the gamedesigninitiative at cornell university

Lecture 13

Concurrency & Multithreading

Games are Naturally Multithreaded

- The core game loop is **time constrained**
  - Frame rate sets a budget of how much you can do
  - Exceeding that budget causes frame rate drops
- Sometimes we need an extra thread to …
  - Offload tasks that *block* drawing (**asset loading**)
  - Offload tasks that *slow* drawing (**pathfinding**)
  - Execute tasks *decoupled* from drawing (**audio**)
- Part of architecture spec: **computation model**

Multithreading in CUGL

- CUGL has **three** primary threads
  - The `Application`, or main graphics thread
  - The `AssetManager` thread, for loading assets
  - The `AudioEngine` thread, for audio playback
  - Note that only `Application` is required
- Also has tools for making your own threads
  - Most are built on top of C++ and `std::thread`
  - But there are some unique features too

Multithreading in CUGL

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  - The `Application`, or main graphics thread
  - The `AssetManager` thread, for loading assets
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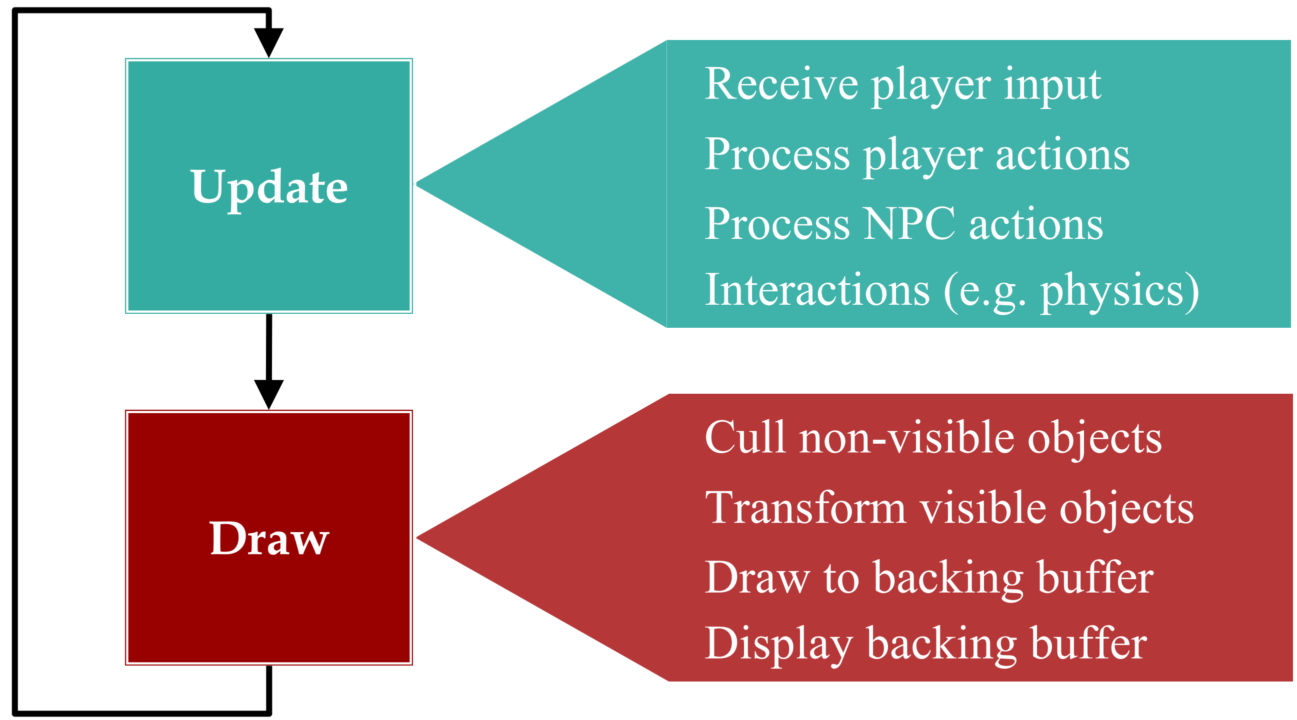
Understanding the three threads can help us to make our own.

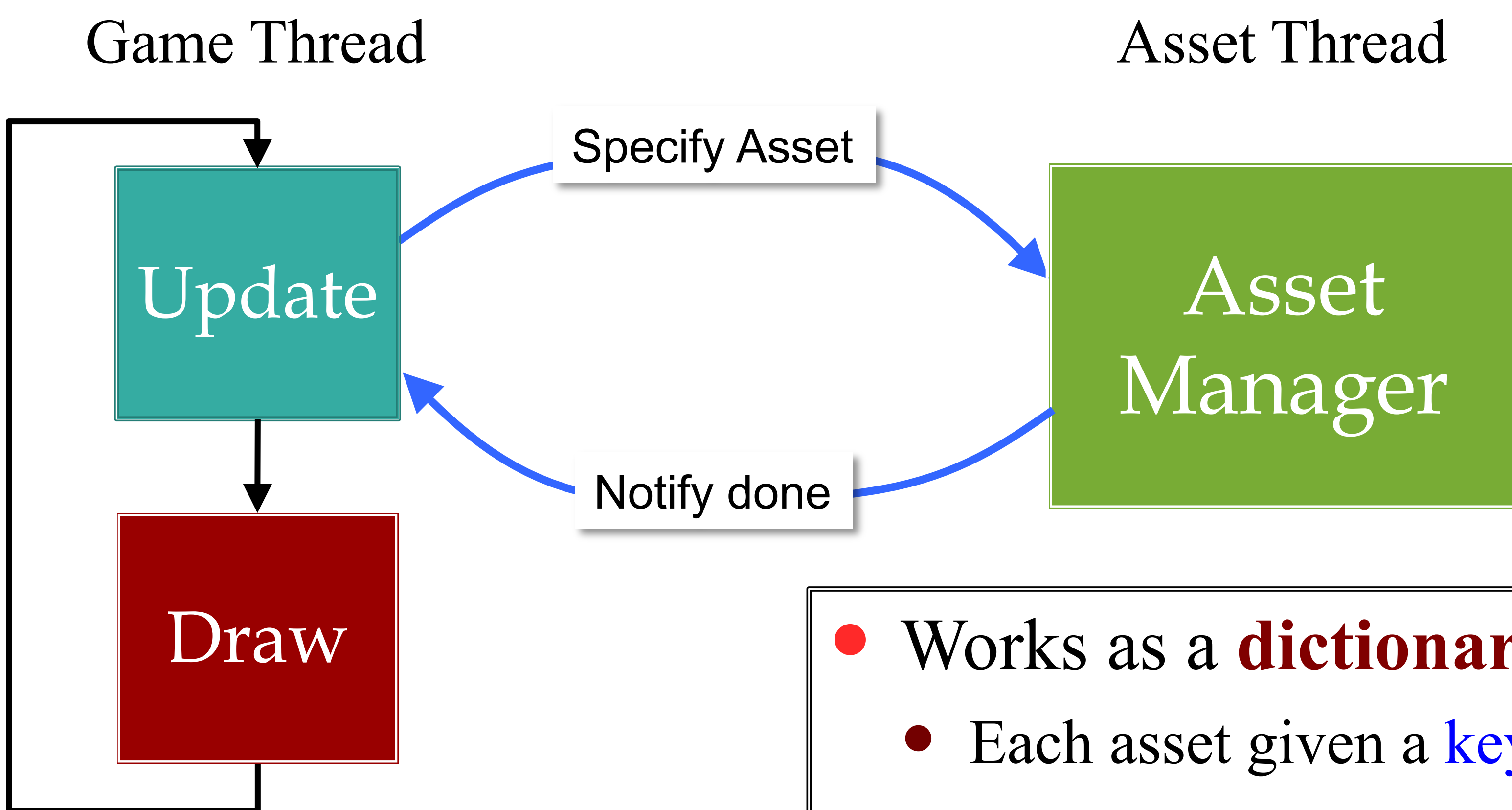
- Also has tools for making your own threads
  - Most are built on top of C++ and `std::thread`
  - But there are some unique features too

