CS241 Principles and Practice of Problem Solving

Lecture 21: GUI Programming with Qt IV

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This lecture covers some preliminary ideas about Operating system. I have reused some lecture notes from Prof. David Culler of UC Berkeley. Details could be found here.
For the Qt part, the original materials could be found here.

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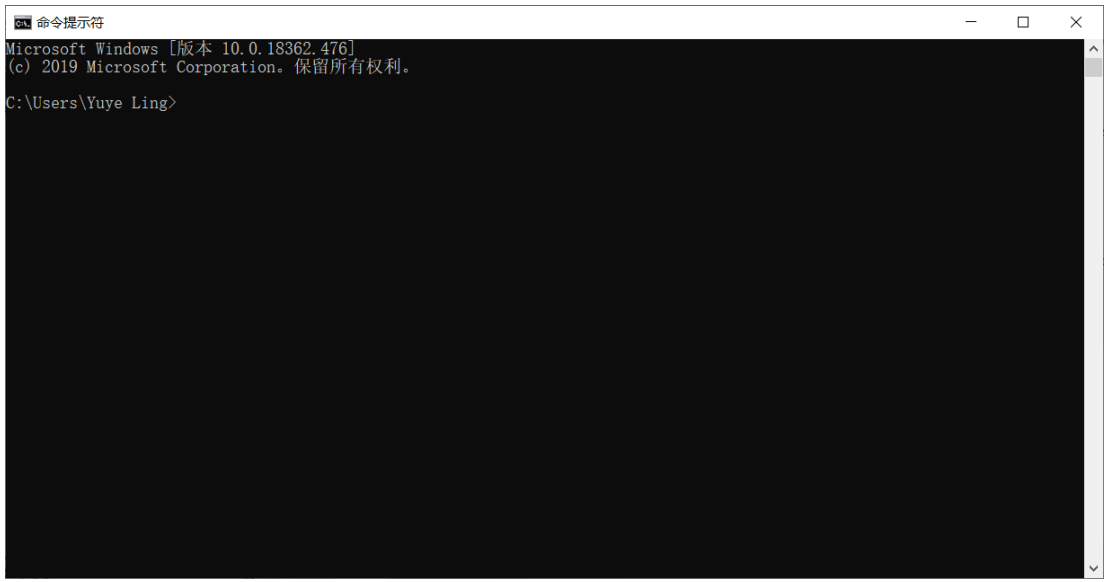

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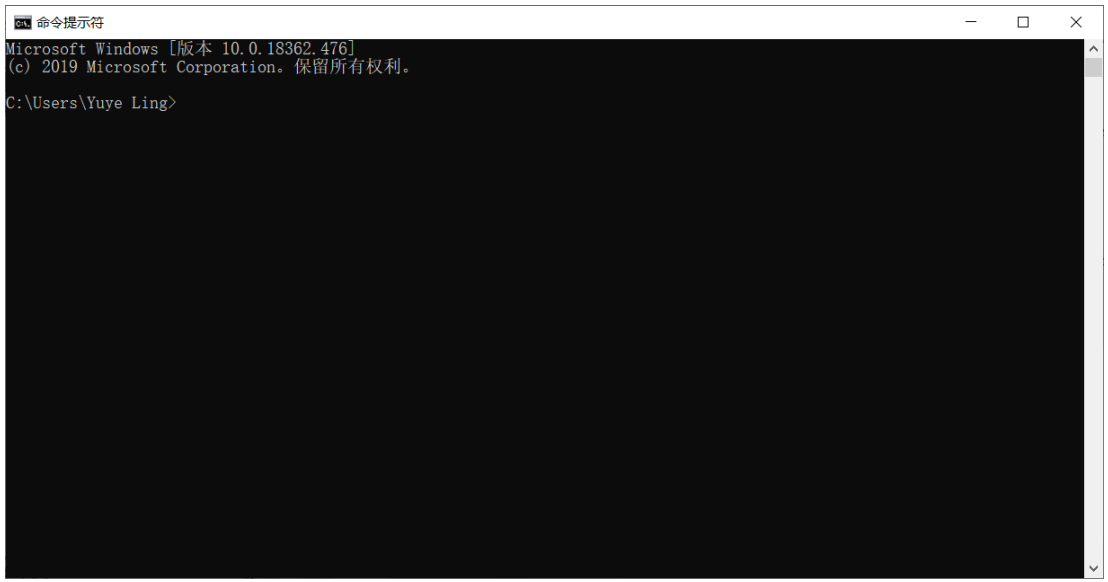

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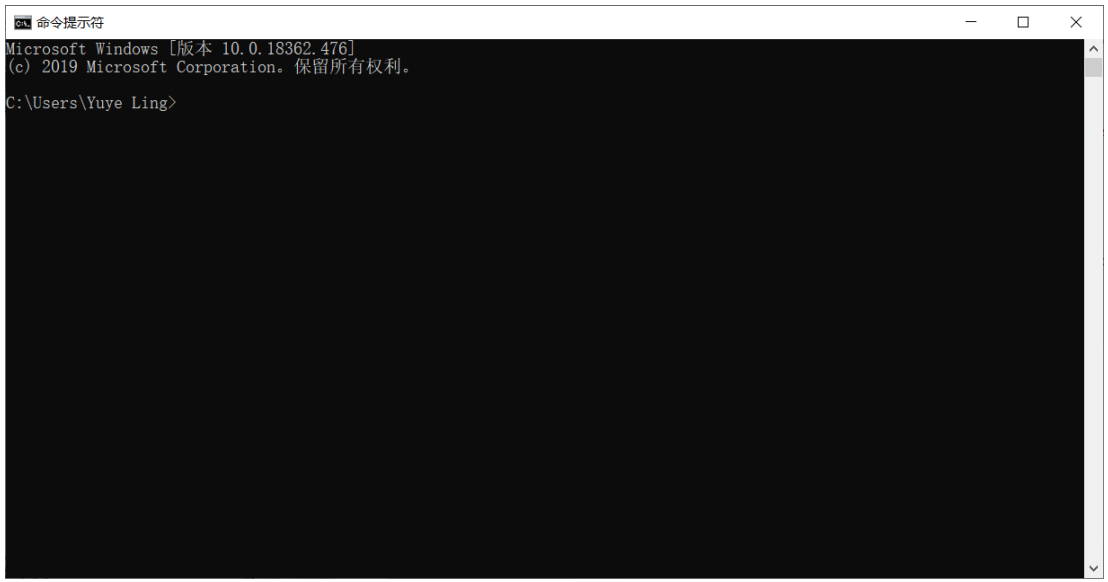

