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Lecture 11

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

- CUGL has **three** primary threads
  - The `Application`, or main graphics thread
  - The `AssetManager` thread, for loading assets
  - Th… …ck
  - N…

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

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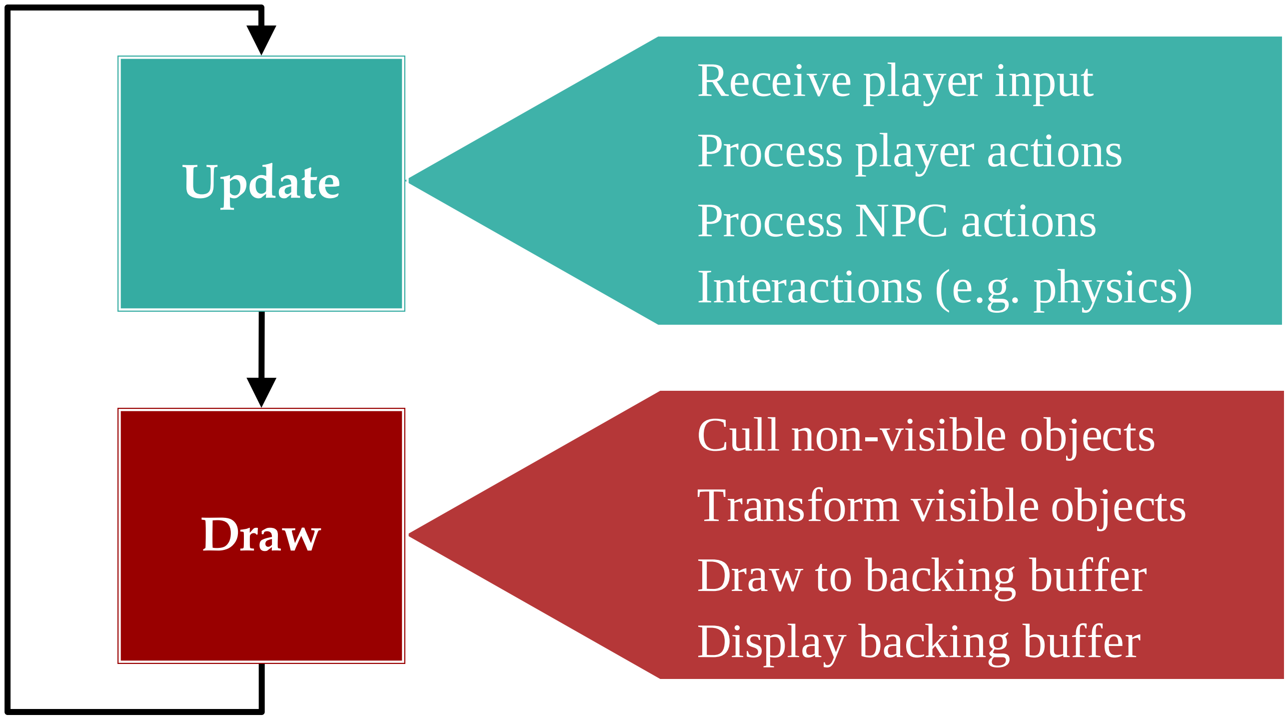
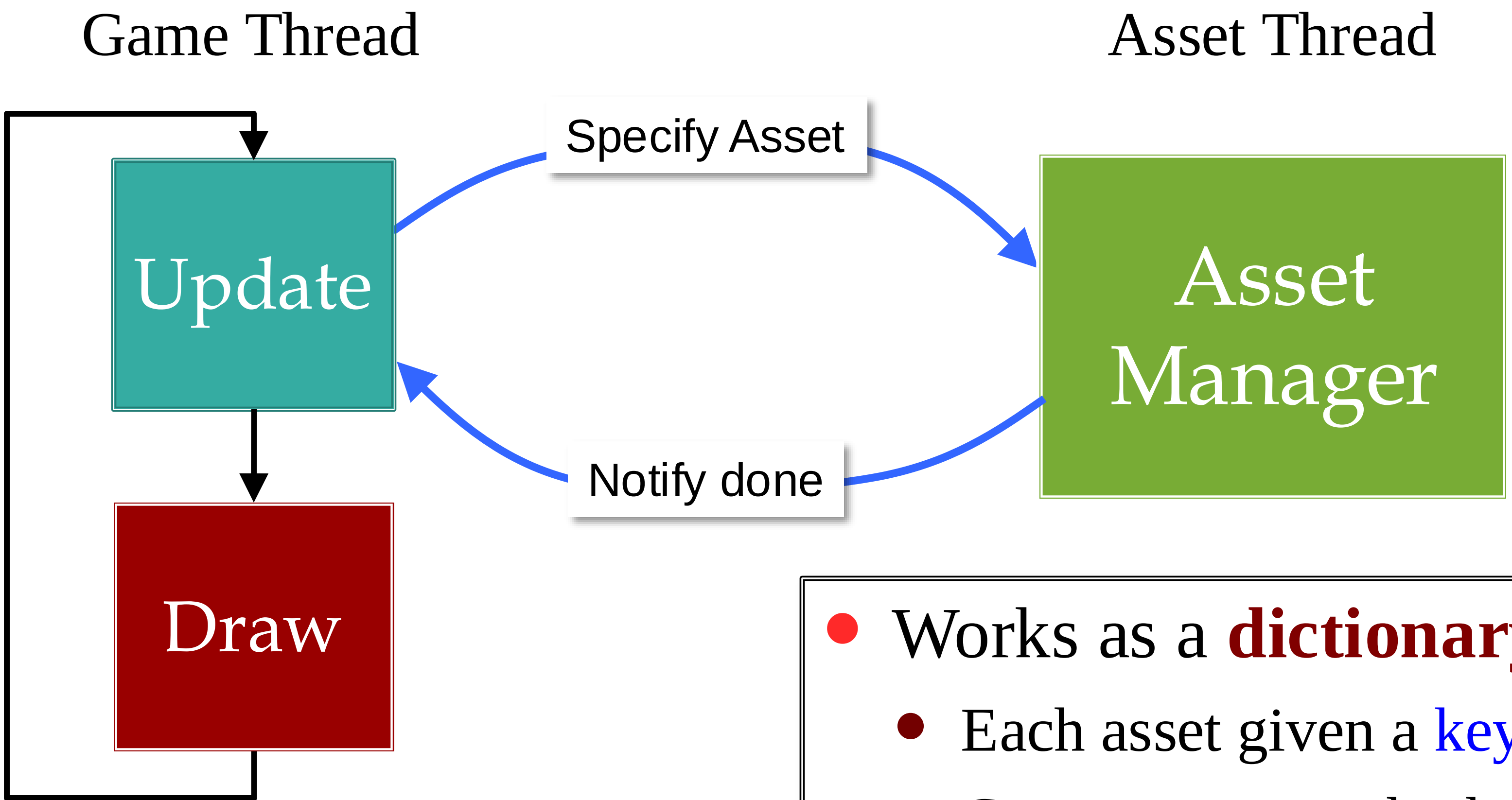
Recall: The `Application` Thread