Recall: The Application Thread

60 times/s
=
16.7 ms

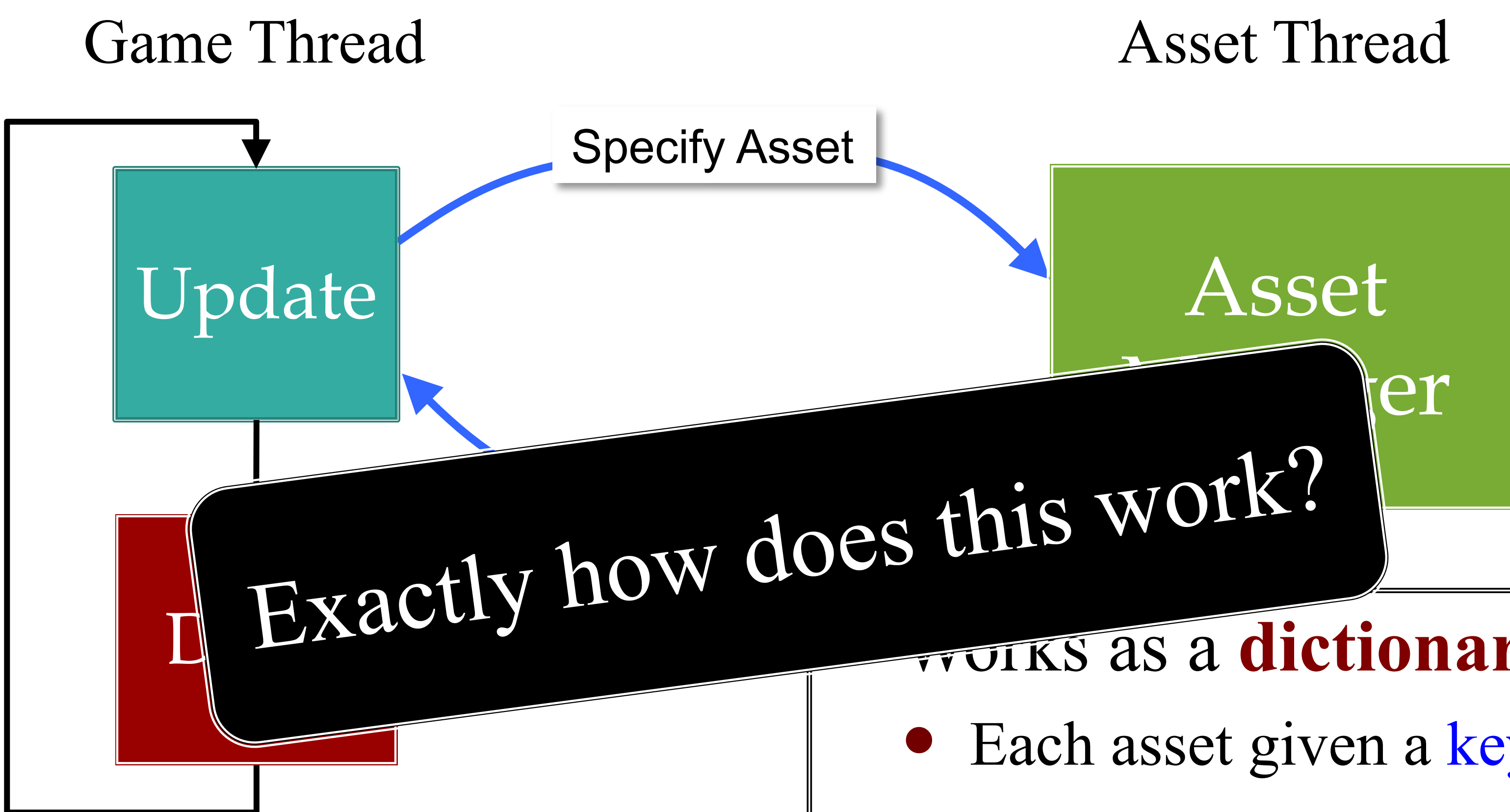


Recall: The `AssetManager` Thread



- Works as a **dictionary**
  - Each asset given a key
  - Can access asset by key
  - But templated by type

Recall: The AssetManager Thread



Exactly how does this work?

Works as a **dictionary**

- Each asset given a key
- Can access asset by key
- But templated by type

Asset Loading Consists of Tasks

Task 1	Task 2	Task 3	Task 4
Load Font "Times.ttf"	Load Image "smile.png"	Load Sound "music.ogg"	Load Widget "menu.json"

Ideally, Each One is a Thread

Task 1	Task 2	Task 3	Task 4
Load Font "Times.ttf"	Load Image "smile.png"	Load Sound "music.ogg"	Load Widget "menu.json"

Thread 1	Thread 2	Thread 3	Thread 4

Ideally, Each One is a Thread

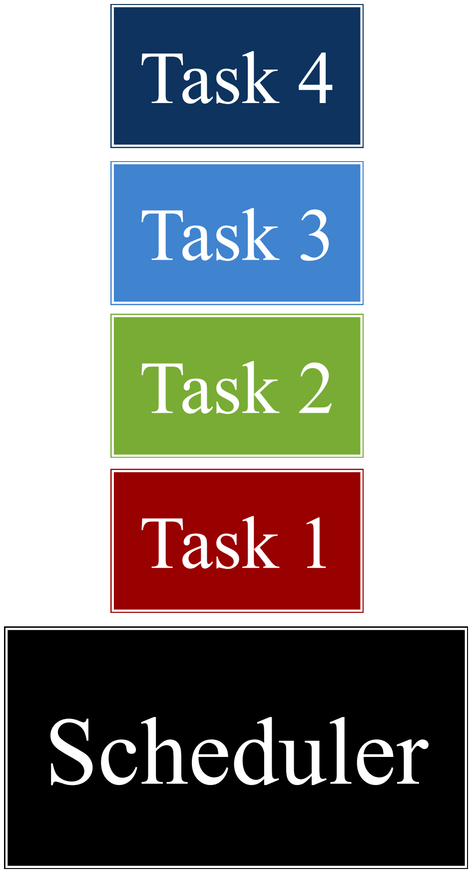
Task 1	Task 2	Task 3	Task 4
Load Font "Times.ttf"	Load Image "smile.png"	Load Sound "music.ogg"	Load Widget "menu.json"
Thread 1	Thread 2	Thread 3	Thread 4

But We Cannot Do This

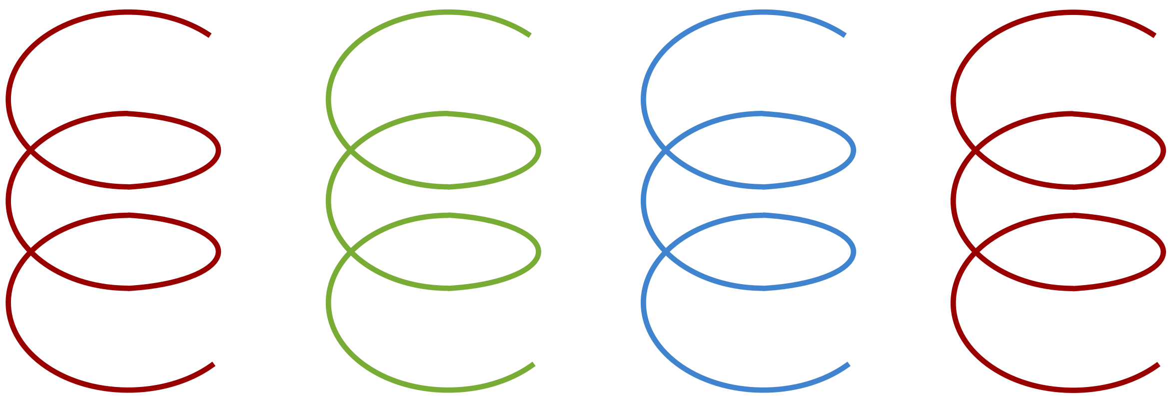
What is the Problem?

- Some tasks have **shared resources**
  - **Example:** Fonts all use same engine to make atlases
  - Cannot execute without protecting critical section
  - Typically easier to just **not** do them concurrently
- Some tasks have **dependencies**
  - **Example:** Widgets must come after images, fonts
  - Forces an order on the asset loading
- What we want is a task **service manager**
  - Executes given tasks in a *partial order*

Solution: Thread Pool



- Threads + scheduler
- Scheduler puts tasks thread
- Uses first available thread
- Holds tasks if all busy



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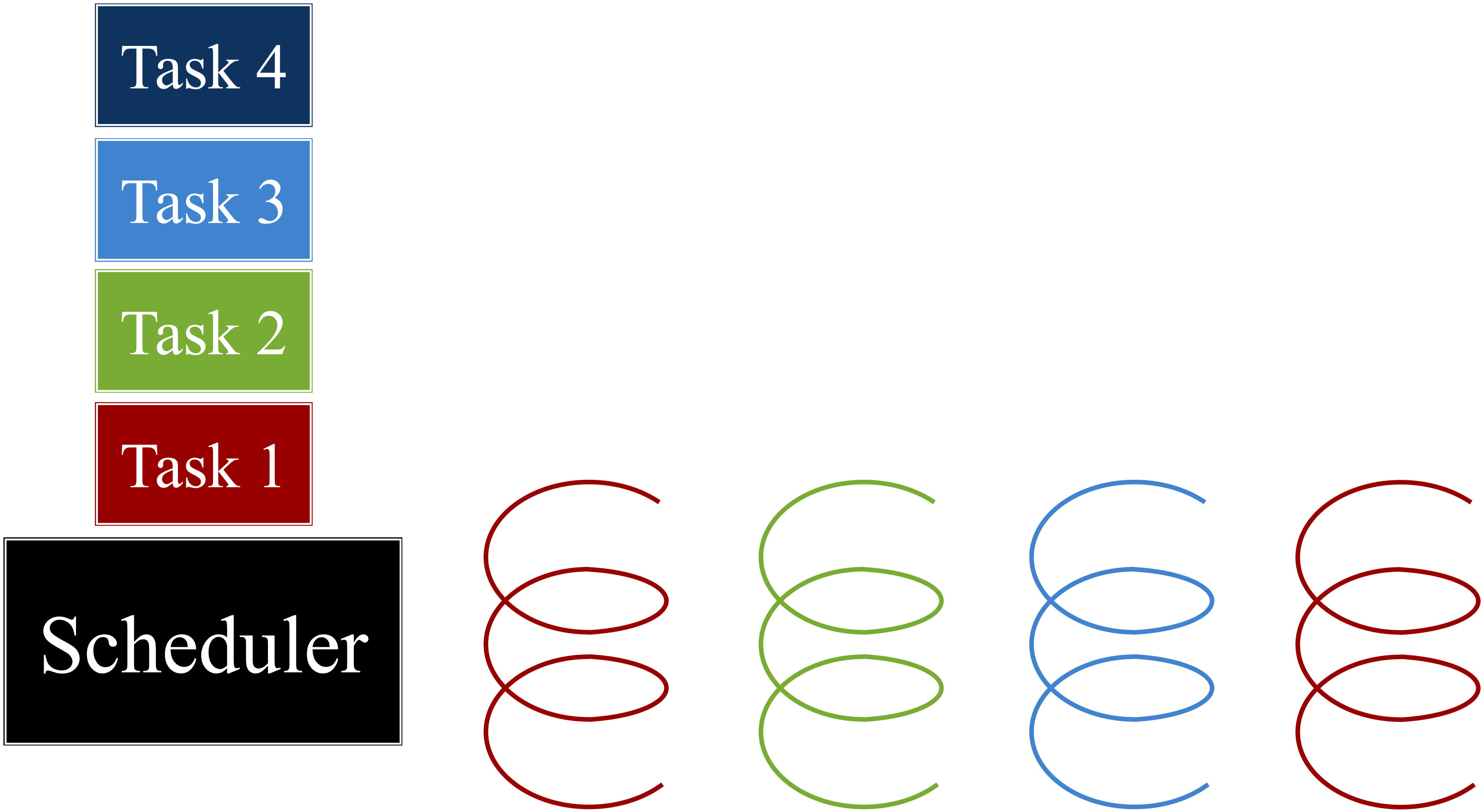