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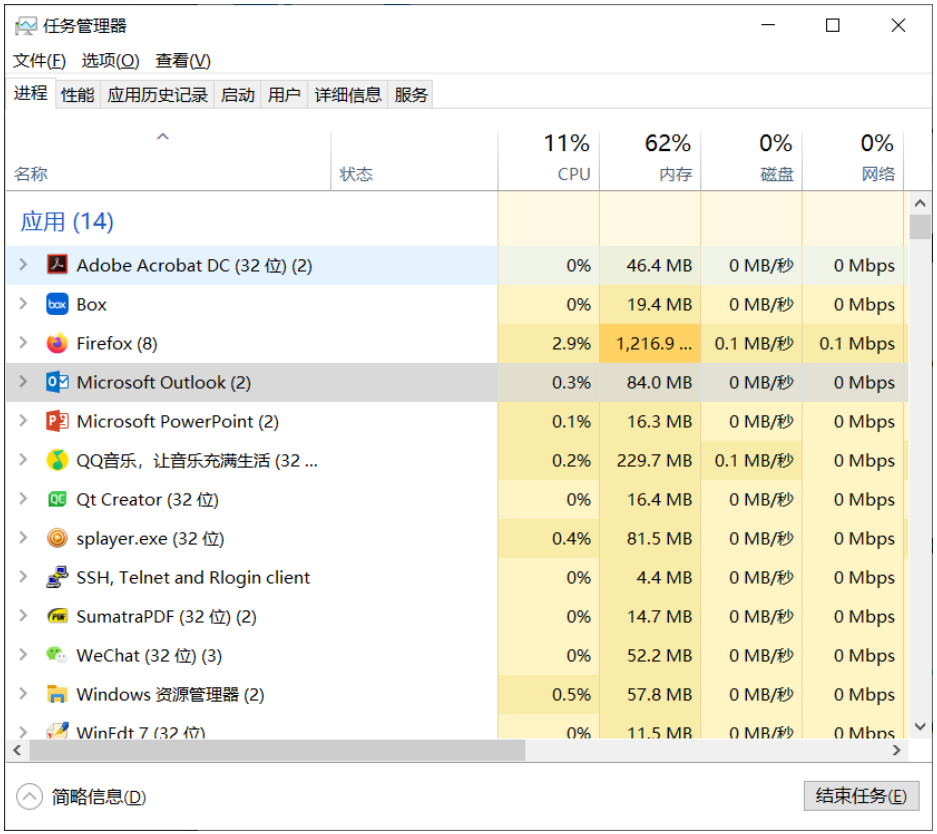

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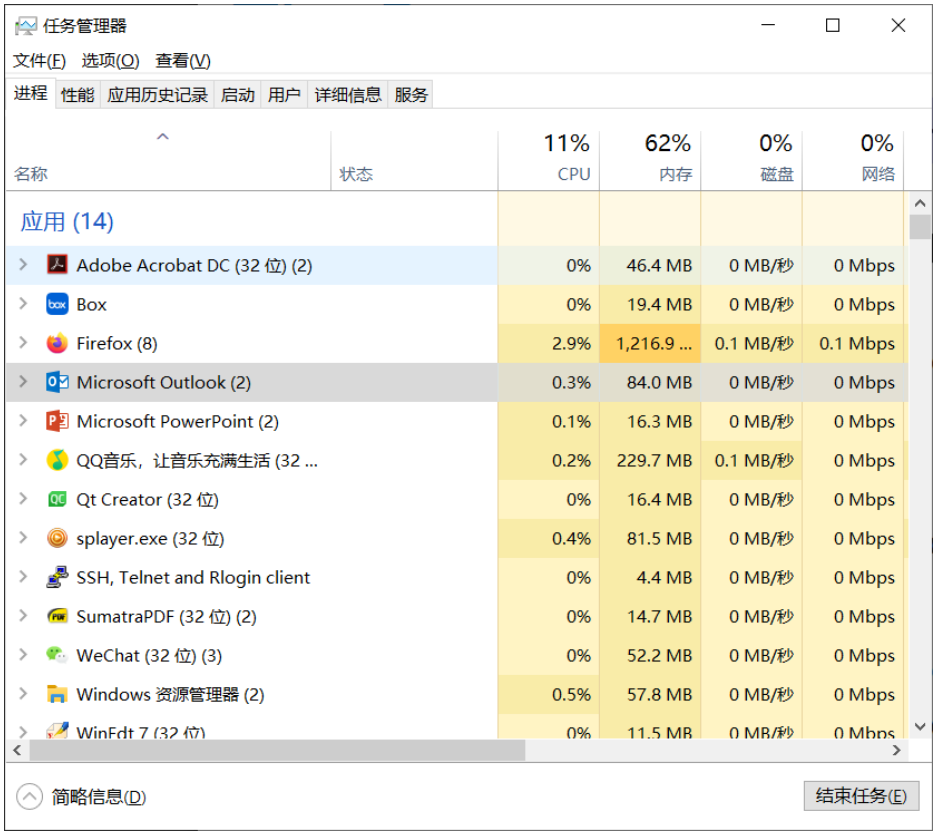

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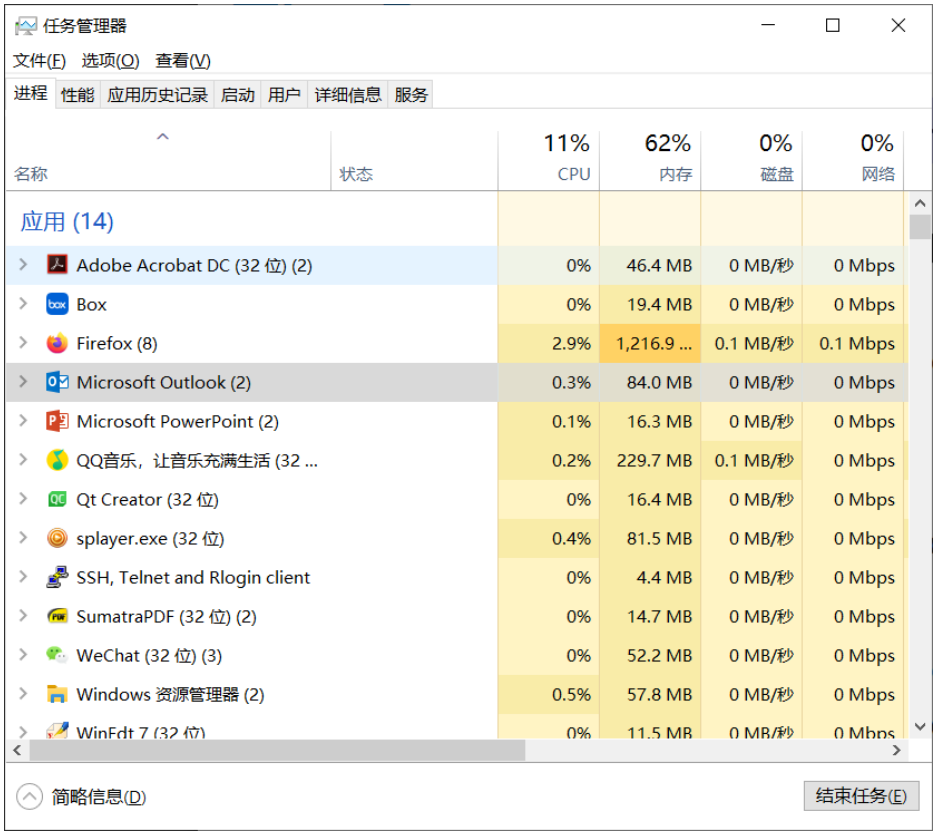
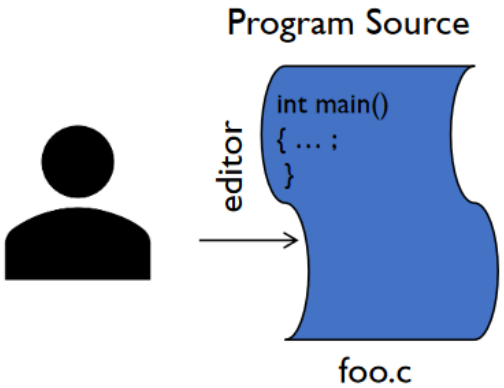


