A lot of this is collision detection and physics.
- The game logic itself typically involves lots of branchy code and can be expensive as well.

Bot AI



Sound Engine
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Bot AI

- The development of ETQW AI/bots did not start at the beginning of the project.
- On one hand this was a good thing because the AI implements thousands of game dependent rules that would have to change as the game is changed and tweaked during development.
- On the other hand the ETQW AI was developed in about a year which really is a short period of time to develop AI for a game with the complexity of ETQW.

Bot AI

- The AI threading in ETQW was designed and planned from the start.
- As a result the threading had little impact on the development time.
- The threading actually forced us to implement AI with clear data separation from the game code because the data has to be buffered.
- This is a good thing!

Bot AI

- The path and route finding system only run in the AI thread and as such do not need to be "thread safe".
- The collision detection system had to be made thread safe.
- At any point in time the AI can query the current collision state of the world.
- Unfortunately this introduces a source of non-determinism because the AI can query the collision state while the physics, which runs in the game thread, is moving objects around at the same time.

Bot AI

```
static const int MIN_FRAME_DELAY = 0;
static const int MAX_FRAME_DELAY = 4;
HANDLE      gameSignal;
HANDLE      aiSignal;
Int         gameFrameNum;
int         lastAIGameFrameNum;

void GameThread() {
   for ( ; ; ) {
      SetCurrentGameOutputState();
      AdvanceWorld();
      SetCurrentGameWorldState();

      gameFrameNum++
      // let the AI thread know there's another game frame
      ::SetEvent( gameSignal );
      // wait if the AI thread is falling too far behind
      while( lastAIGameFrameNum < gameFrameNum - MAX_FRAME_DELAY ) {
          ::SignalObjectAndWait( gameSignal, aiSignal, INFINITE, FALSE );
      }
   }
}
```

Bot AI

```
void AIThread() {
   for ( ; ; ) {
      // let the game thread know another AI frame has started
      ::SetEvent( aiSignal );
      // never run more AI frames than game frames
      while( lastAIGameFrameNum >= gameFrameNum - MIN_FRAME_DELAY ) {
         ::SignalObjectAndWait( aiSignal, gameSignal, INFINITE, FALSE );
      }
      lastAIGameFrameNum = gameFrameNum;

      SetCurrentAIWorldState();
      AdvanceAI();
      SetCurrentAIOutputState();
   }
}
```

Bot AI

- The last optimization we did in ETQW cut AI CPU usage in half and it took less than a minute to implement. We simply changed the MIN_FRAME_DELAY from zero to one.
- This reduces the think frequency of the AI to 15Hz.
- In Quake III Arena the bots were only thinking at 10Hz.

Threading On/Off

- Always implement an option to switch between threaded mode and non-threaded in real-time.
- This is very useful to see the true performance difference.
- Also makes it much easier when debugging the threaded code.

Common Issues

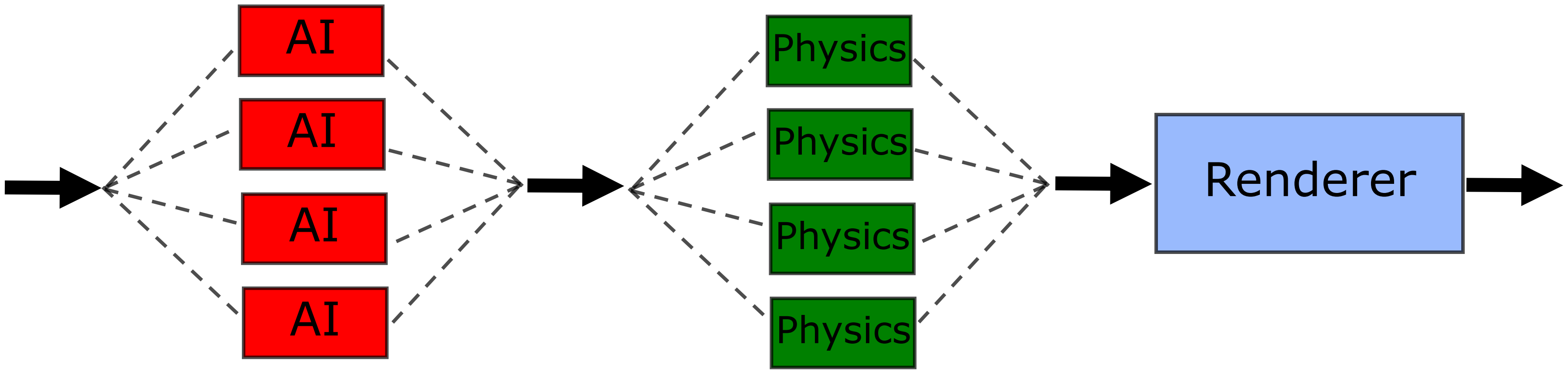
- Load Imbalance
- Under utilization of processors
  - Gustafson’s law increasing the amount of parallel work
  - Adding new features in games like fracture, smoke, cloth, procedural texture
- Amdahl’s law - Need to reduce Serial time to improve scaling
  - Parallelize code as far as possible
  - Vectorize serial code
  - Reduce time spent in a serial memory allocator
- Over subscription
  - Different Threaded subsystems
  - Threading at various levels of the application stack
  - Threaded middleware

Scalability

- PCs have a broad range of capabilities from CPU to Graphics
- Even with a fixed target platform its hard to load balance for real game play.
- Scene complexity, interactivity, physics vary from scene to scene
- Need to think how to make best use of resources
- Granularity Vs Load Balancing
- Common threading infrastructure with priorities/QoS.