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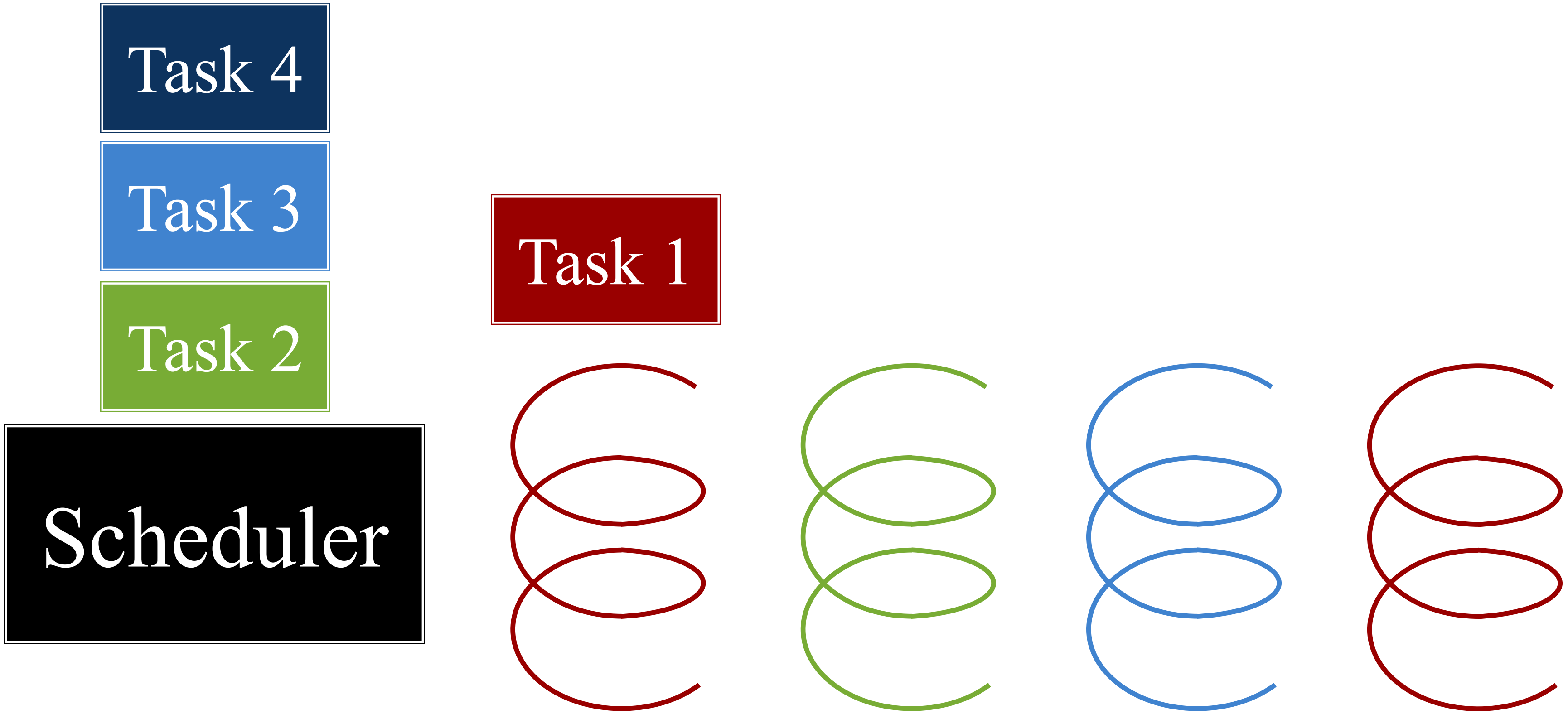

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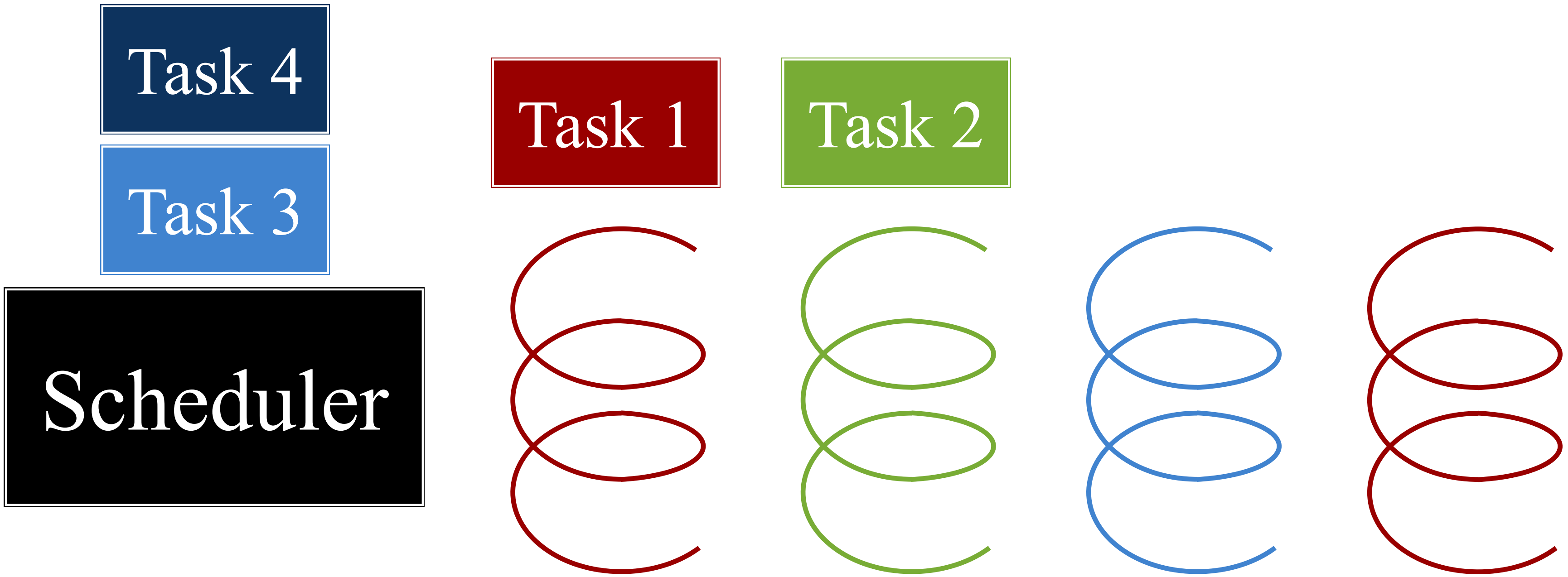

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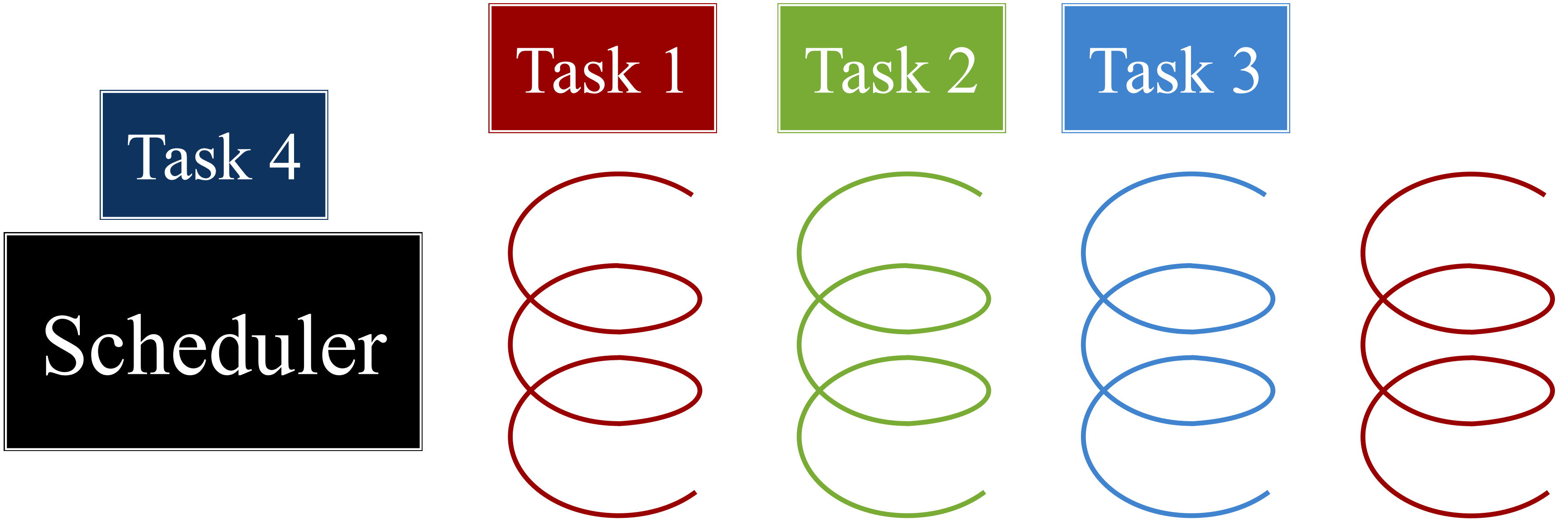