- How is that implemented? Multi-processing/threading

Review: compiling a program and let it run on OS



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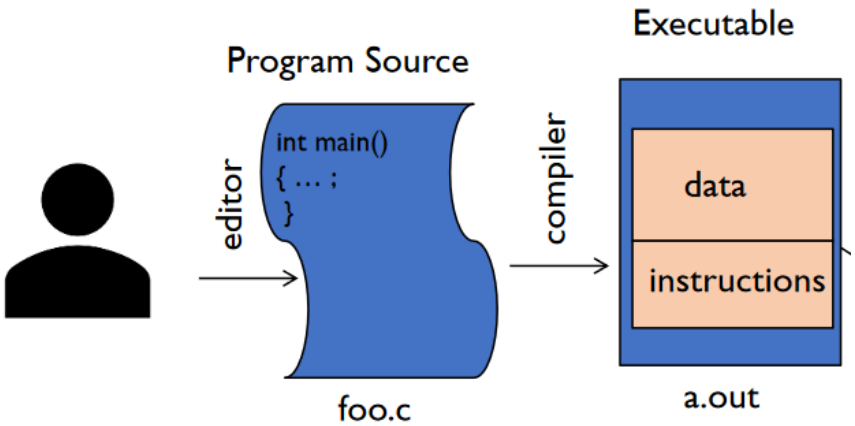

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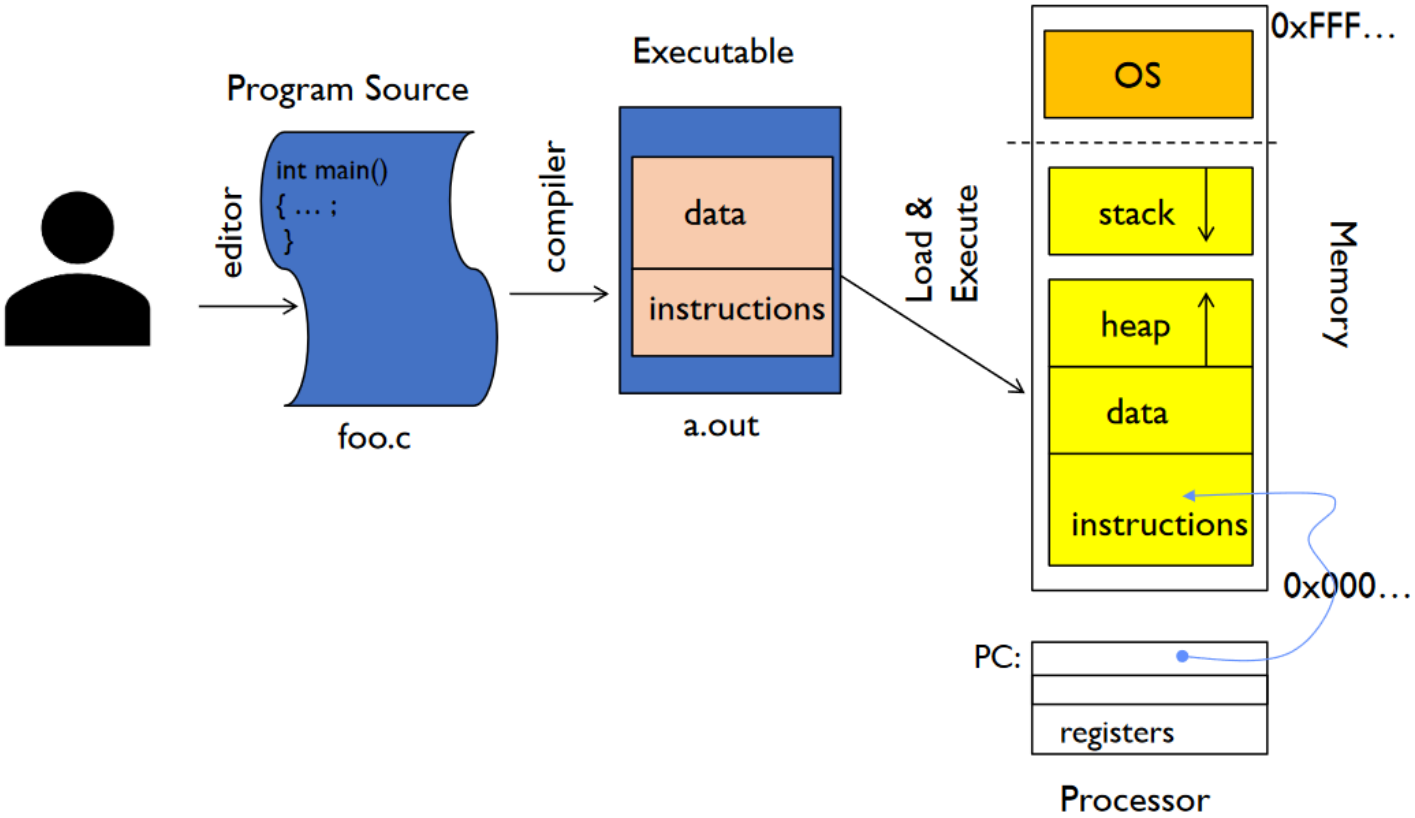

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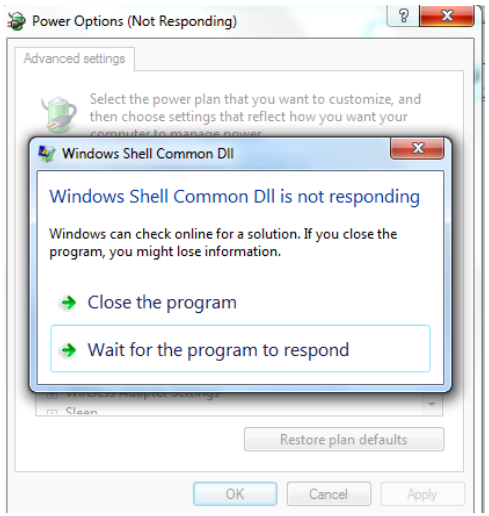
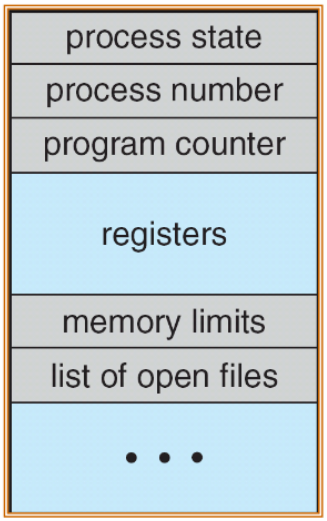


Jeff Dean's "Numbers everyone should know"

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

What is a process

- Definition: **execution environment with restricted rights**



Process Control Block

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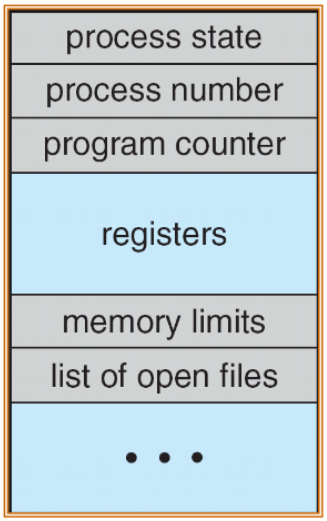

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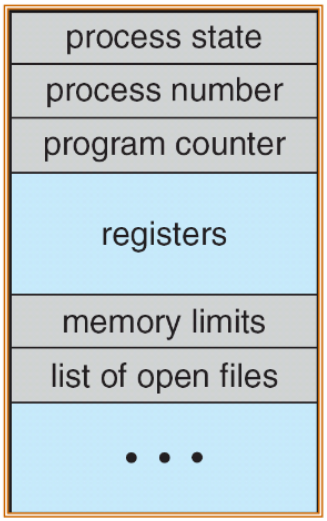