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

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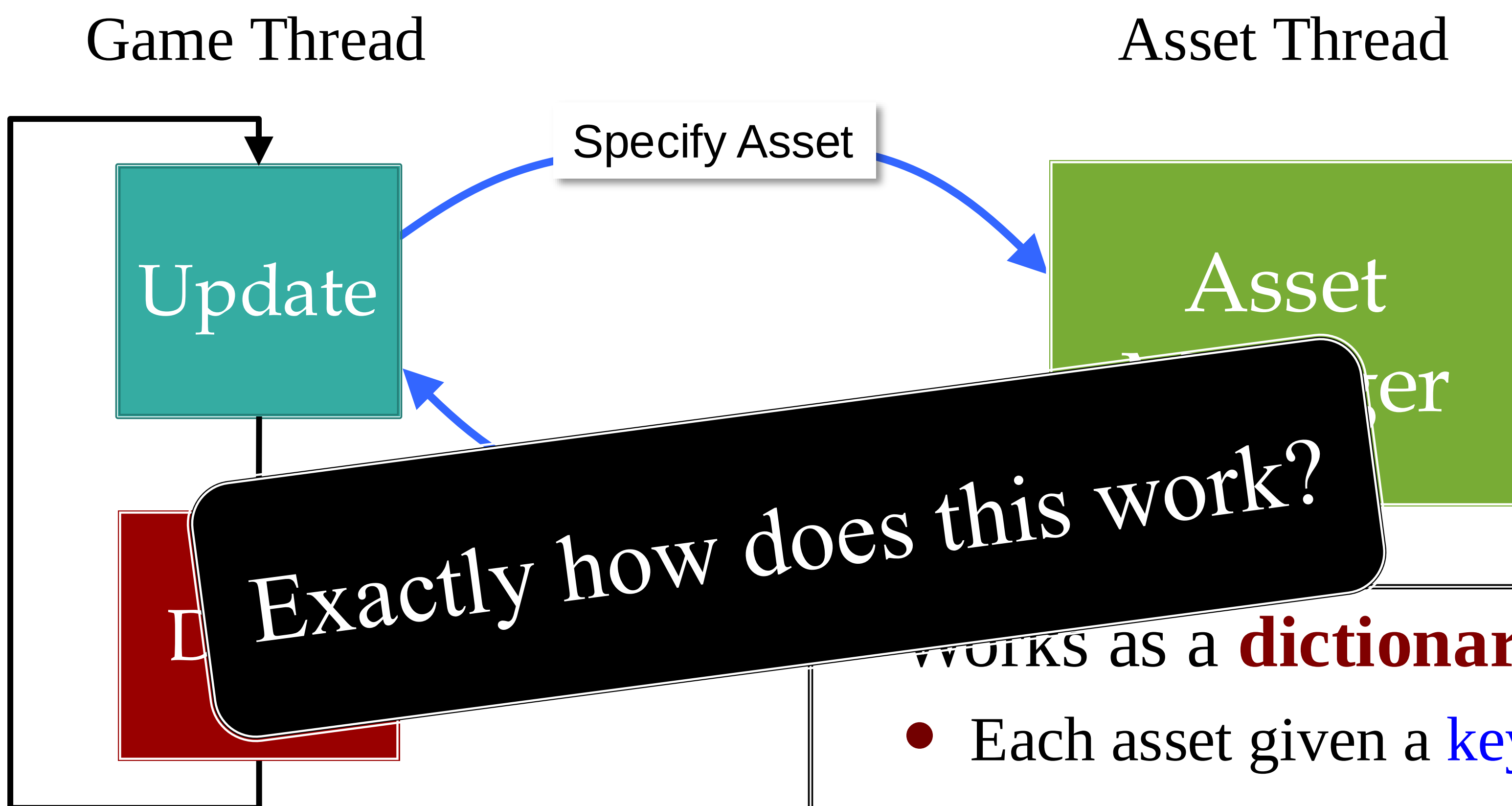
Recall: The `AssetManager` Thread



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.t tf"	Load Image "smile.p	Load Sound "music.o	Load Widget "menu.js on"
Thread 1	Thread 2	Thread 3	Thread 4

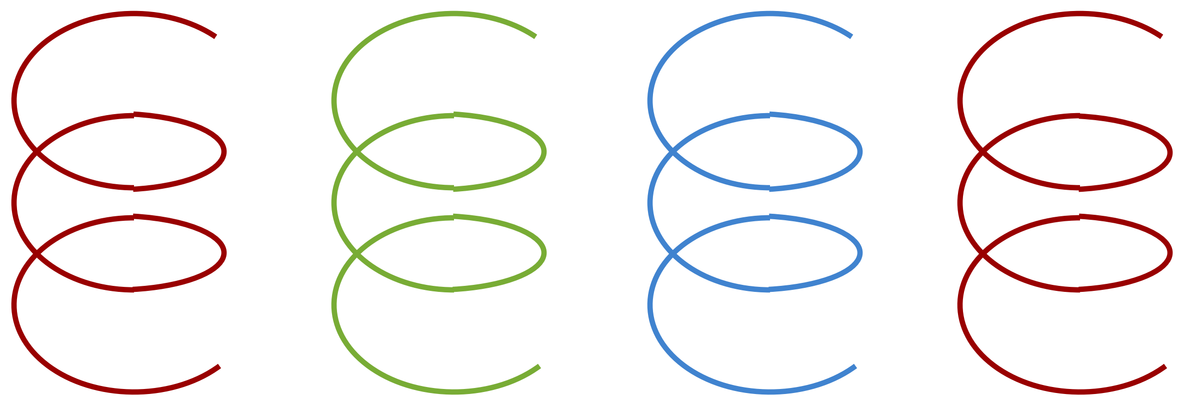
But We Cannot Do This

What is the Problem?

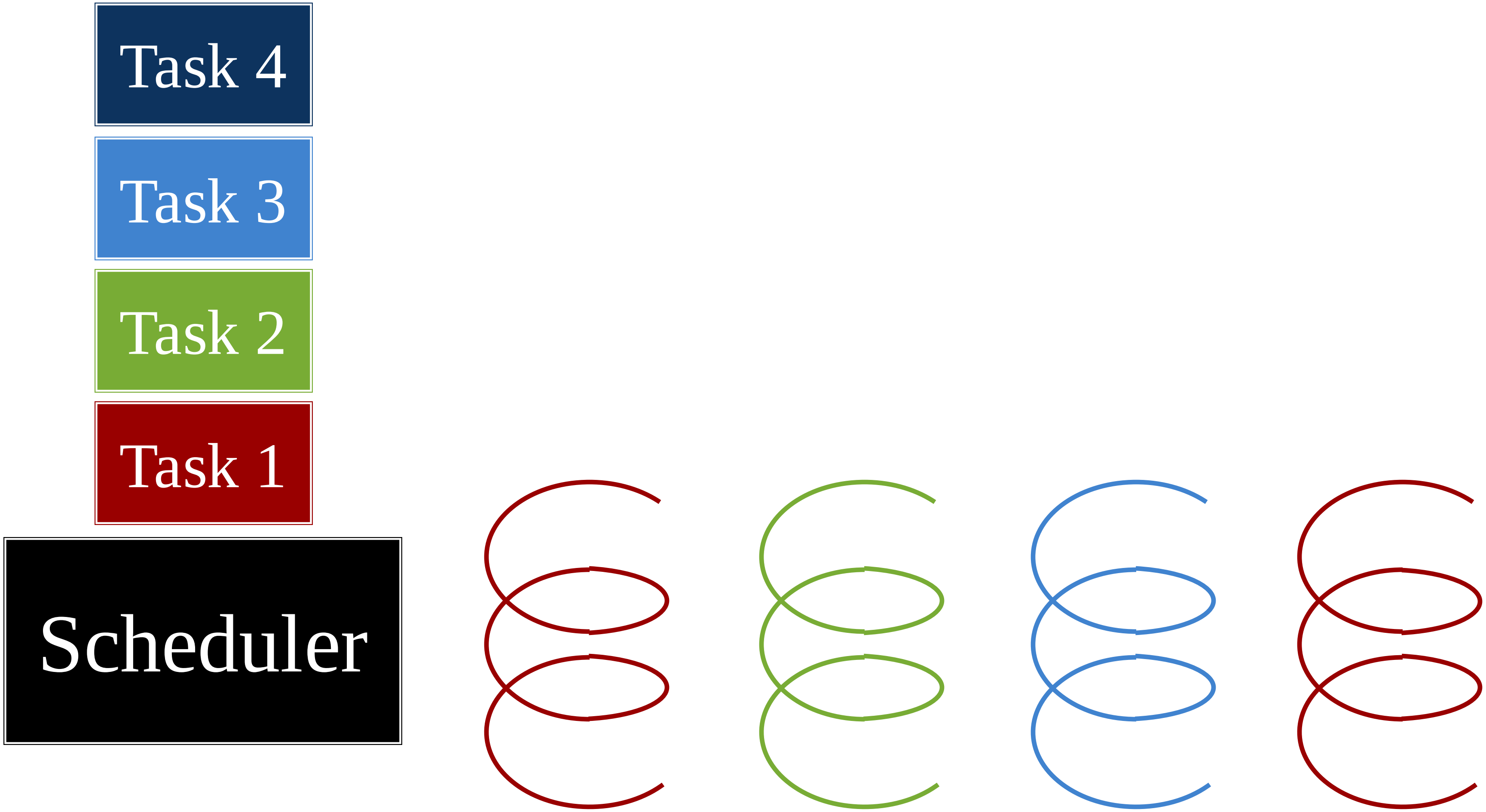
- Some tasks have **shared resources**
  - **Example:** Fonts all use same engine to make atlases
  - Cannot execute without protecting critical section
  - Typically easier to just **not** do them concurrently
- Some tasks have **dependencies**
  - **Example:** Widgets must come after images, fonts
  - 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