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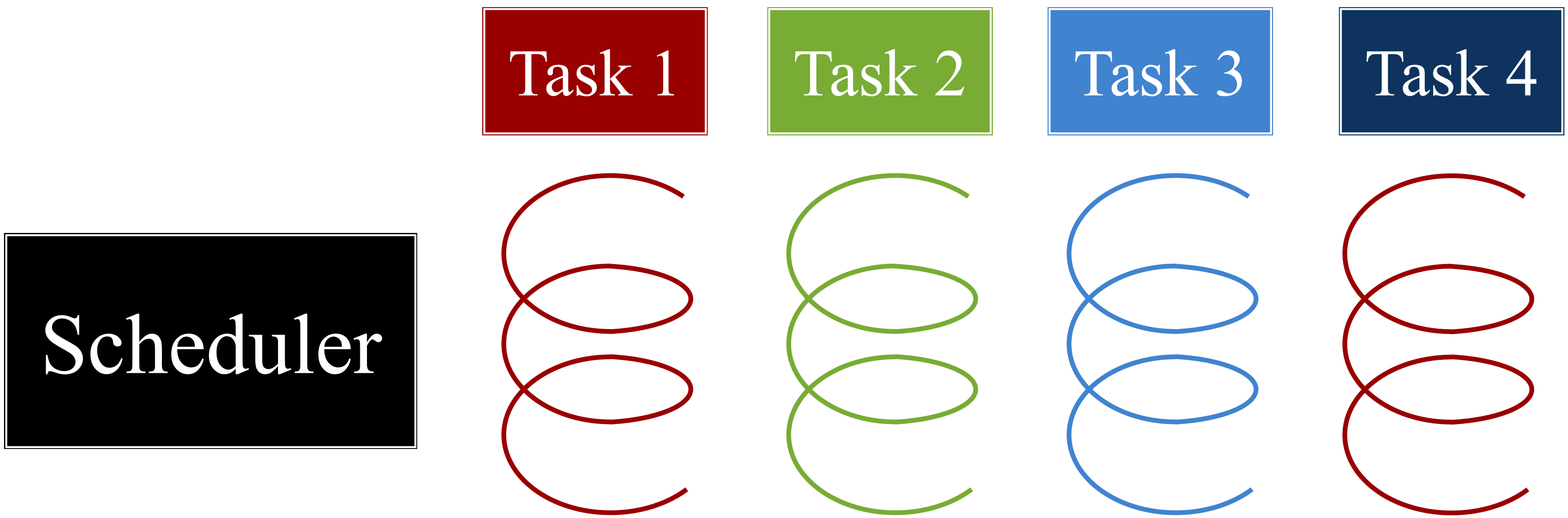

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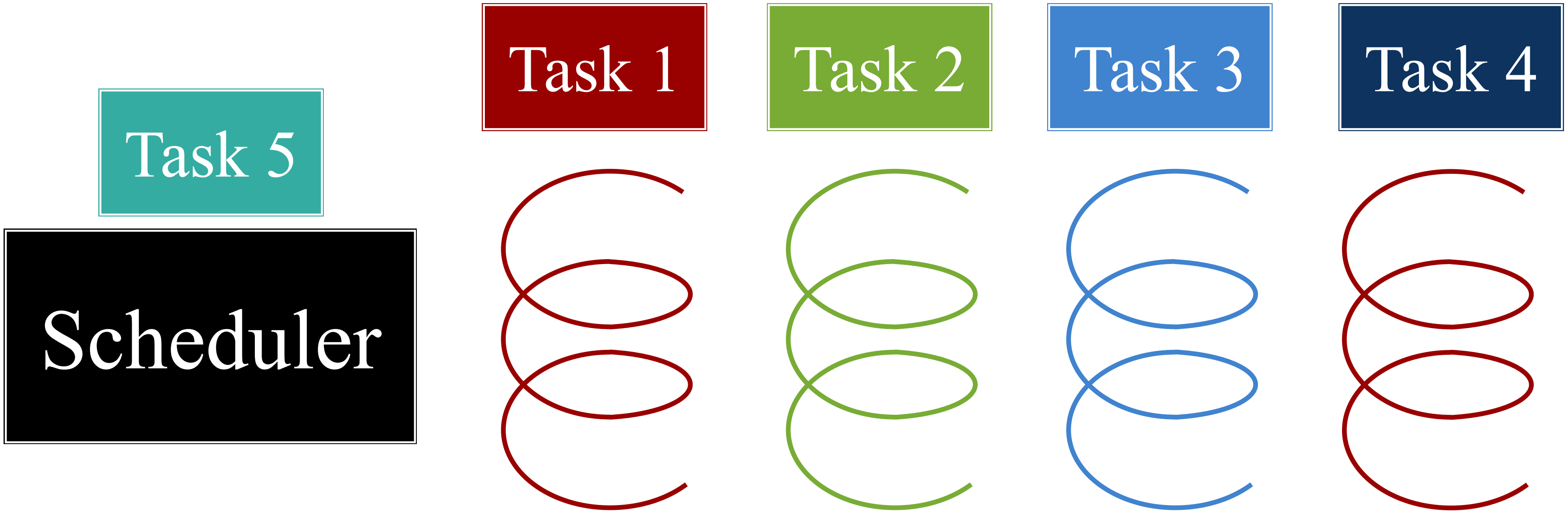

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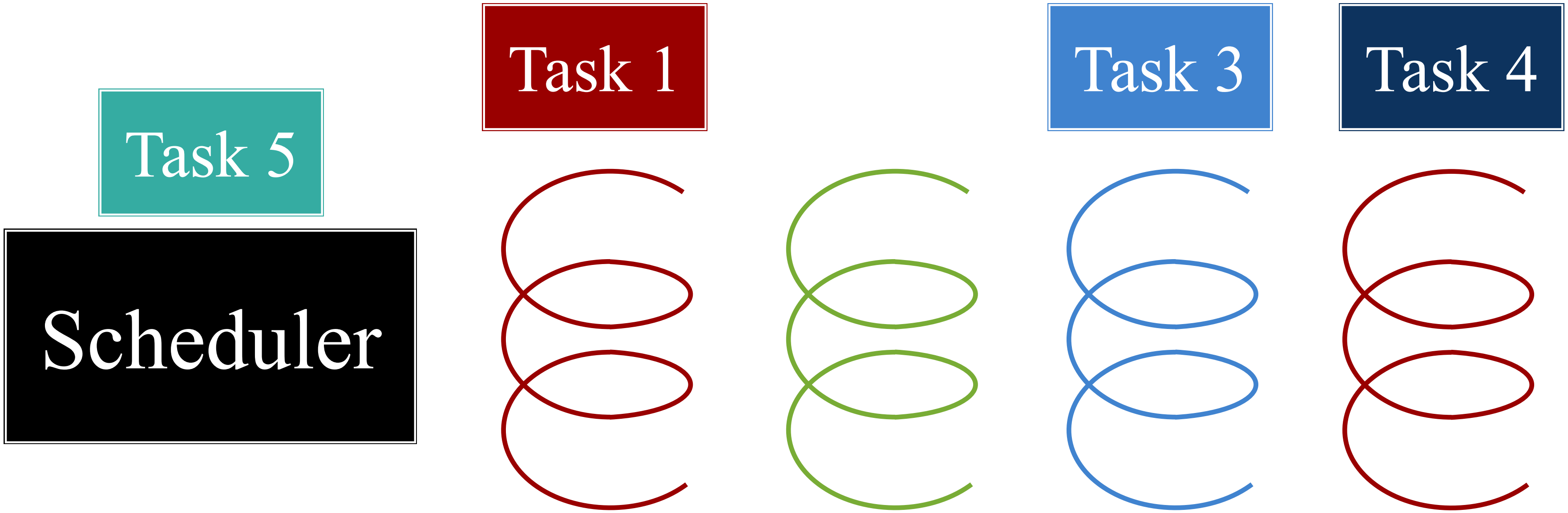

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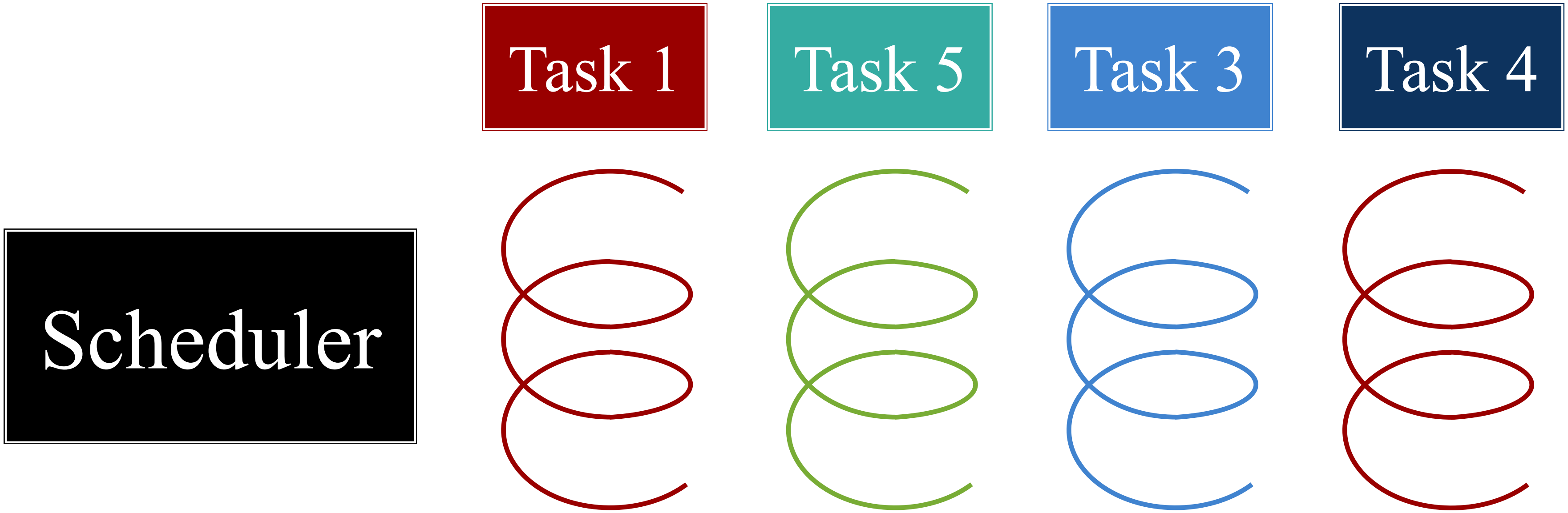