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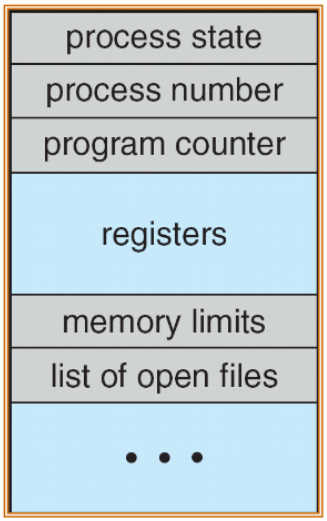

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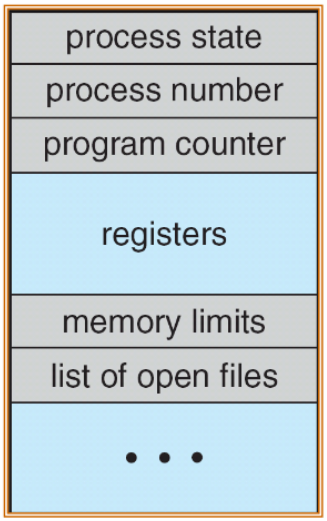

  - Owns memory
  - Owns file descriptors, file system context
  - Encapsulates *one or more threads* sharing process resources
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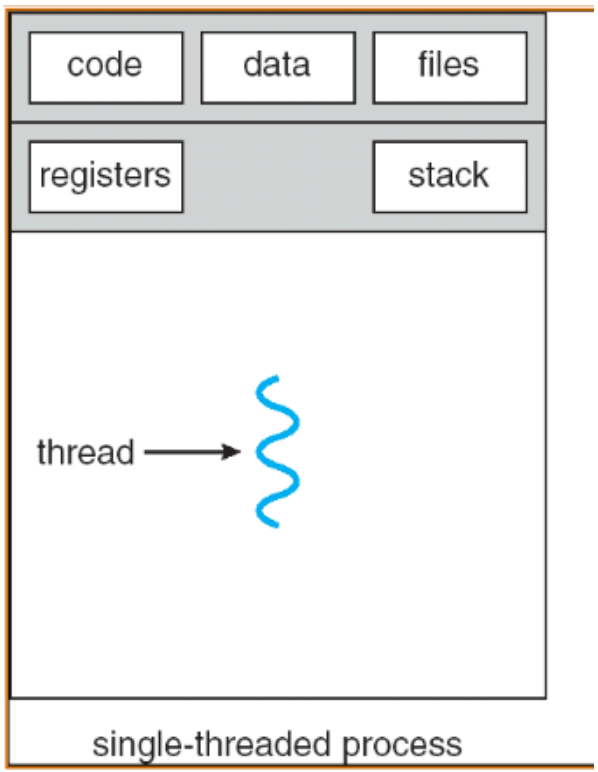

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- Question: how to solve this issue?

Adding one thread

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- Version of program with Threads (loose syntax):

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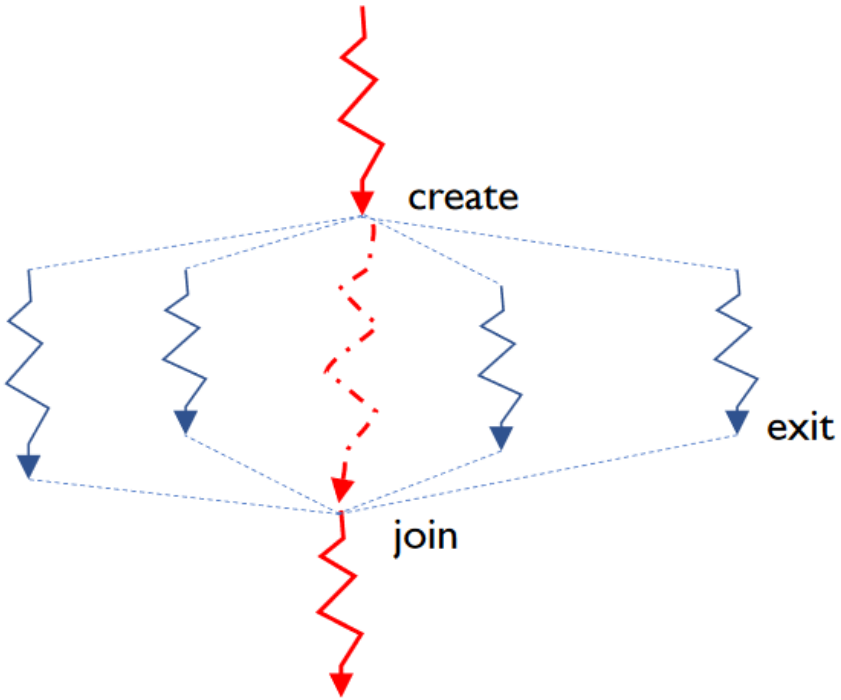
- Multithreading is simple!

Fork-join pattern



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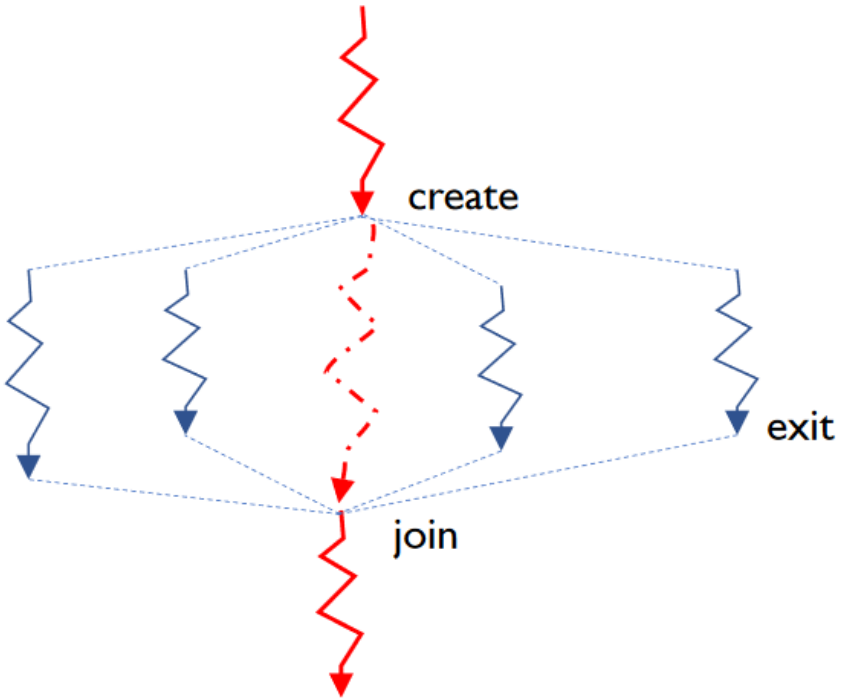