Solution: Thread Pool



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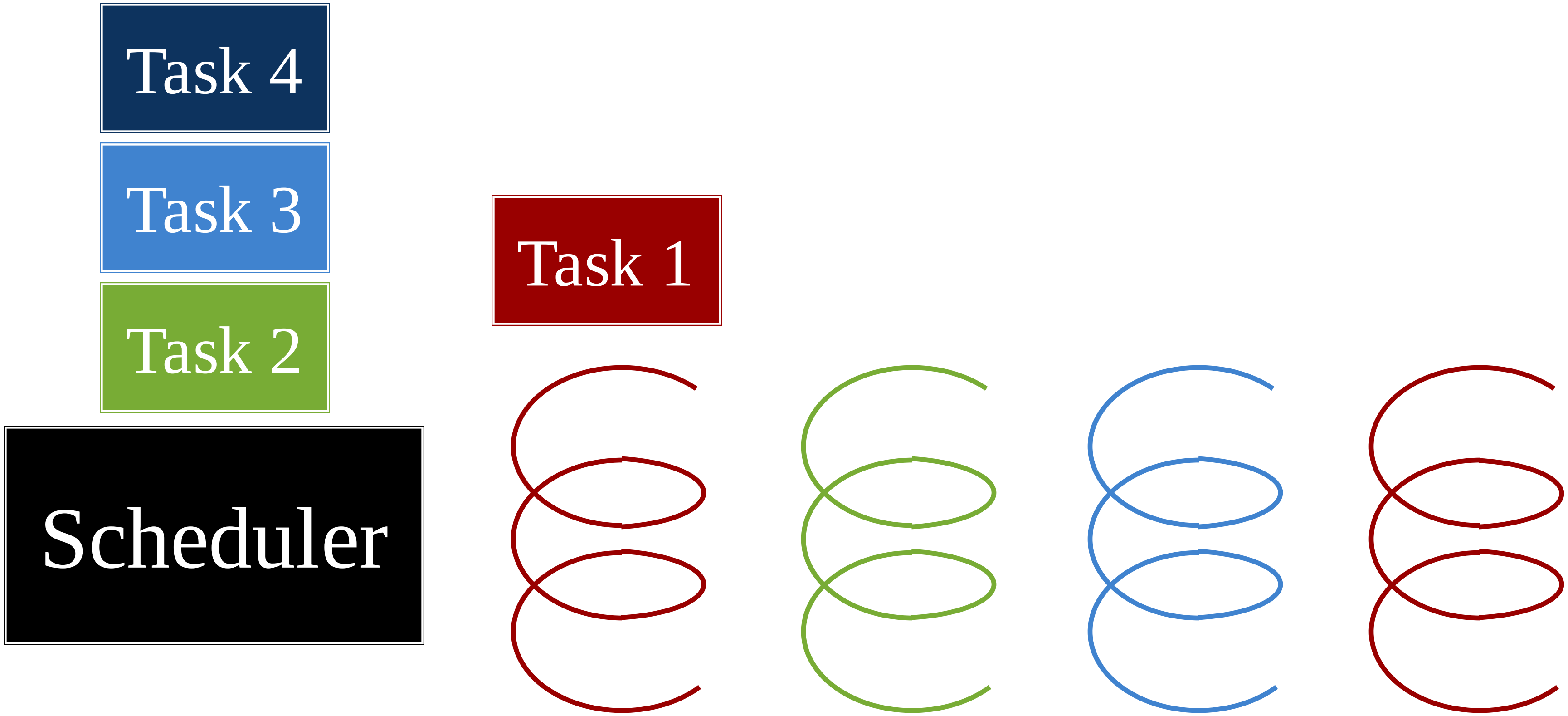

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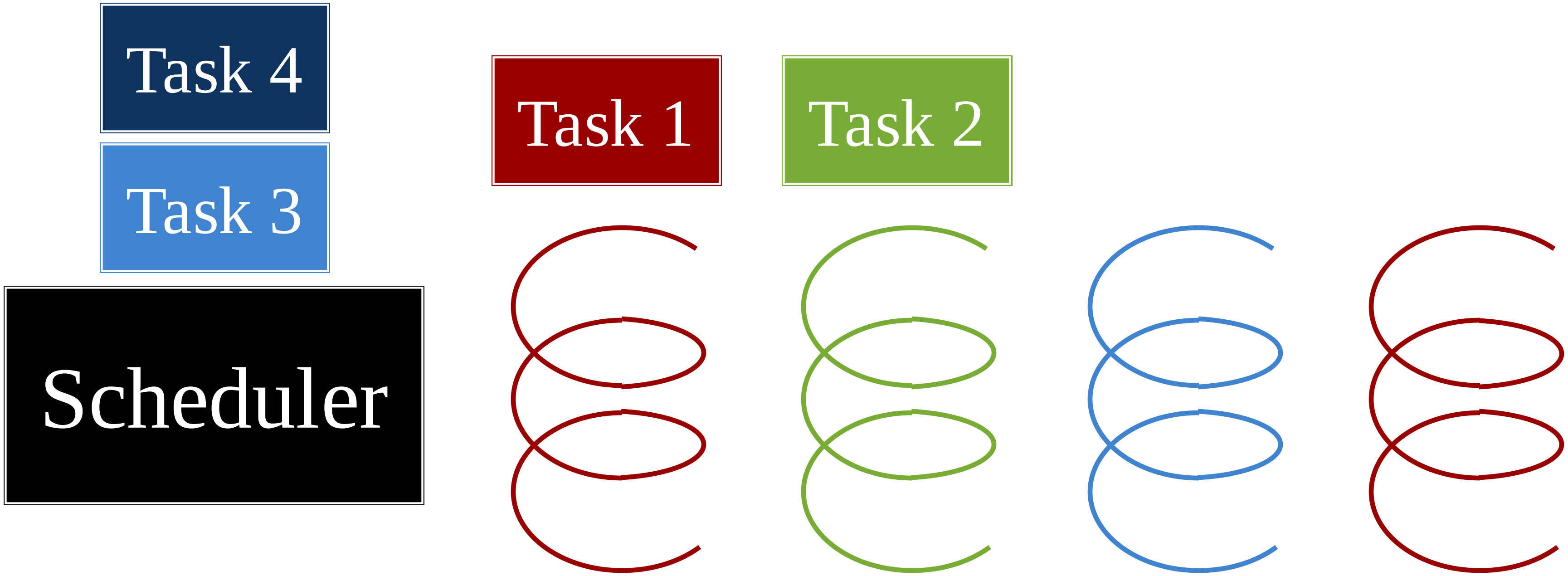

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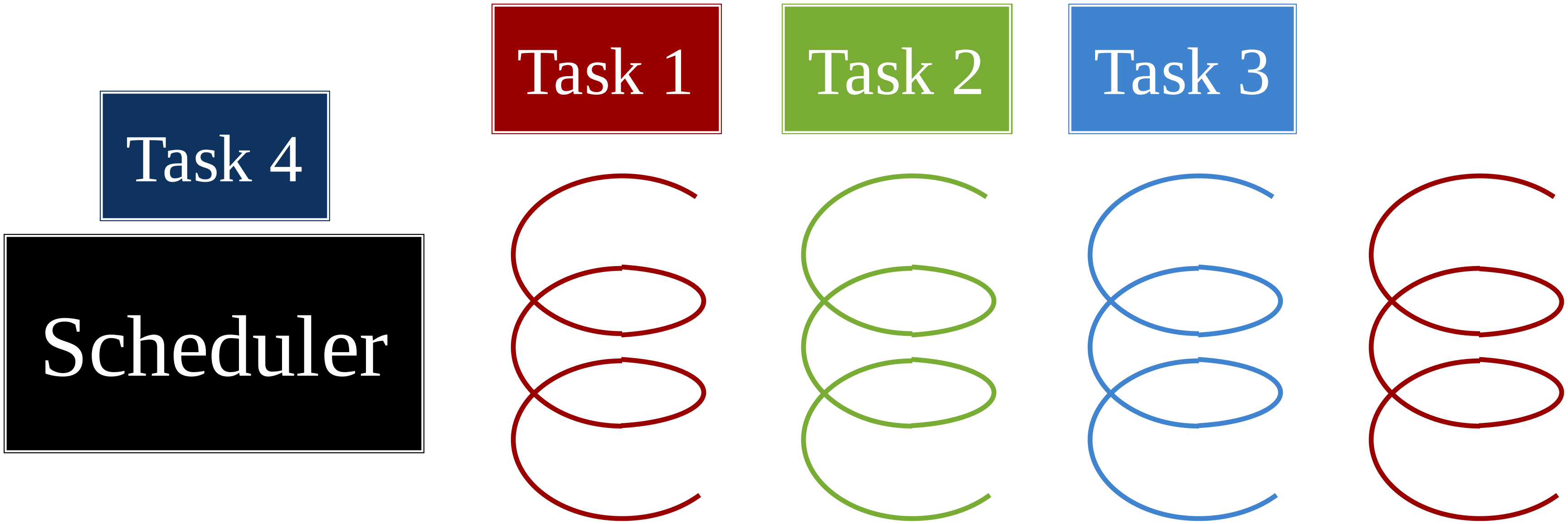