CUGL Support: ThreadPool

- ```
  /**
   * Returns a thread pool with the given number of threads.
   *
   * @param threads   the number of threads in this pool
   *
   * @return a thread pool with the given number of threads.
   */
  static std::shared_ptr<ThreadPool> alloc(int threads = 4)
  ```

- ```
  /**
   * Adds a task to the thread pool.
   *
   * @param  task     the function to add to the thread pool
   */
  void addTask(const std::function<void()> &task)
  ```

CUGL Support: ThreadPool

- ```
  /**
   * Returns a thread pool with the given number of threads.
   *
   * @param threads   the number of threads in this pool
   *
   * …ds.
  ```

AssetManager is a one thread pool

- ```
  /**
   * Adds a task to the thread pool.
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   * @param  task     the function to add to the thread pool
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  void addTask(const std::function<void()> &task)
  ```

Recall: Custom Loaders

- `void read(key, src, cb, async)`
  - Reads asset from file `src`
  - `async` indicates if in sep thread
  - Callback `cb` executed when done

Thread Safe

- `void read(json, cb, async)`
  - Values `key` and `src` now in json
  - As are other special properties

Thread Safe

- `void materialize(key, asset, cb)`
  - Code to "finish" asset
  - Always in the **main thread**

Main Thread Only

Recall: Custom Loaders

- void read(key, src, cb, async)
  - Reads asset from file src
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- void read(json, cb, async)
  - Values key and src now in json
  - As are other special properties
- void materialize(key, asset, cb)
  - Code to "finish" asset
  - Always in the **main thread**

Each of these is its own task

Executing Tasks on the Main Thread

- Any other thread can access the `Application`
  - Use the static method `Application::get()`
  - This class is essentially a singleton
- That object has a `schedule` method
  - Works much like `addTask` in thread pool
  - But executes that task on the main thread
  - Executed just before the call to your `update`
- **Scheduling** this task is thread safe

The Schedule Method

```
/**
 * Schedules a task function on the main thread.
 *
 * @param cb      The task callback function
 * @param ms      The number of milliseconds to delay
 *
 * @return a unique identifier for the task
 */
Uint32 schedule(std::function<bool()> cb, Uint32 ms)
```