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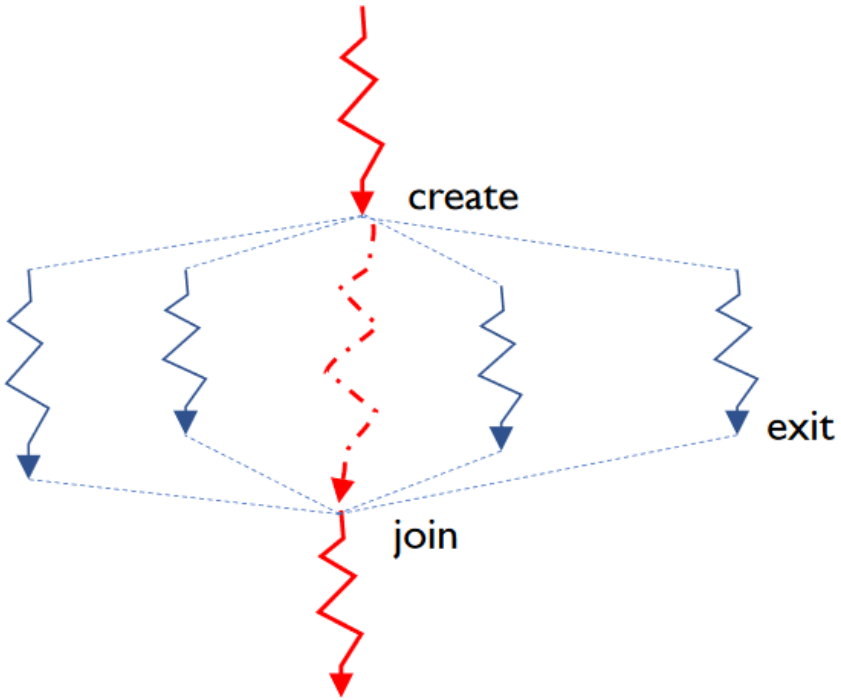

- Main thread creates (forks) collection of sub-threads passing them args to work on, joins with them, collecting results.
- Question: How do you think those threads behaves over time?

Single- and multi-threaded processes

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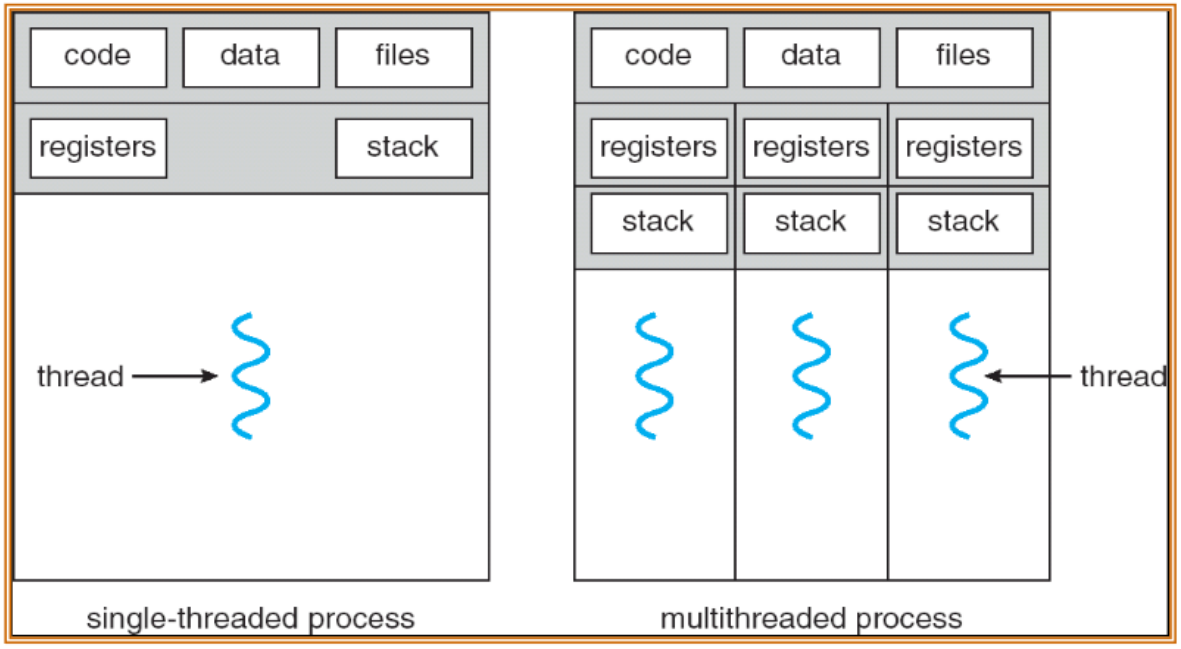

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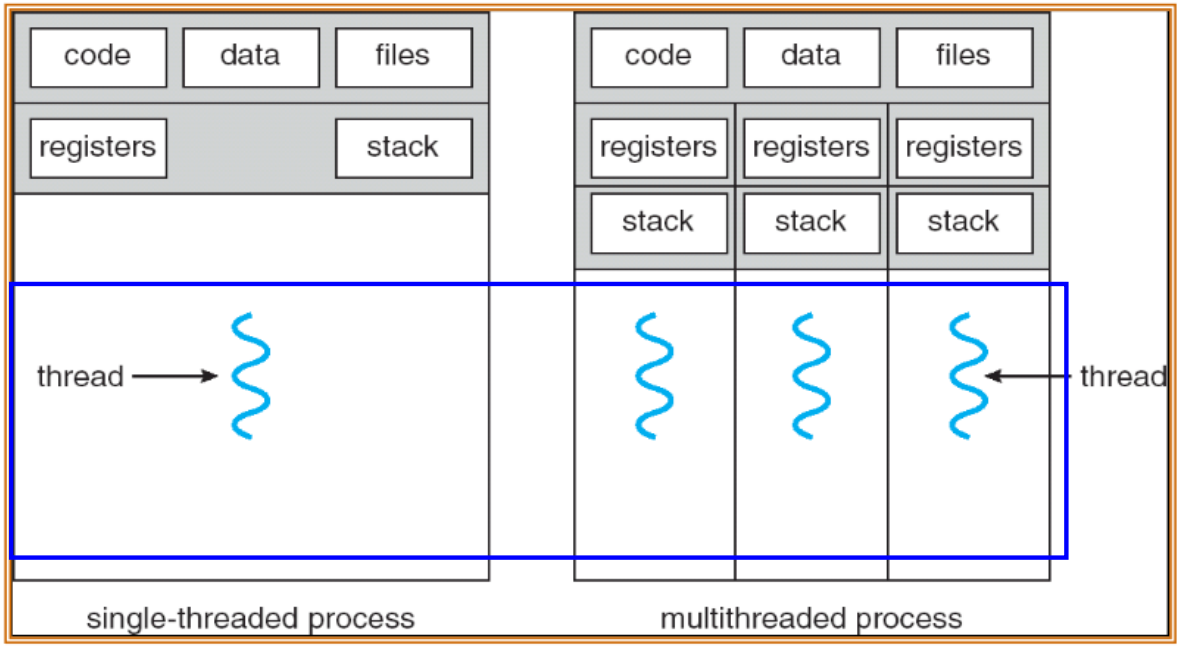