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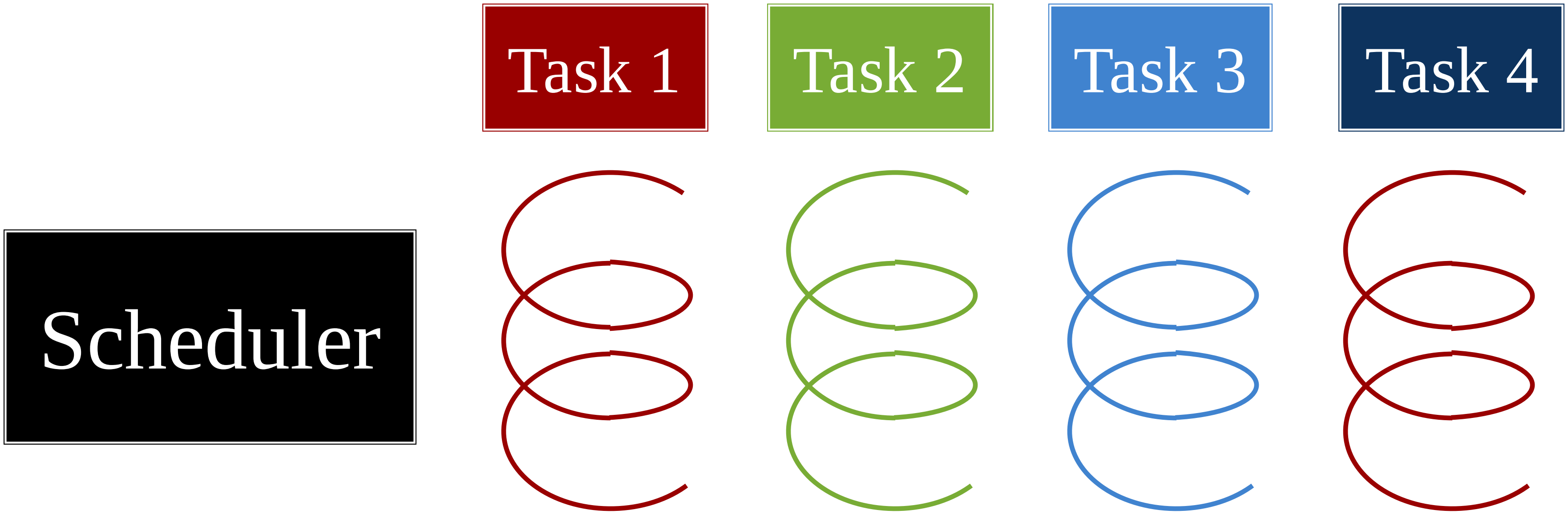

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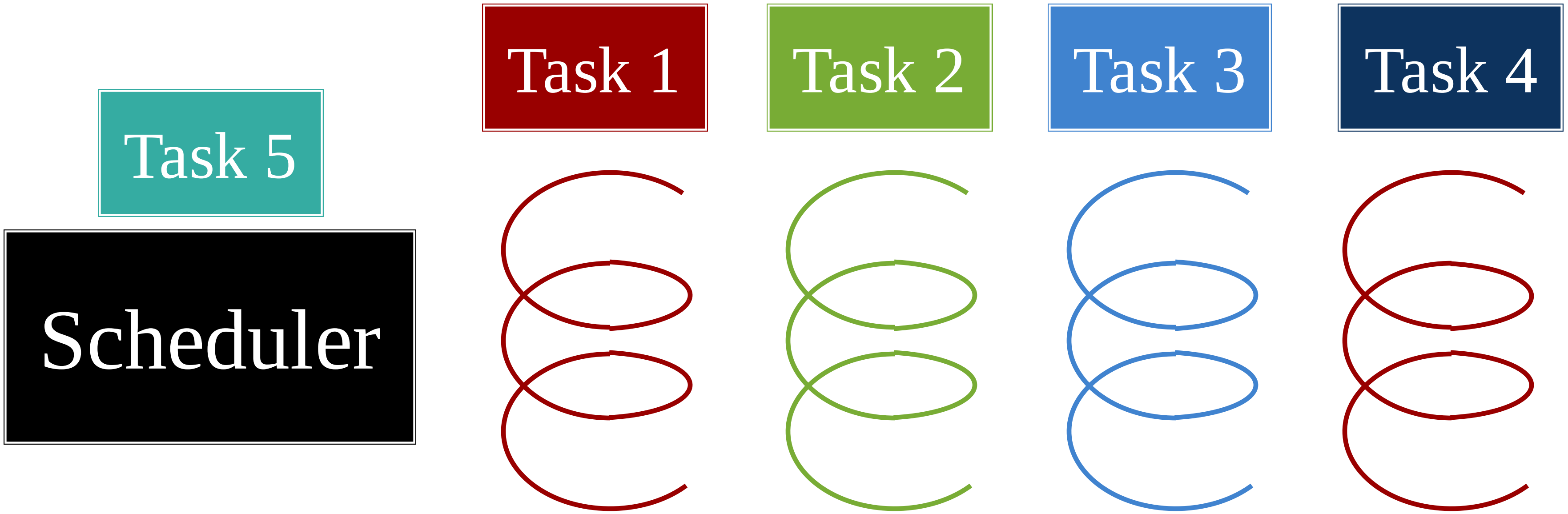

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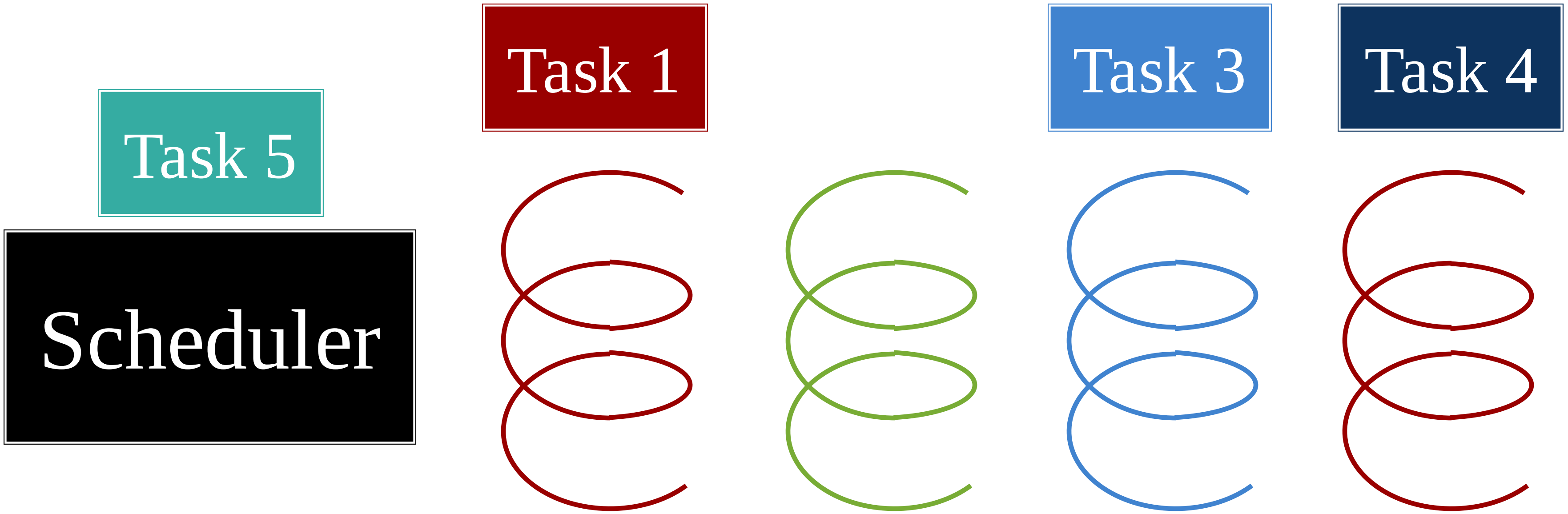
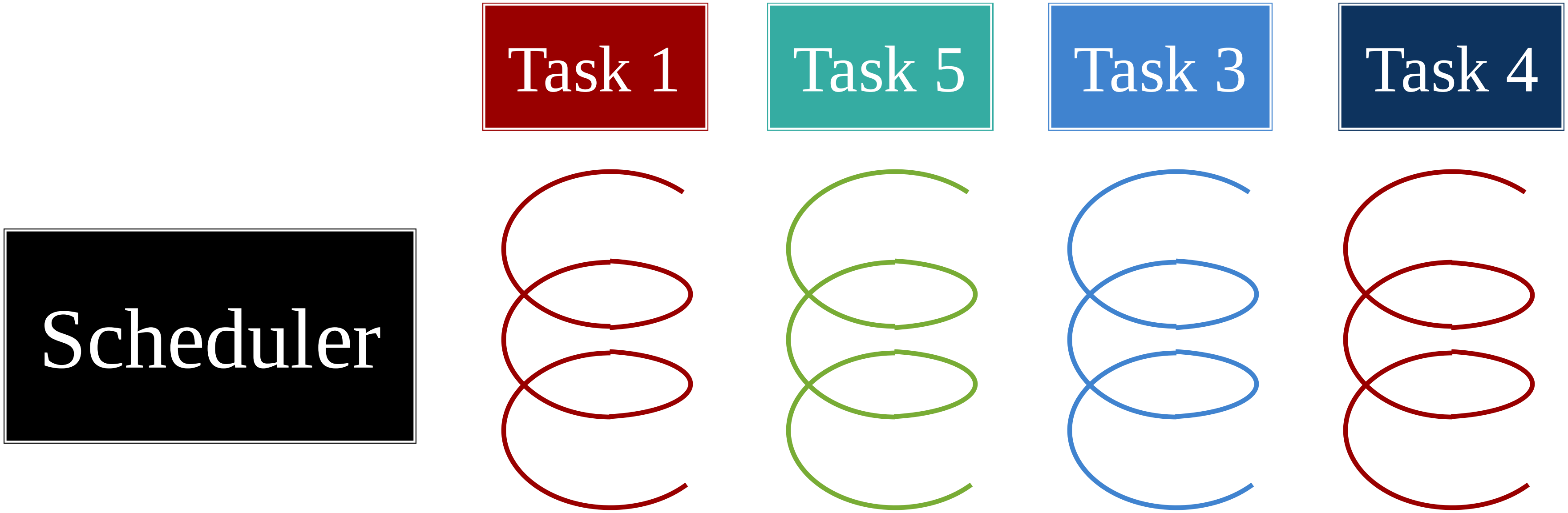