The Schedule Method

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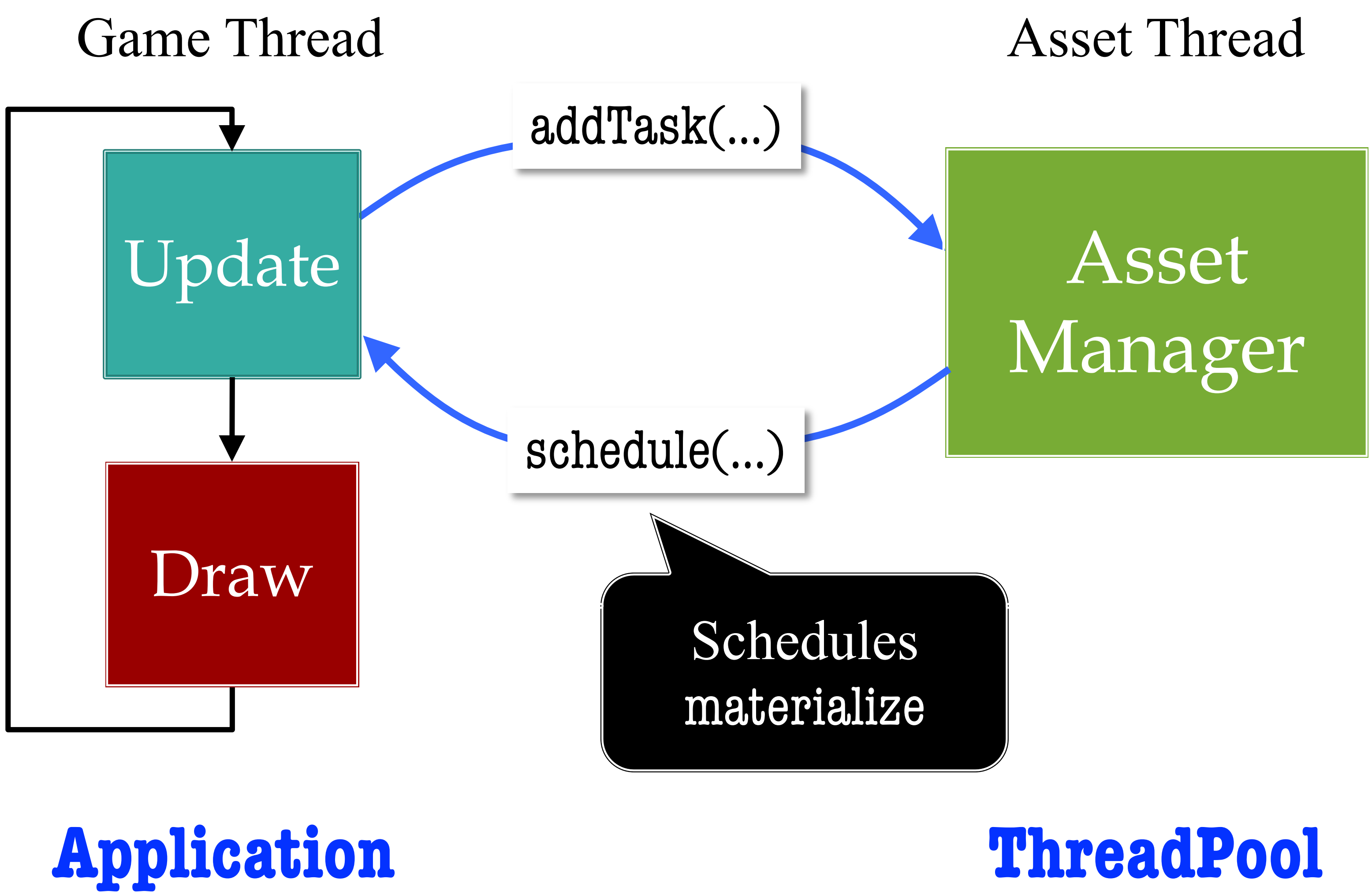
Uint32 schedule(std::function<bool()> cb, Uint32 ms)
```

Return false to stop execution

Picks first frame after ms millisec

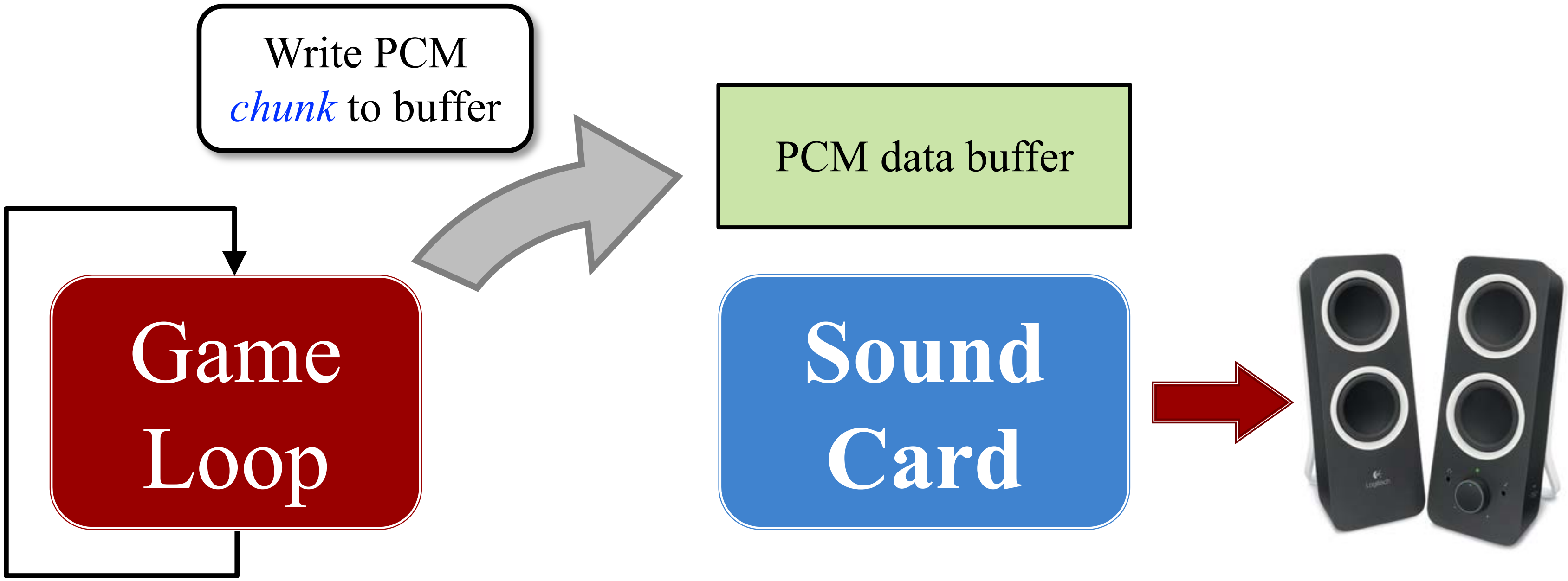
Putting it All Together



Aside: Schedule is Useful in General

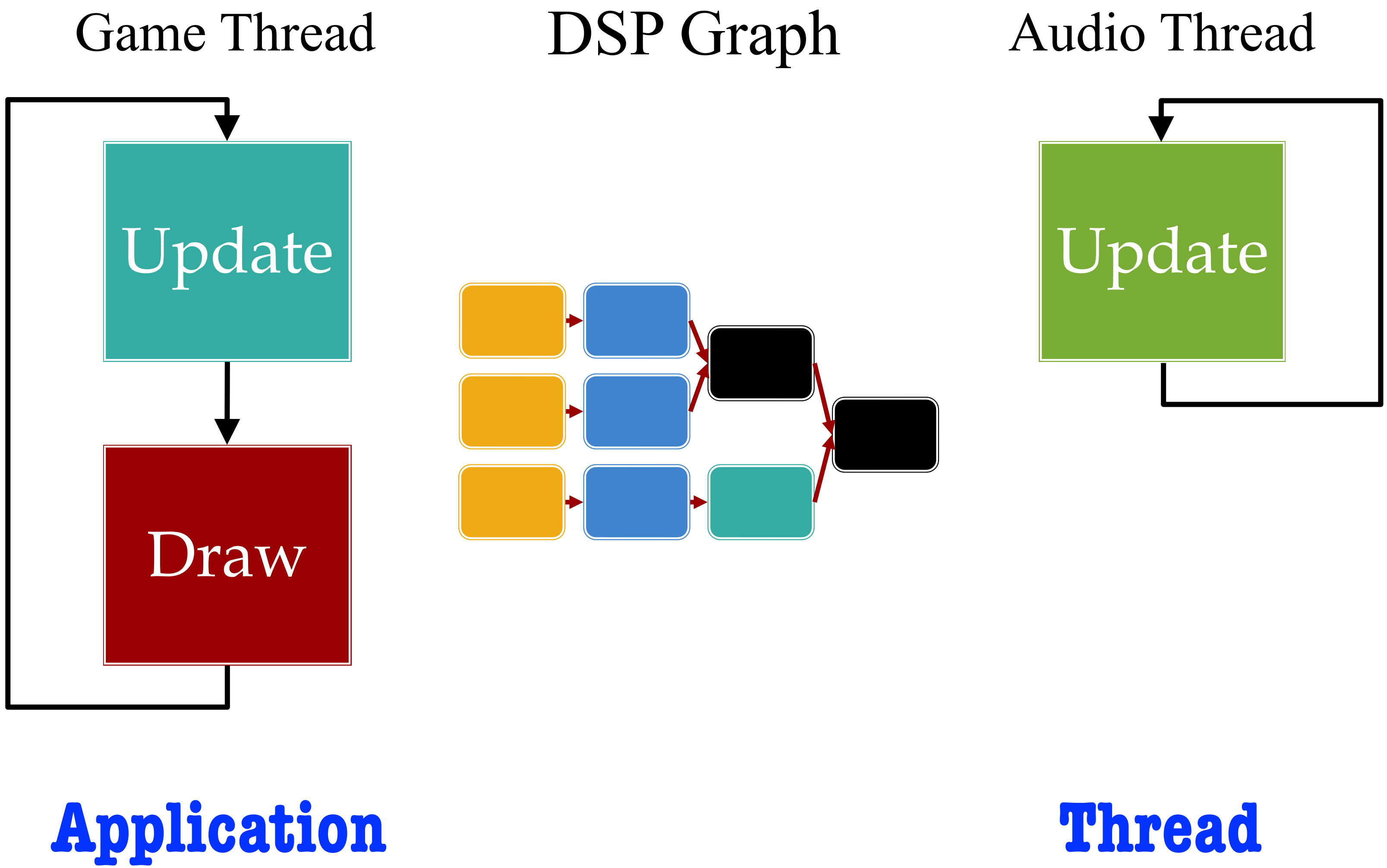
- Can specify an event to **run in the future**
  - This is the purpose of the milliseconds
  - May be easier than tracking a timer yourself
- Can specify a task to **run periodically**
  - **Example:** Spawning enemies
  - The task returns `true` if it wants to run again
  - Same delay is applied as the first time
  - Alternate `schedule` separates **delay** and **period**

Recall: Playing Sound Directly



Missing a write causes pops/clicks

The CUGL Approach



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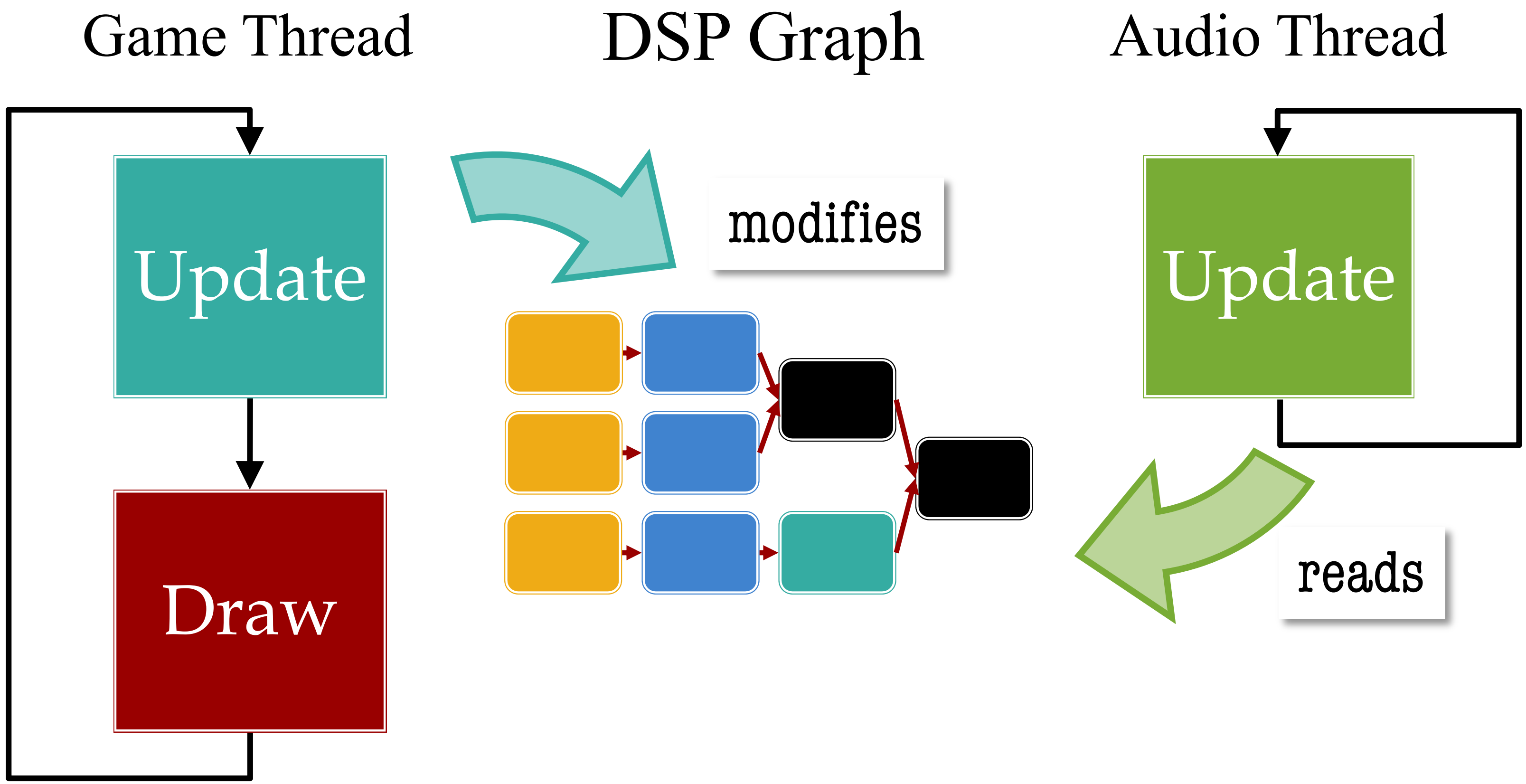
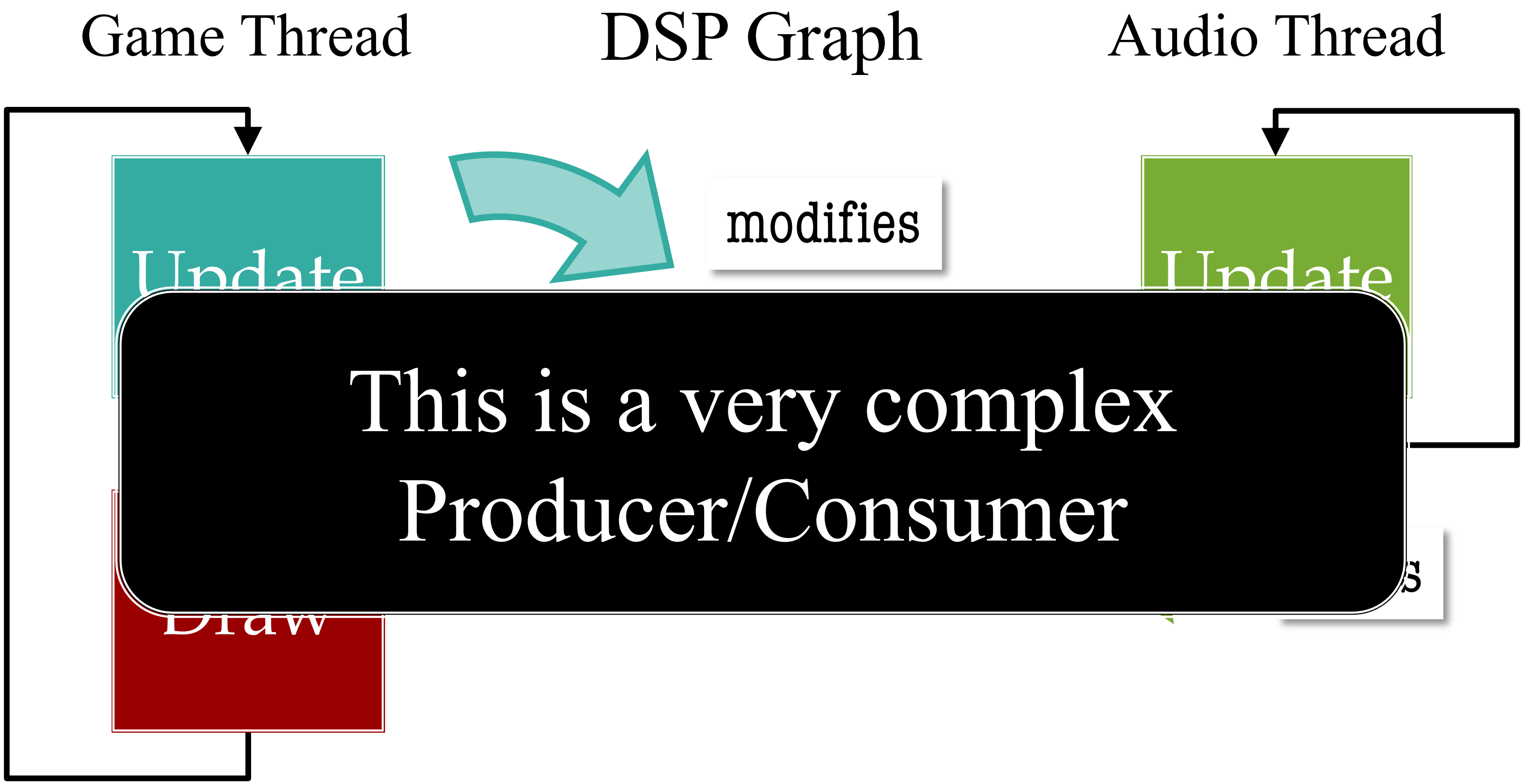


Application **Thread**

The CUGL Approach



This is a very complex Producer/Consumer

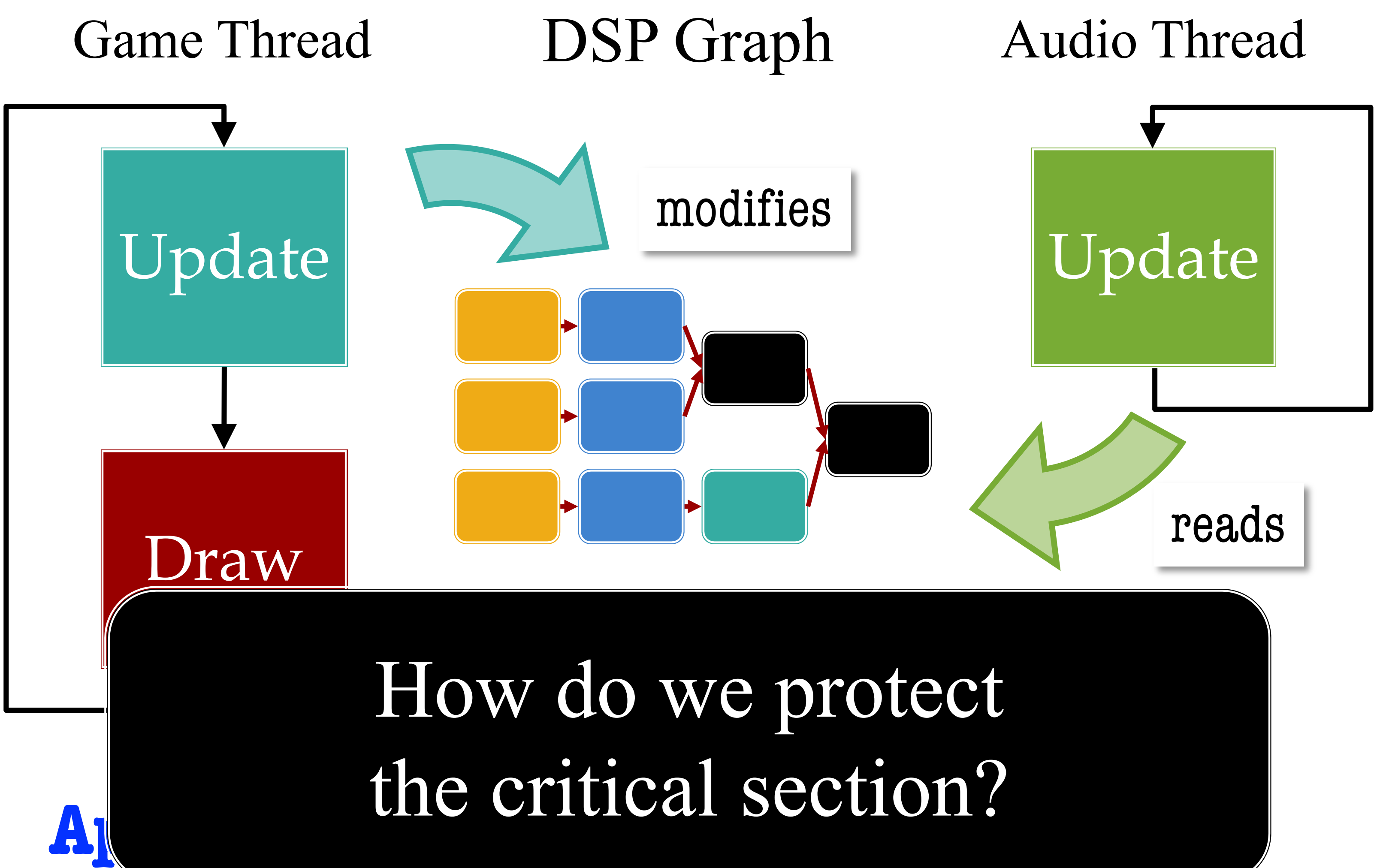
Application

Thread

Aside: Audio is Not a ThreadPool

- Audio is a dedicated std::thread
  - Because it needs to run as long as the game does
  - Started when you initialized AudioEngine
- But process is similar to ThreadPool
  - Package your task as a std::function<void()>
  - Pass this when you create the thread object
- Difference is that task is in a loop
  - Has an attribute called running to manage loop
  - When you set to false, the thread is done

The CUGL Approach



How do we protect the critical section?

The Java Approach: Synchronized