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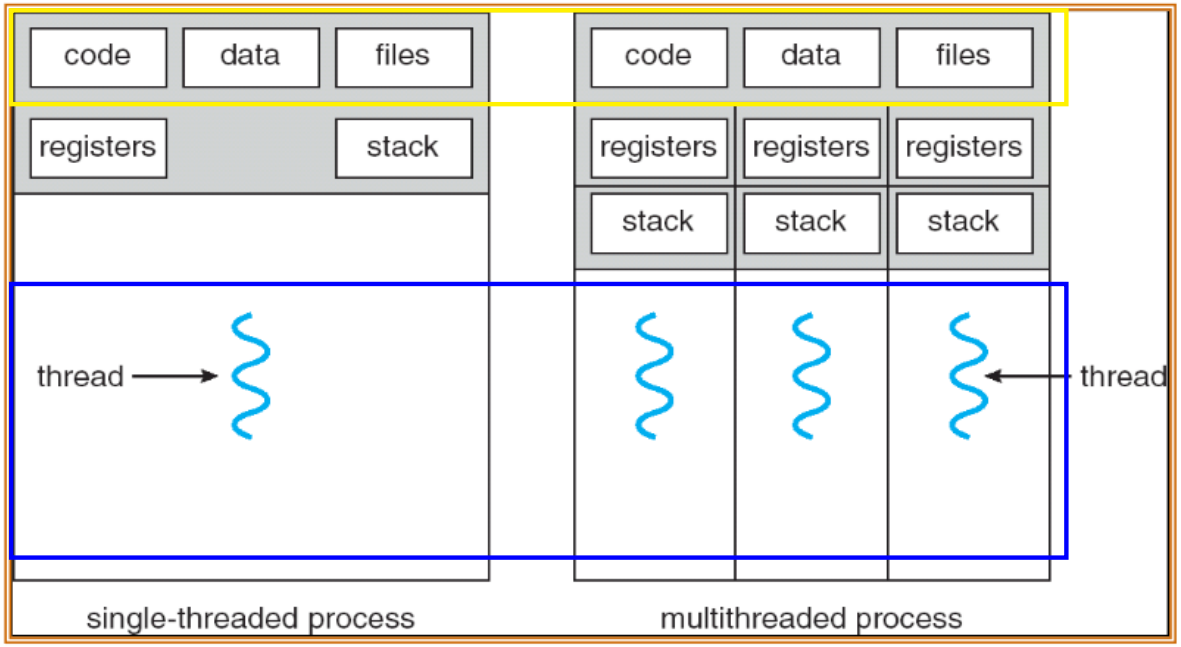

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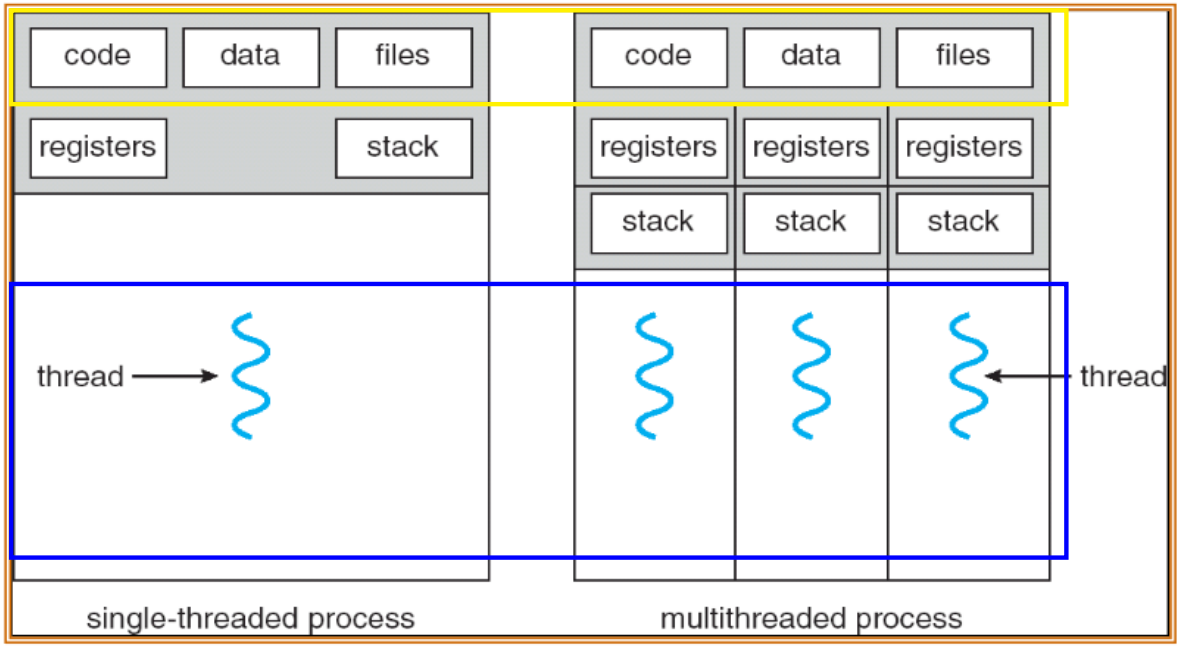

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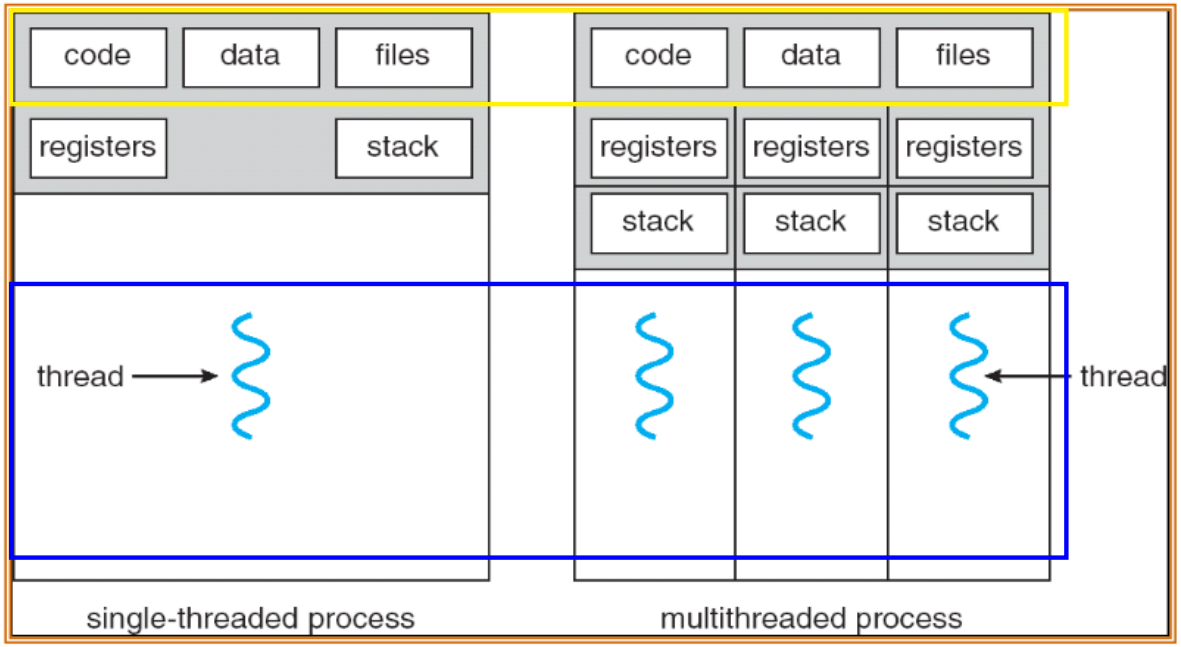

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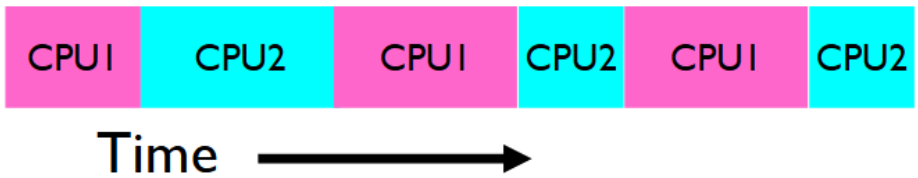

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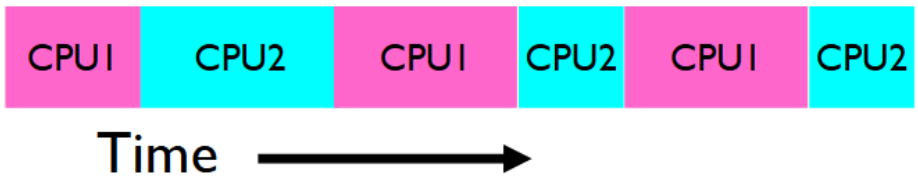

- Does this bother you?