Solution: Thread Pool



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
  ```

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`AssetManager` is a **one** thread pool

- ```
  /**
   * Adds a task to the thread pool.
   *
   * @param  task   the function to add
  to the thread pool
  ```

CUGL Asset Management

AssetManager

- Map from keys to assets
  - All access is templated
  - assets->get<Texture>("image")
  - Keys unique *per asset*
- Requires attached loaders
  - a->attach<T>(load1->getHook());
  - a->attach<F>(load2->getHook());
- "Hook" is C++ workaround
  - For template subclassing

Loader

- void read(key, src, cb, async)
  - Reads asset from file src
  - async indicates if in sep thread
  - Callback cb executed when done
- void read(json, cb, async)
  - Values key and src now in json
  - As are other special properties
- void

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CUGL Asset Management

AssetManager

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  - All access i
  - `assets->get<Tex")`
  - Keys uniqu
- Requires att
  - `a->attach<T>(loader->getHook());`
  - `a->attac >getHook`
- "Hook" is C++ workaround
  - For template subclassing

Thread Safe

Thread Safe

Main Thread Only

Loader

- `void read(key, src, cb, async)`
  - Reads asset from file `src`
  - `async` indicates if in sep thread
  - Callback `cb` executed when done
- `void read(json, cb, async)`
  - Values `key` and `src` now in `json`
  - As are other special properties
- `void`

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CUGL Asset Management

AssetManager

- Map from keys to assets
  - All access is templated

Each loader is its own task

```
>getHook());
```

- "Hook" is C++ workaround
  - For template subclassing

Loader

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

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

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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
  */
```

The Schedule Method

```
/**
  * Schedules a task function on the main thread.
  *
  * @param c              tas
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  * @param m              umb
milliseconds to dela
  *
  * @return a unique identifier for the task
  */
```

Return false to stop execution

Picks first frame after ms millisec

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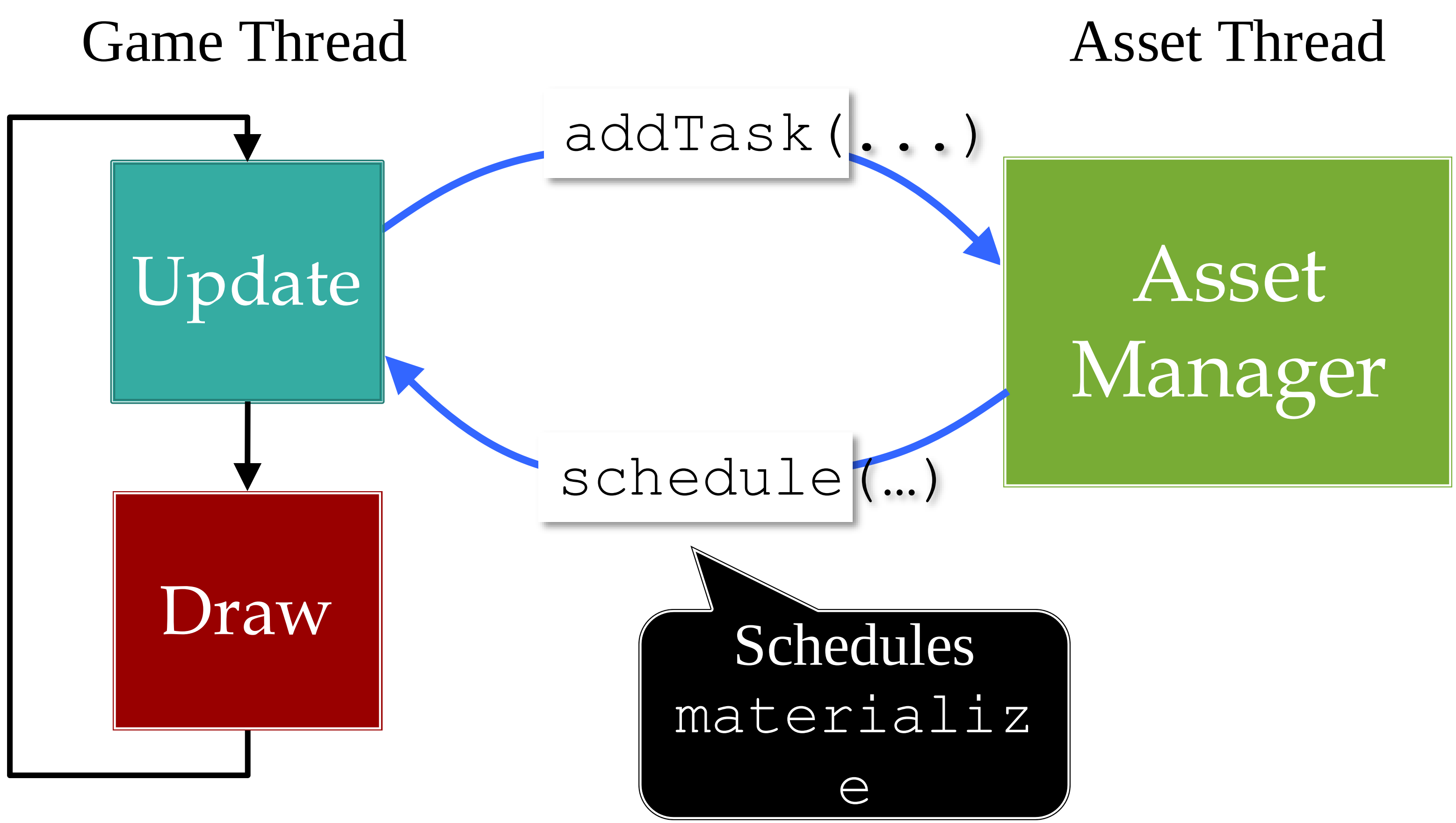
Putting it All Together