```
public class CriticalSection {

    synchronized void method1() {...}

    synchronized void method2() {...}

    synchronized void method3() {...}

}
```

Locked to one thread at a time

The Java Approach: Synchronized

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public class CriticalSection {

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```

Locked to one thread at a time

Lock applies to **all** of the methods

C++ Actually Has Two Tools

`std::mutex`

- Used to protect a **code block**
  - Places lock on code block
  - Only one thread can access
- **Advantages**
  - Can replicate `synchronized`
  - Relatively easy to use
- **Disadvantages**
  - Locking has some cost
  - Deadlocks easy if careless

`std::atomic`

- Used to protect a **variable**
  - Prevents data races
  - Useful for shared setters
- **Advantages**
  - 10x faster than `std::mutex`
  - *Sometimes* easy to use
- **Disadvantages**
  - Extremely limited in use
  - Advanced use is **advanced**

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Audio thread uses only when it must do so

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Audio thread uses whenever it is possible

Replicating Synchronized

```
class CriticalSection {
private:
    /** Mutex to synchronize methods */
    std::mutex _mutex;

public:
    void method() {
        _mutex.lock();      // Lock method code
        ...
        _mutex.unlock();    // Release when done
    }
}
```

Obervations About std::mutex

- It is **not** a **reentrant lock** (unlike synchronized)
  - Locking it again inside same class will deadlock
  - This matters when you have locks on helpers
  - Must use std::recursive_mutex for reentrant lock
- Manual lock/unlock calls are **frowned upon**
  - To easy to forget to unlock and deadlock
  - Preferred way is to attach a **locking object**
  - When locking object is deleted, so is lock

Using a Locking Object

```
class CriticalSection {
private:
    /** Mutex to synchronize methods */
    std::mutex _mutex;

public:
    void method() {
        std::lock_guard<std::mutex> lock(_mutex);
        ...
        // Mutex unlocked once lock variable deleted
    }
}
```

What If Critical Section is a Variable?

- **Example**: `running` attribute controlling thread
  - Audio thread loops so long as it is `true`
  - Setting it to `false` stops the audio
- Mutexes exist to prevent **inconsistent states**
  - Either all code is executed, or none is
  - Cannot happen to variable assignment, right?
- C++ is not **assembly code**!
  - A single assignment is multiple lines of assembly
  - This is not thread safe (*especially* on Windows)

What If Critical Section is a Variable?

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This leads to data races!

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std::atomic Protects Assignment

- **Template** around a type: `std::atomic<int>`
  - Supports all primitive C++ types
  - Cannot apply to objects in general, but …
  - Is possible to make `std::shared_ptr` atomic
- Supported by two methods
  - `load()`: An atomic **getter** for the value
  - `store(value)`: An atomic **setter** for the value
  - Shared pointers are slightly more complicated

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Means assignment is atomic, **not** methods

Only Use If Read/Write Are Separate

```
class WithAtomics {
private:
    std::atomic<int> _xvar;   // Atomic integer
public:
    /** Change the value of X */
    void writeX(int val) { _xvar.store(val); }