Programmer vs processor view

- Let's use a little bit more complicated example

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- Assume x, y, and z are all initialized by 0

Programmer's View

```
.
.
.
x = x + 1;
y = y + x;
z = x +5y;
.
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Programmer vs processor view

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Programmer's View	Possible Execution #1
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.	.
.	.
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y = y + x;	y = y + x;
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.	.
.	.
.	.

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Reality: nondeterministic

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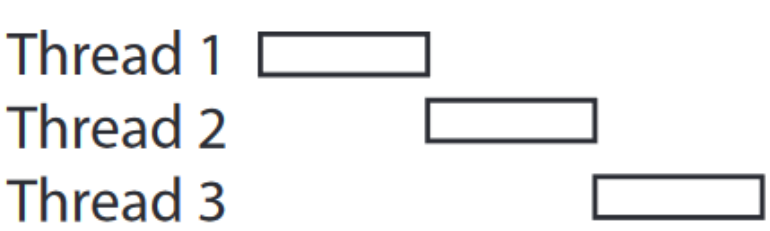

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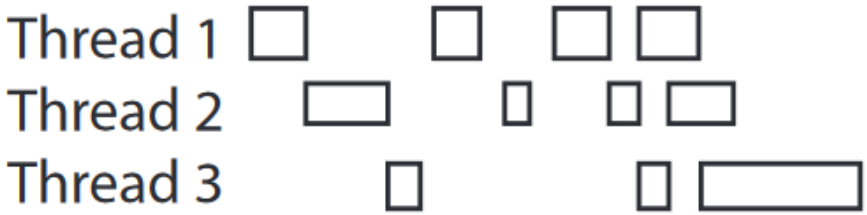

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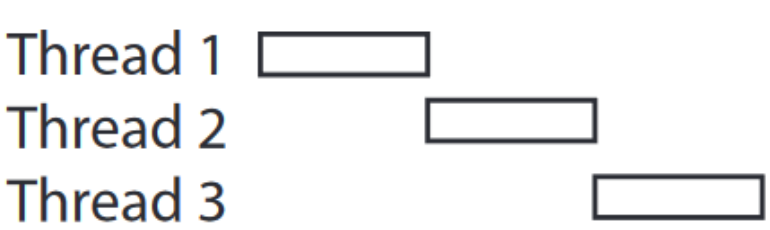

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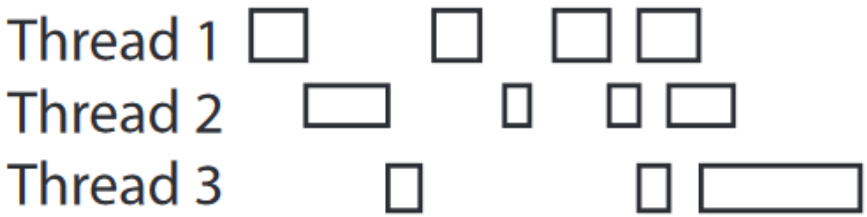

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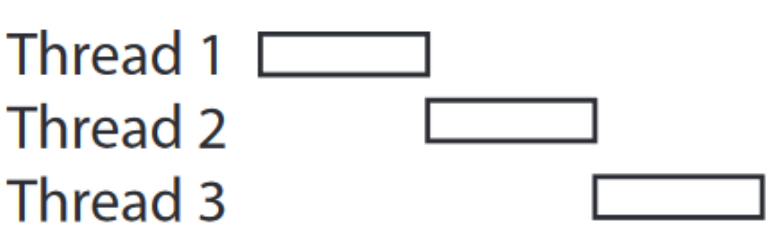

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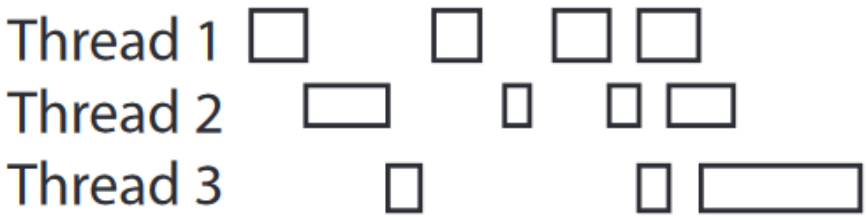

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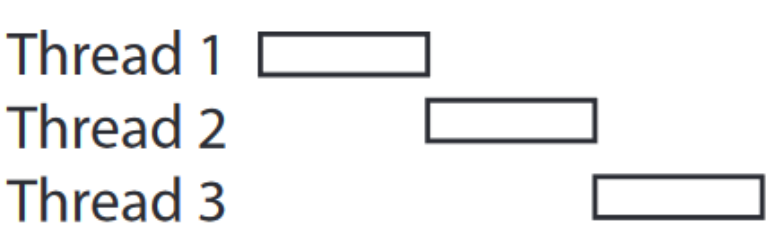

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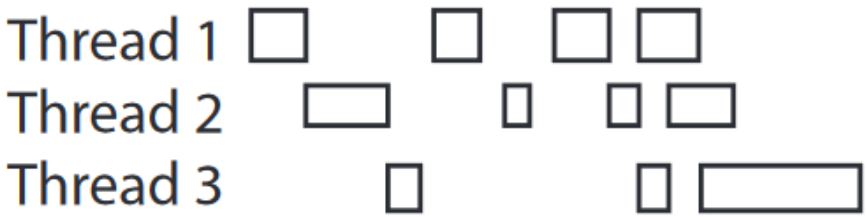

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- BTW, is case 3 even possible?

Example I

What are the possible values of x below?

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What are the possible values of x below?

- Initially x = y = 0;
  - Thread A

```
1 x = y + 1;
2
```

  - Thread B

```
1 y = 2;
2 y = y * 2;
3
```

Example I

What are the possible values of x below?

- Initially x = y = 0;
  - Thread A

```
1 x = y + 1;
2
```

  - Thread B

```
1 y = 2;
2 y = y * 2;
3
```

- 1 or 3 or 5 (non-deterministic!)

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- 1 or 3 or 5 (non-deterministic!)
- Race Condition: Thread A races against Thread B

Real-life analogy

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
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- How can we avoid this?
- Where does the problem come from?

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3     inc eax
4     mov [count],eax
5
```

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- Does the case 3 start to make more sense?

Relevant definitions

Mutual Exclusion (Mutex)

Ensuring only one thread does a particular thing at a time (one thread excludes the others)

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- This is a result of mutual exclusion

Lock

An object only one thread can hold at a time.

- Provides mutual exclusion
- Take advantage of two atomic operations
  - `Lock.Acquire()` – wait until lock is free; then grab
  - `Lock.Release()` - unlock, wake up waiters

Using locks

```
MilkLock.Acquire()
if (noMilk) {
    buy milk
}
MilkLock.Release()
```

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- How does this work out?