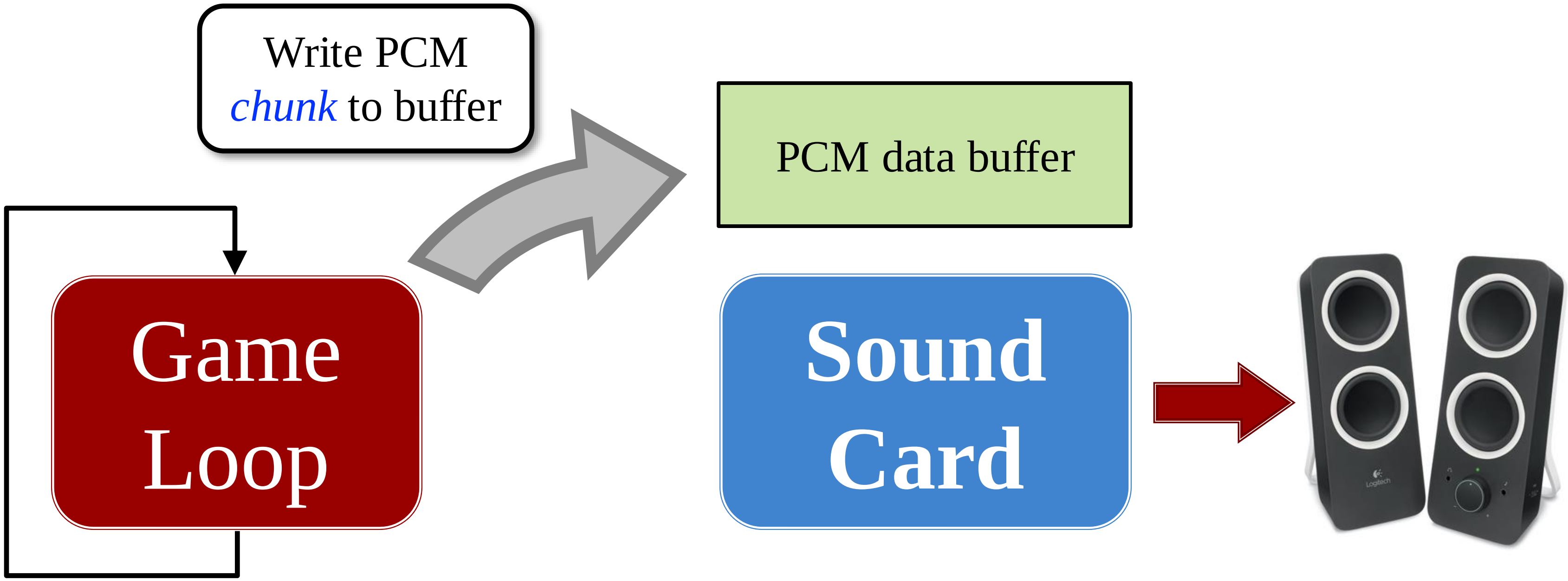


`Application` **`ThreadPool`**

Aside: Schedule is Useful in General

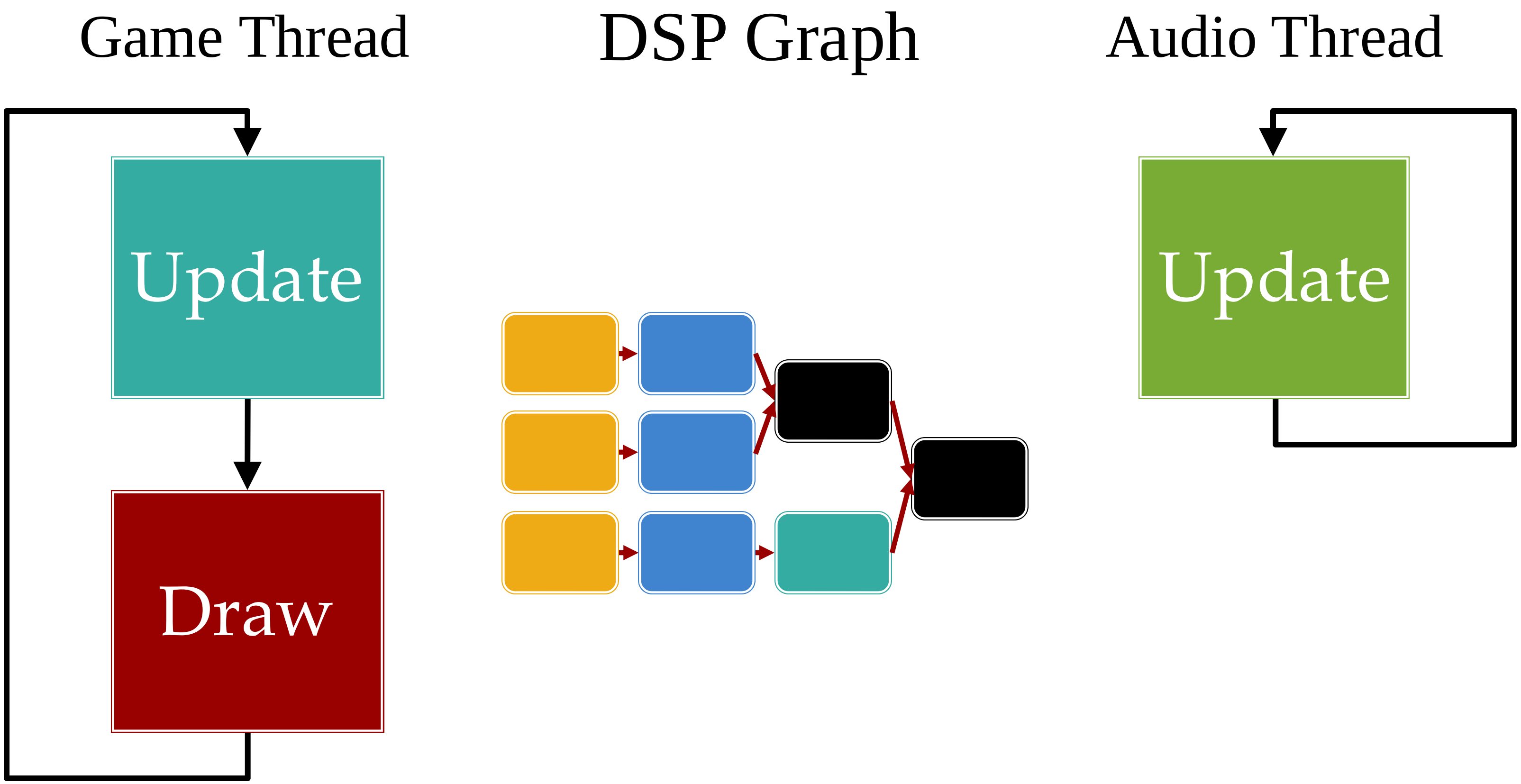
- Can specify an event to **run in the future**
  - This is the purpose of the milliseconds
  - May be easier than tracking a timer yourself
- Can specify a task to **run periodically**
  - **Example:** Spawning enemies
  - The task returns `true` if it wants to run again
  - Same delay is applied as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