    /** Use the value of X to compute something */
    void readX() {
        int x = _xvar.load();  // Copy value to local variable
        // Use x in local computation
    }
}
```

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```

Never **store** _xvar
in same method

This Is Only Scratching the Surface

- C++ supports **monitors** and **semaphores**
  - These are used for producer/consumer problem
  - Monitor allows consumer to **wait** on producer
- C++ supports **promises**
  - These are threads that return a value
  - Simplify critical section in that case
- Atomics support **memory orders**
  - These are used to **optimize performance**
  - Best avoided unless you know what you are doing

This Is Only Scratching the Surface

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See readings if want more

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  - Best avoided unless you know what you are doing

So Why Do We Care?

- All of these threads are made for you!
- But how about making **your own threads**?
  - **Pathfinding** is a classic example
  - **NPC behavior** can also be long-running
- How can **extreme** can we go?
  - What if all **updates** are in separate thread?
  - Then the main thread just **draws**!
  - This can give us potentially very high FPS

This Will Not Quite Work

Frame 1

Frame 2

Frame 3

Without update, redraw **same** image.
We need animation in the core loop.

Recall: Two Approaches to Animation

Tweening

- Animates **timed actions**
  - Given a duration and a start
  - Interpolates scene over time
- Render thread simply…
  - accesses all active actions
  - moves them forward by `dt`
- Gameplay **creates** actions
  - Happens less frequently
  - Decoupled from render

Physics

- Animates **physical objects**
  - Bodies with force and mass
  - Also shape for collisions
- Render thread simply…
  - steps simulation forward
  - renders objects at end
- Gameplay **nudges** objects
  - *Might* be less frequent
  - If so, can also decouple

Recall: Two Approaches to Animation

Tweening	**Physics**

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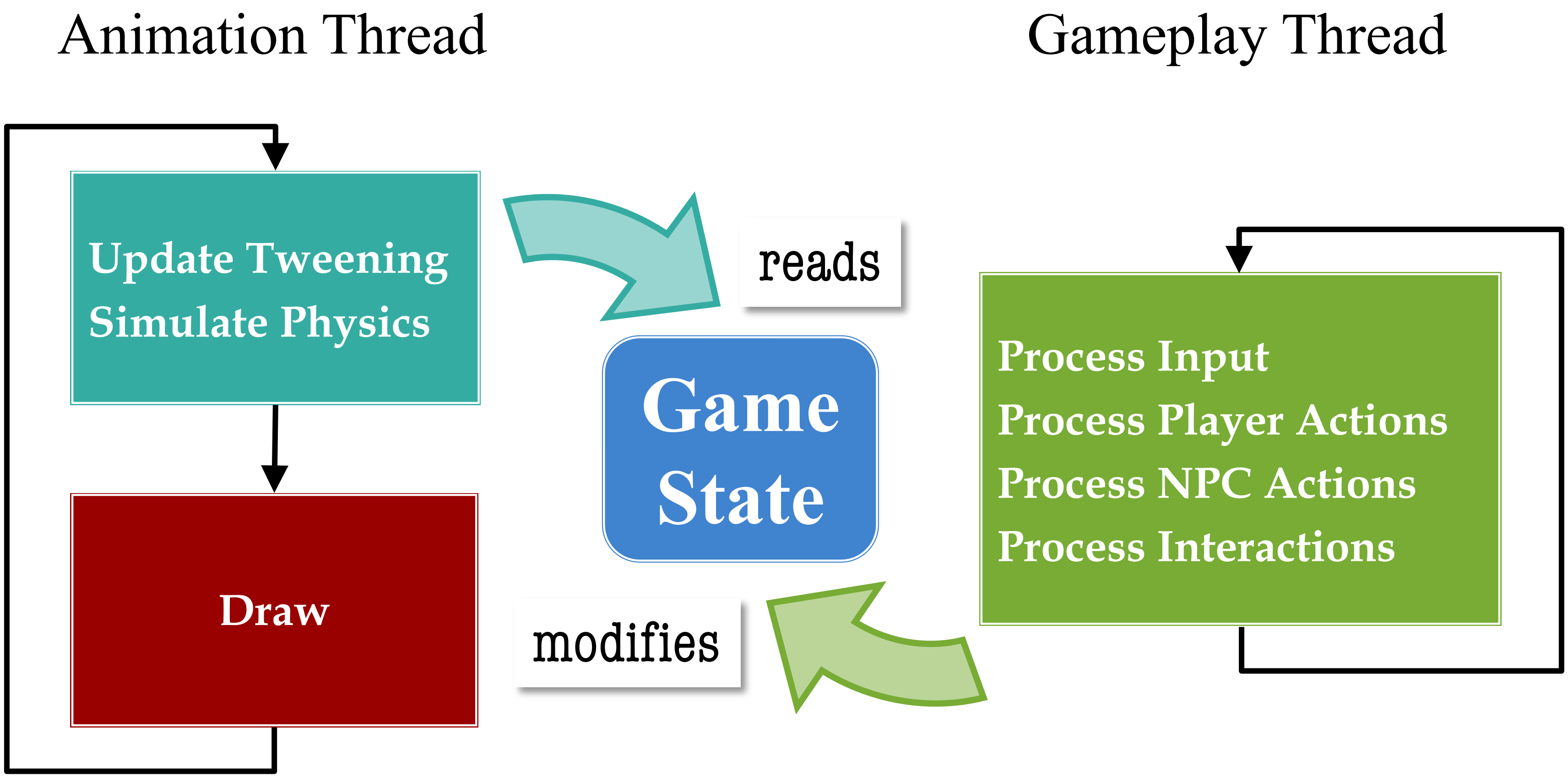
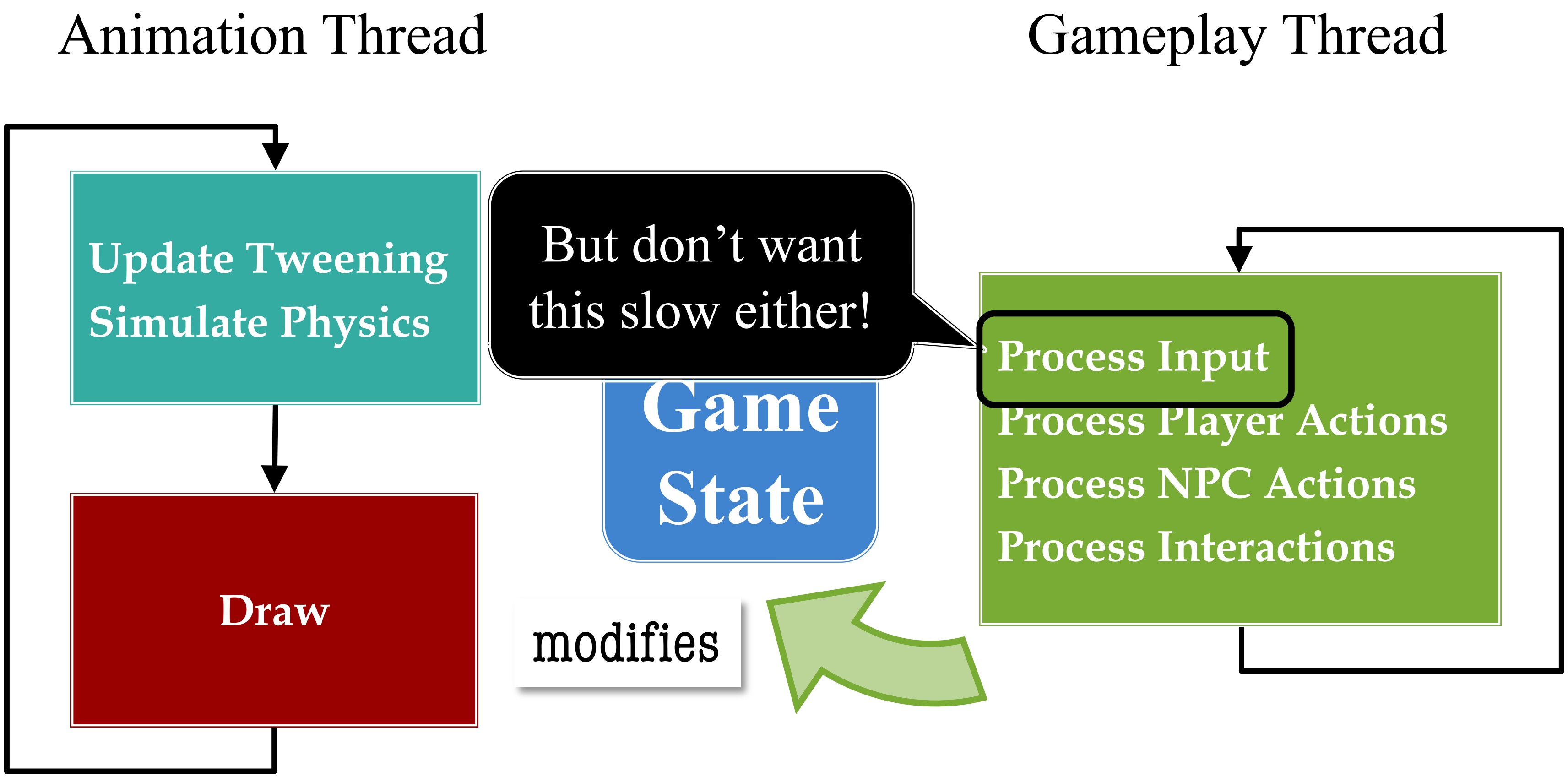
Like networking, animation uses
dead reckoning when missing input

A New Architecture



A New Architecture



Summary

- Games engines are naturally multithreaded
  - Offload tasks that *block* drawing (**asset loading**)
  - Offload tasks that *slow* drawing (**pathfinding**)
  - Execute tasks *decoupled* from drawing (**audio**)
- CUGL has native **task-based parallelism**
  - `ThreadPool` for tasks off the main thread
  - `Application::schedule` for tasks on main thread
- C++ has general-purpose tools for parallelism
  - `std::thread` class for managing other threads
  - `std::mutex` and `std::atomic` for critical sections