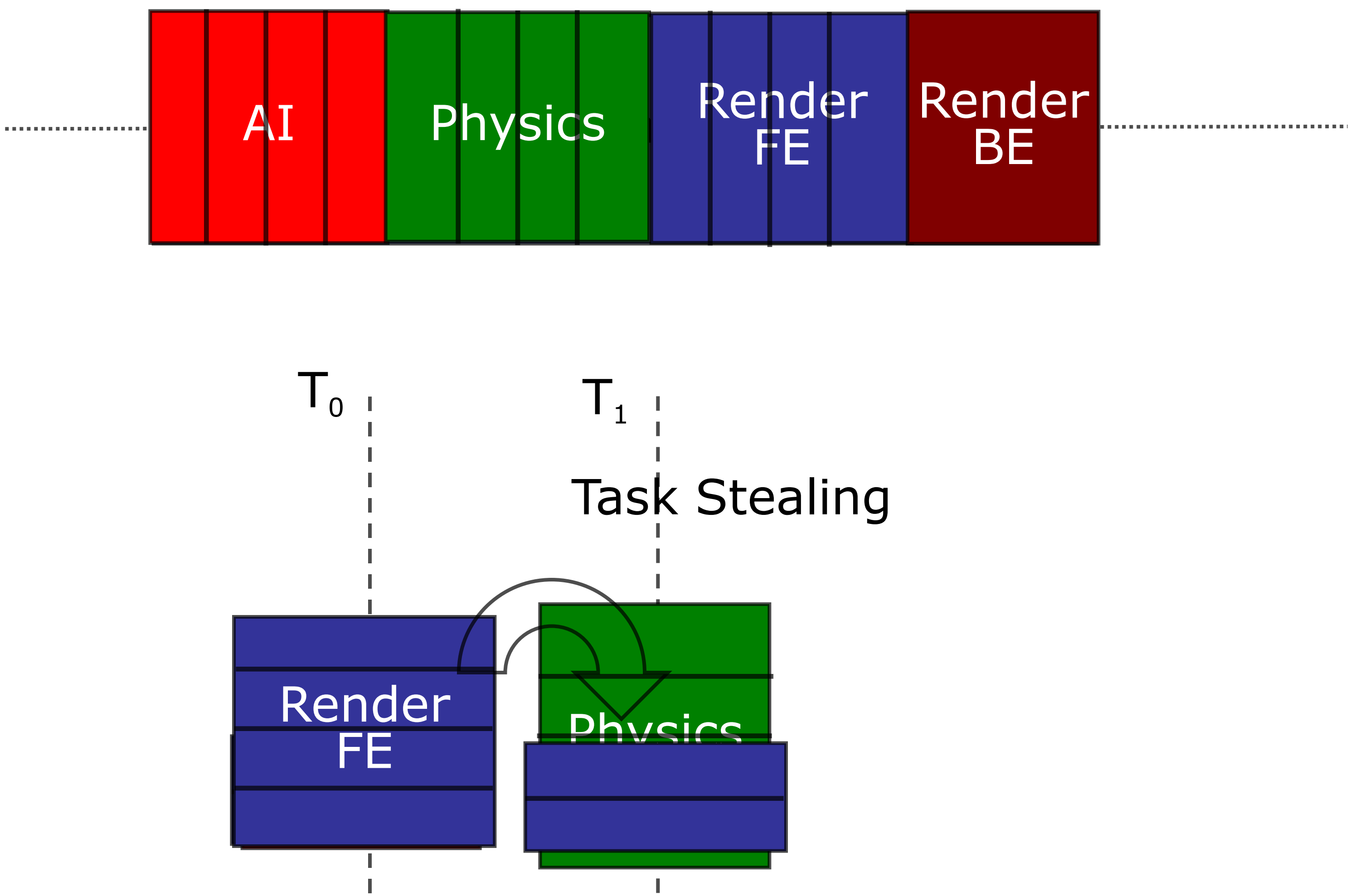
Alternate Threading Paradigms

- Data Decomposition



Alternate Threading Paradigms

- Task/Work decomposition / Pipeline



Design with threading in mind

- Lot easier to thread code that’s designed well.
- Reduce the coupling (data-dependence) between subsystems
- Make them as asynchronous as far as possible.
- Factor a given subsystem into data and operations performed on the data (iterators).
- Make sure that data classes don’t store any iterator data and are reentrant.
- Have a mechanism to ensure validity of shared, mutable data.
- Intel's Threading Building Blocks (TBB) has some good resources like thread safe containers, efficient memory allocator, generic parallel algorithms (parallel for, ….) and its open source.

Summary

- Threading Game Engines is not a trivial task - Game engines are very complex pieces of code with a relatively short shelf life.
- Game engines naturally lend themselves to functional decomposition but interdependence between the various subsystems can cause excessive synchronization and performance overheads.
- Functional decomposition leads to load imbalance and often performance is limited by the main thread. Need to Investigate alternate paradigms like Task Queues to improve load balance.
- Need to design and implement debugging aids into the threading infrastructure
  - Interaction with the GPU makes debugging harder

www.intel.com/software/graphics

Wednesday

10:30am - Gaming on the Go
12:00pm - COLLADA in the Game
02:30pm - Interactive Ray Tracing in Games
04:00pm - Speed Up Synchronization Locks

Thursday

09:00am - The Future of Programming for Multi-Core with the Intel Compilers
10:30am - Getting the Most Out of Intel Graphics
12:00pm - Comparative Analysis of Game Parallelization
02:30pm - Threading Quake 4 and Quake Wars