Recall: Playing Sound Directly



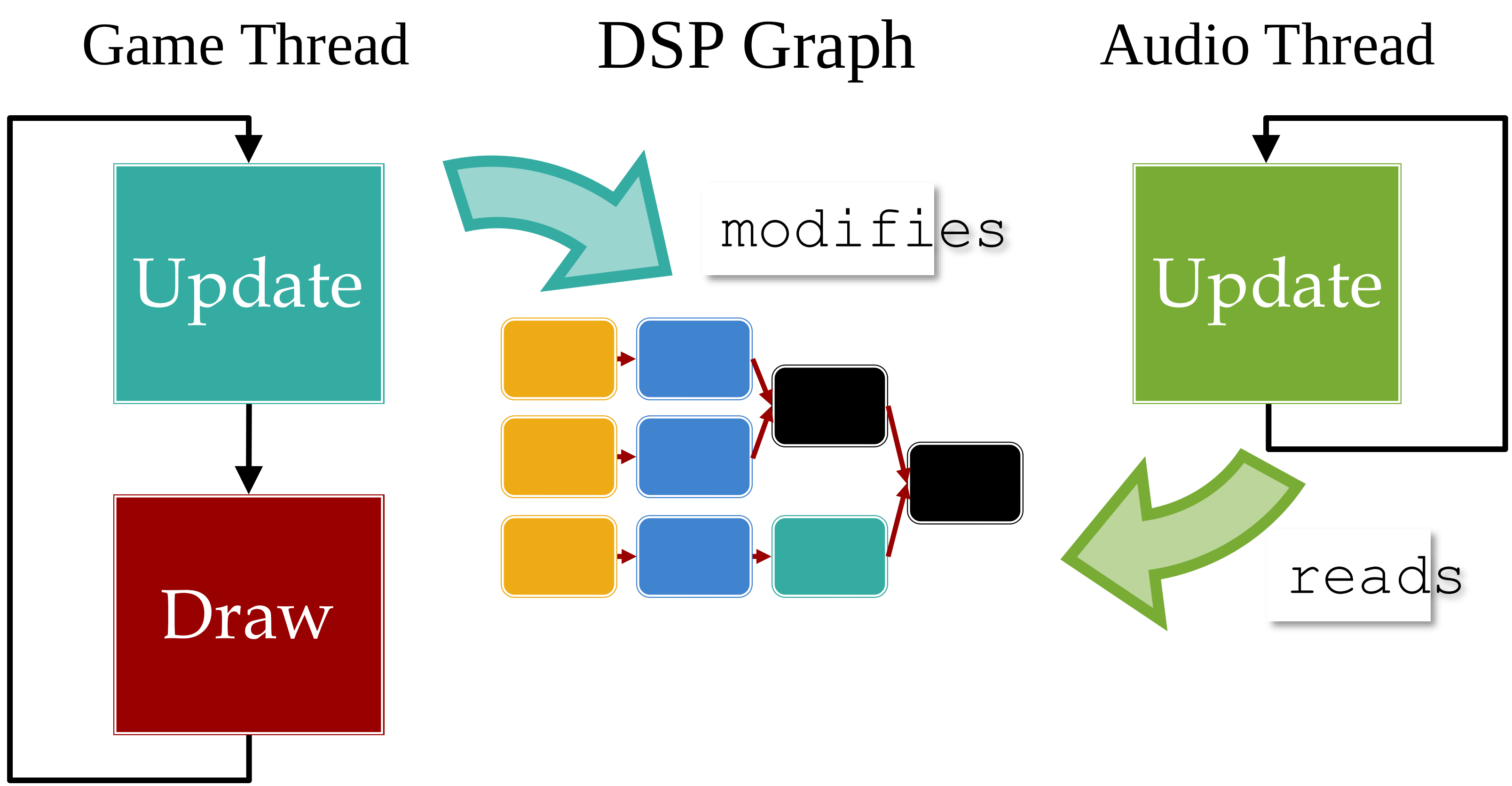
Missing a write causes pops/clicks

The CUGL Approach



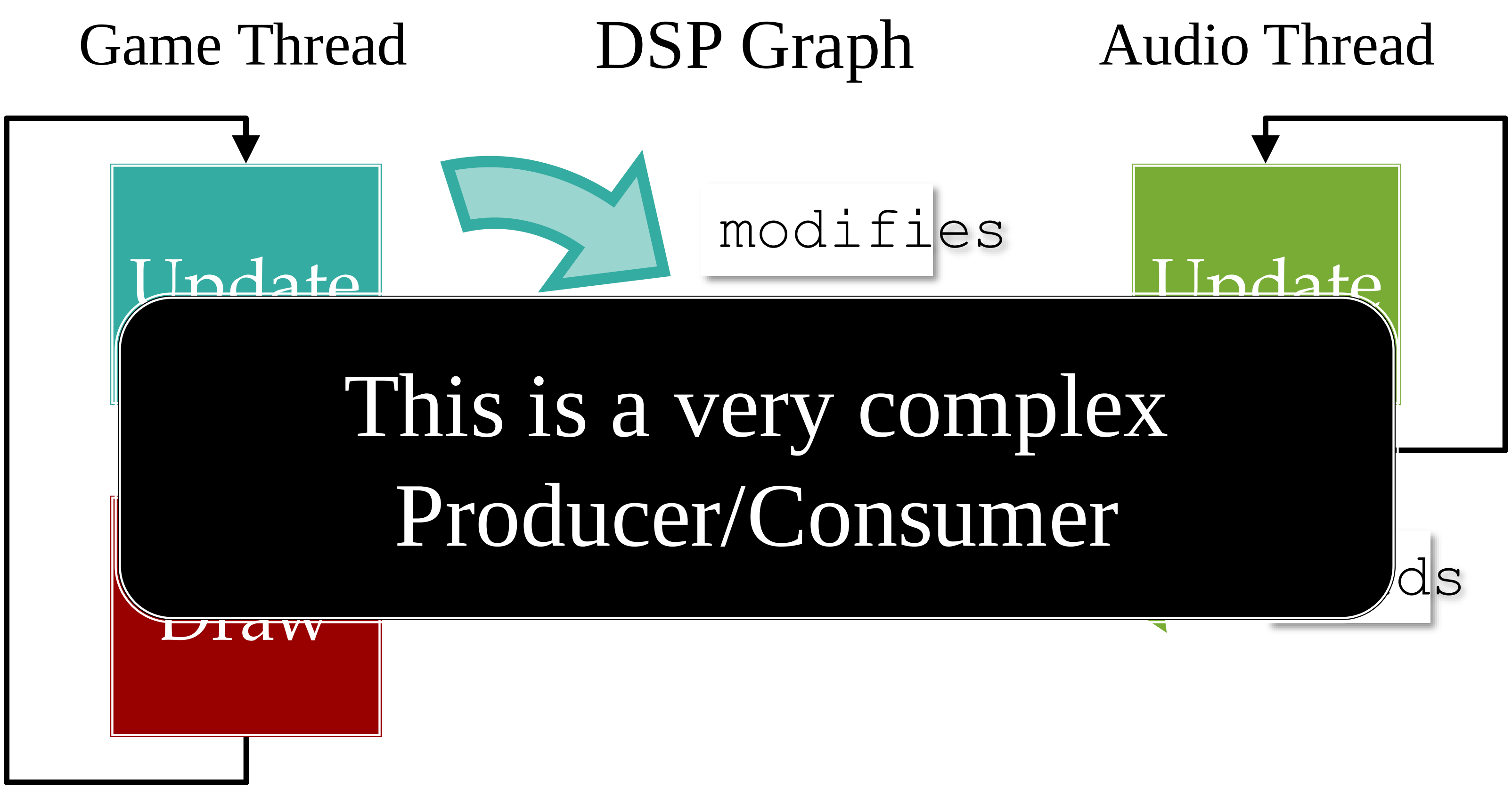
`Application` **`Thread`**

The CUGL Approach



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

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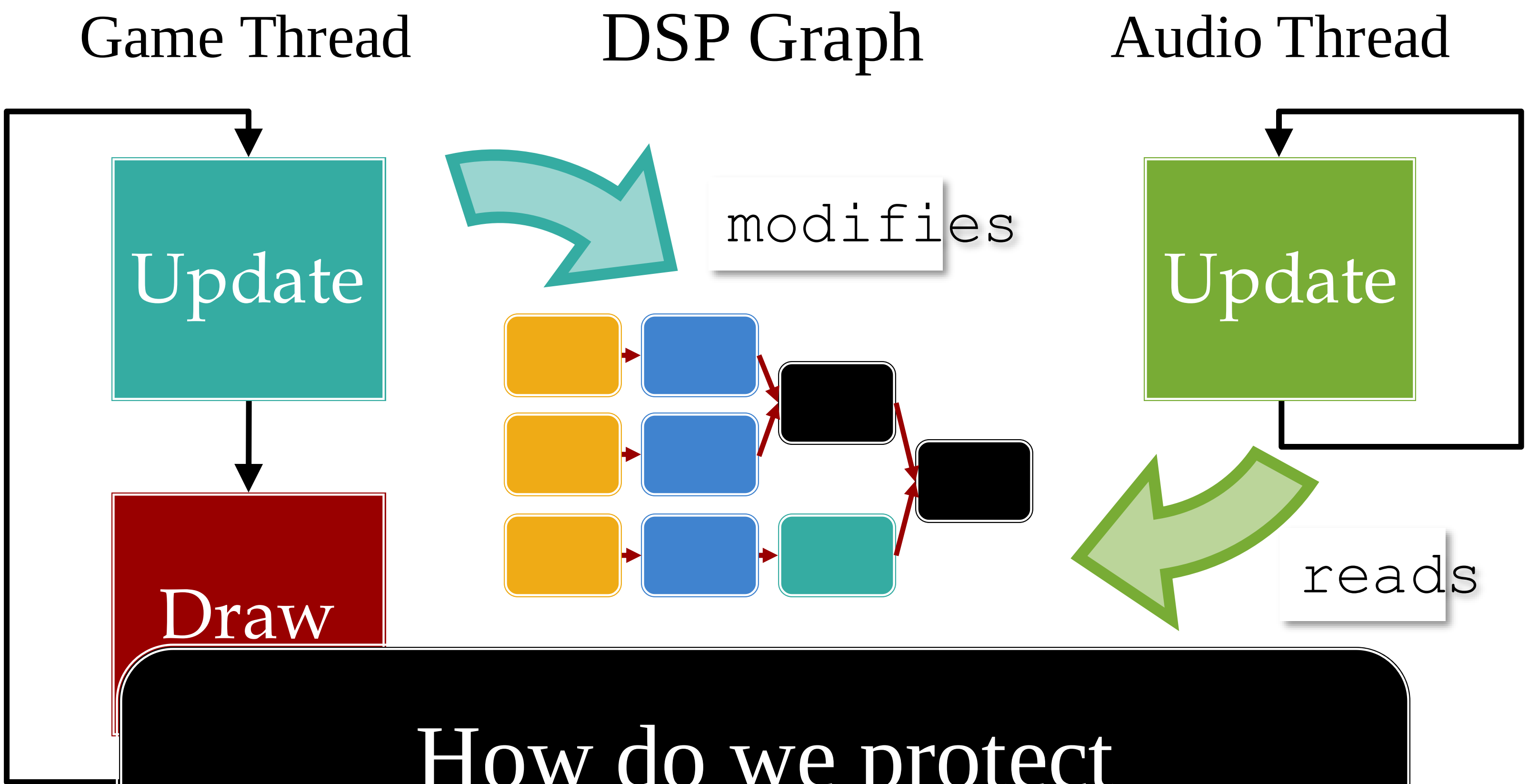
The CUGL Approach



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

```
public class CriticalSection {
    synchronized void met
{…}
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{…}
    synchronized void method3()
{…}
}
```

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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  -
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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
    }
```


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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?

- **Example**: `running` attribute controlling thread
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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

std::atomic Protects Assignment

- **Template** around a type:

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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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Only Use If Read/Write Are Separate

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    void readX(
        int x =                    // Copy
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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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  - Sim

See readings if want more

- Atomics support **memory orders**
  - These are used to **optimize performance**
  - 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

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Like networking, animation uses *dead reckoning* when missing input

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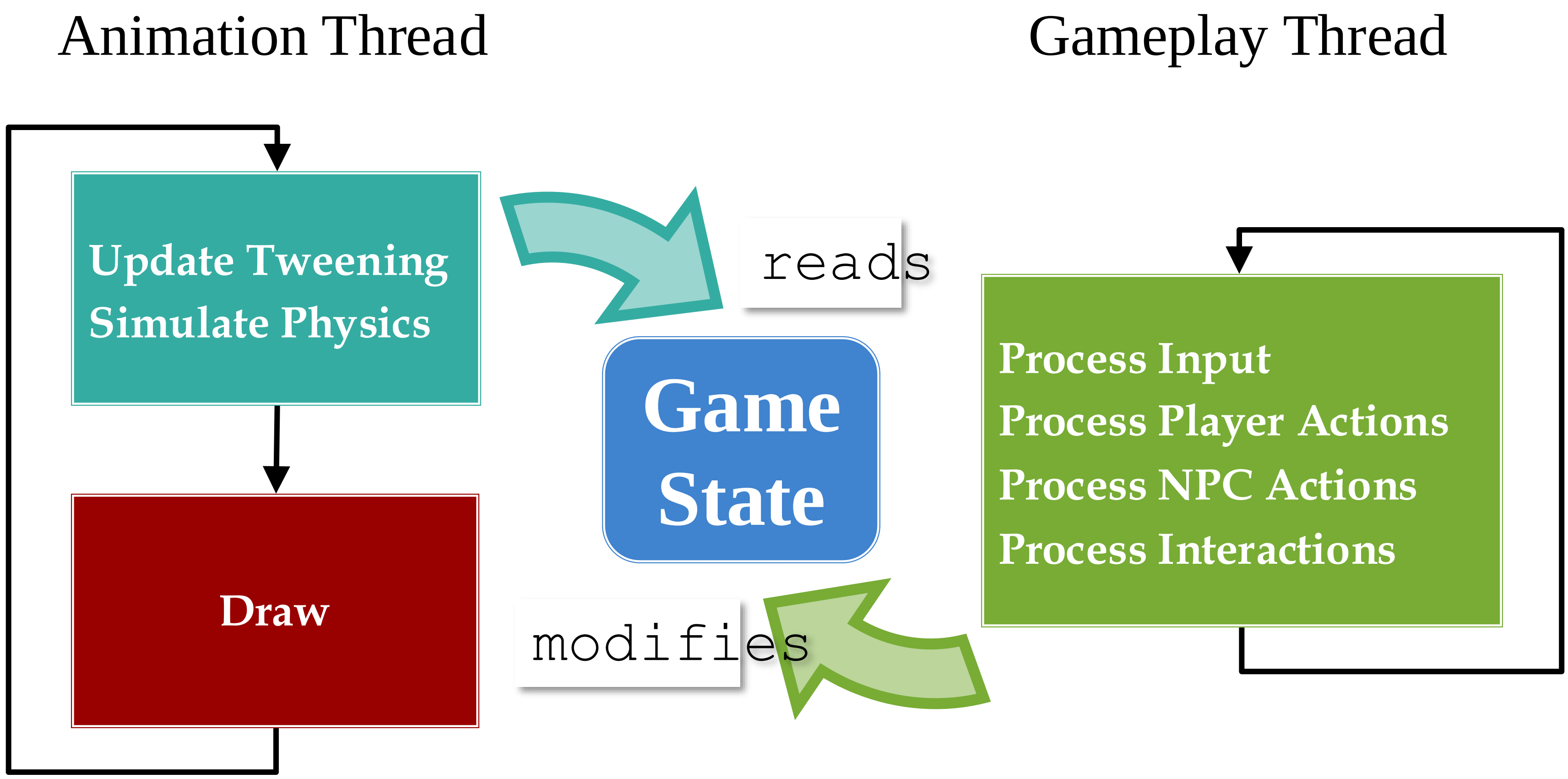
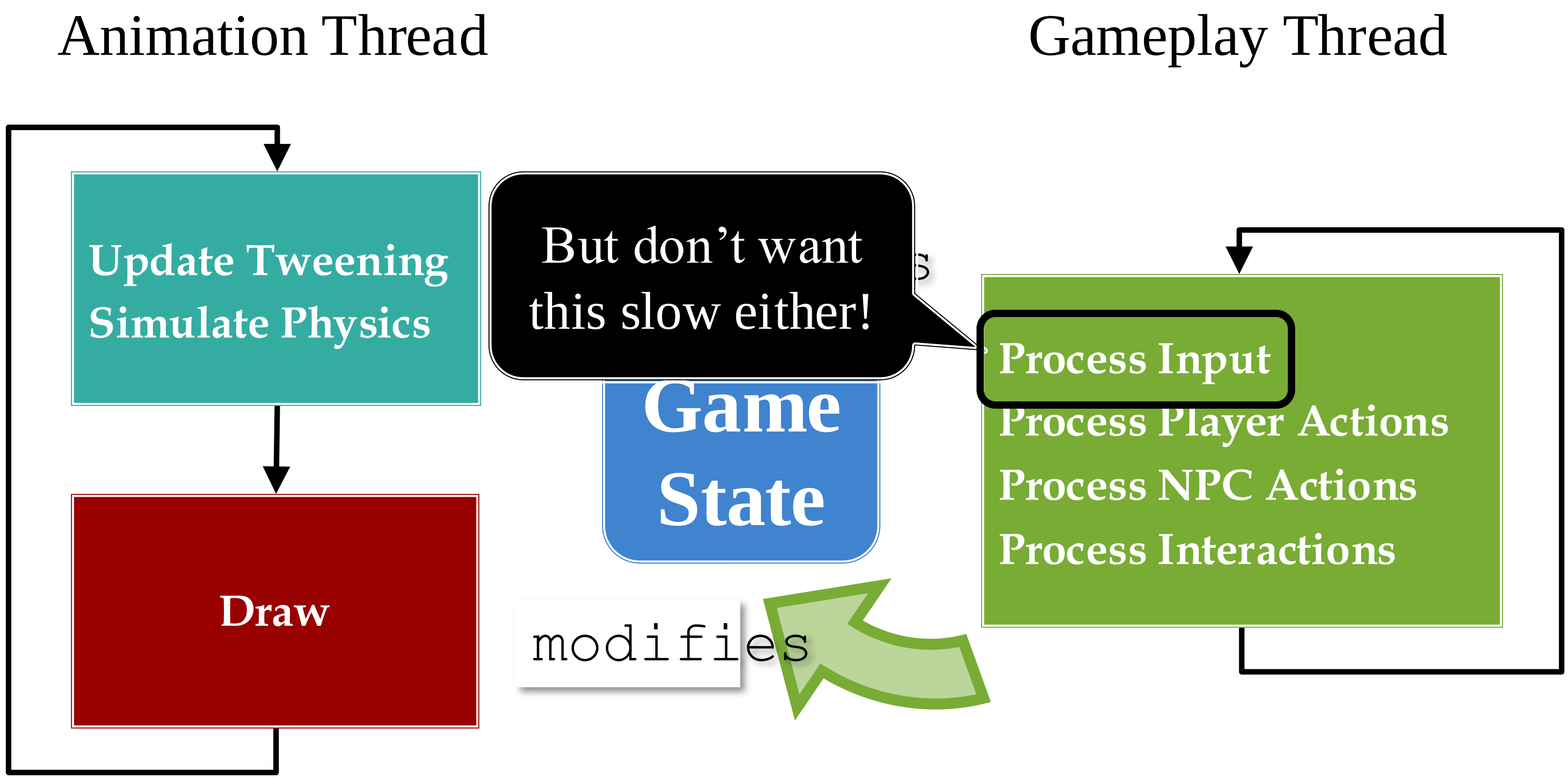
A New Architecture



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