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- Semaphores are a kind of generalized locks
- First defined by Dijkstra in late 60s

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- P() or down(): atomic operation that waits for semaphore to become positive, then decrements it by 1
- V() or up(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any

Semaphores

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Definition

A semaphore has a non-negative integer value and supports the following two operations:

- P() or down(): atomic operation that waits for semaphore to become positive, then decrements it by 1
- V() or up(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
- P()stands for "proberen" (to test) and V()stands for "verhogen" (to increment) in Dutch

Two important semaphore patterns

Lock like

Also called a "binary lock"

```
1 // initial value of semaphore = 1;
2 semaphore.down();
3 // Critical section goes here
4 semaphore.up();
5
```

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Resource management

Signaling other threads

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Resource management

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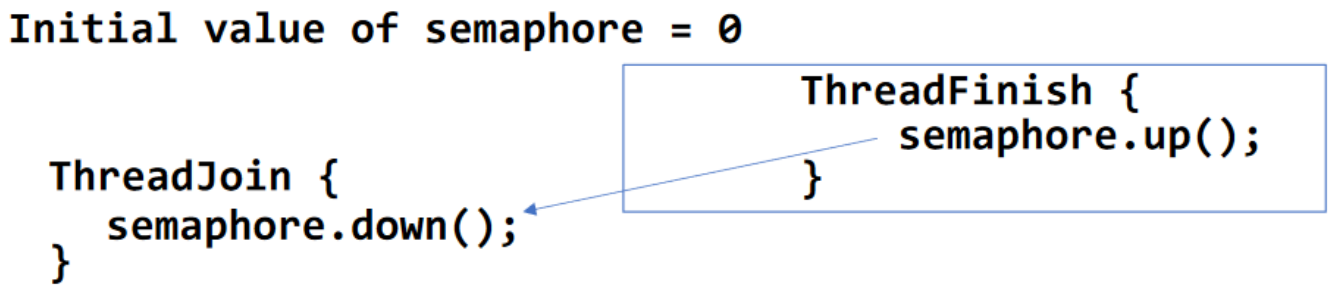


QThread

- `QThread` is the central class in Qt to run code in a different thread
- It's a `QObject` subclass
  - Not copiable/moveable
  - Has signals to notify when the thread starts/finishes
- It is meant to *manage* a thread

QThread usage

- To create a new thread executing some code, subclass `QThread` and reimplement `run()`
- Then create an instance of the subclass and call `start()`
- Threads have priorities that you can specify as an optional parameter to `start()`, or change with `setPriority()`

QThread usage


```
1 class MyThread : public QThread {
2 private:
3     void run() override {
4         // code to run in the new thread
5     }
6 };
```

```
1 MyThread *thread = new MyThread;
2 thread->start(); // starts a new thread which calls run()
3 // ...
4 thread->wait(); // waits for the thread to finish
```

QThread usage

- The thread will stop running when (some time after) returning from `run()`
- `QThread::isRunning()` and `QThread::isFinished()` provide information about the execution of the thread
- You can also connect to the `QThread::started()` and `QThread::finished()` signals
- A thread can stop its execution temporarily by calling one of the `QThread::sleep()` functions
  - Generally a *bad idea*, being event driven (or polling) is much much better
- You can wait for a `QThread` to finish by calling `wait()` on it
  - Optionally passing a maximum number of milliseconds to wait

QThread caveats

From a non-main thread you cannot:

- Perform any GUI operation
  - Including, but not limited to: using any `QWidget` / Qt Quick / `QPixmap` APIs
  - Using `QImage`, `QPainter`, etc. (i.e. "client side") is OK
  - Using OpenGL may be OK: check at runtime `QOpenGLContext::supportsThreadedOpenGL()`
- Call `Q(Core|Gui)Application::exec()`

Ensuring destruction of QObjects

- Create them on `QThread::run()` stack
- Connect their `QObject::deleteLater()` slot to the `QThread::finished()` signal
  - Yes, this will work
- Move them out of the thread

QThread usage

There are two basic strategies of running code in a separate thread with QThread:

- Without an event loop
- With an event loop

QThread usage without an event loop

- Subclass `QThread` and override `QThread::run()`
- Create an instance and start the new thread via `QThread::start()`

QThread usage without an event loop

- Subclass `QThread` and override `QThread::run()`
- Create an instance and start the new thread via `QThread::start()`

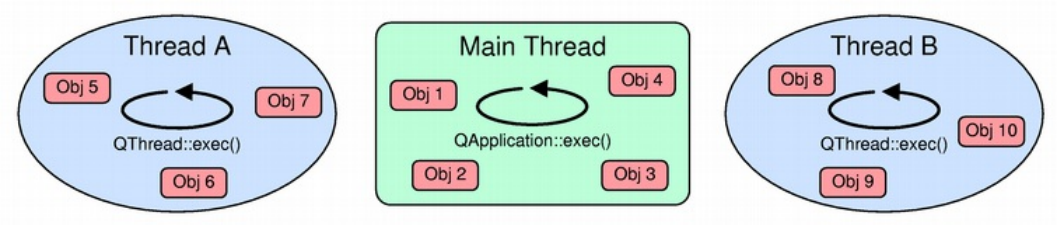
```
1 class MyThread : public QThread {
2 private:
3     void run() override {
4         loadFilesFromDisk();
5         doCalculations();
6         saveResults();
7     }
8 };
```

```
1 auto thread = new MyThread;
2 thread->start();
3 // some time later...
4 thread->wait();
```

QThread usage with an event loop

KDAB

- An event loop is necessary when dealing with timers, networking, *queued connections*, and so on.
- Qt supports per-thread event loops:



- Each thread-local event loop delivers events for the QObjects living in that thread.

QThread usage with an event loop

- We can start a thread-local event loop by calling `QThread::exec()` from within `run()`:

```
1  class MyThread : public QThread {
2  private:
3      void run() override {
4          auto socket = new QTcpSocket;
5          socket->connectToHost(...);
6
7          exec(); // run the event loop
8
9          // cleanup
10     }
11 };
```

- `QThread::quit()` or `QThread::exit()` will quit the event loop

- We can also use `QEventLoop`
  - Or manual calls to `QCoreApplication::processEvents()`

What is the single most important thing about threads?

Synchronization

Qt has a complete set of cross-platform, low-level APIs for dealing with synchronization:

- `QMutex` is a mutex class (recursive and non-recursive)
- `QSemaphore` is a semaphore
- `QWaitCondition` is a condition variable
- `QReadWriteLock` is a *shared mutex*
- `QAtomicInt` is an atomic `int`
- `QAtomicPointer<T>` is an atomic pointer to T

There are also RAII classes for lock management, such as `QMutexLocker`, `QReadLocker` and so on.

Mutex Example


```
1  class Thread : public QThread
2  {
3      bool m_cancel;
4  public:
5      explicit Thread(QObject *parent = nullptr)
6        : QThread(parent), m_cancel(false) {}
7
8      void cancel()   // called by GUI
9      {
10         m_cancel = true;
11     }
12
13 private:
14     bool isCanceled() const   // called by run()
15     {
16         return m_cancel;
17     }
18
19     void run() override { // reimplemented from QThread
20         while (!isCanceled())
21             doSomething();
22     }
23 };
```

Mutex Example (cont'd)

KDAB

```
1  class Thread : public QThread
2  {
3      mutable QMutex m_mutex; // protects m_cancel
4      bool m_cancel;
5  public:
6      explicit Thread(QObject *parent = nullptr)
7        : QThread(parent), m_cancel(false) {}
8
9      void cancel() { // called by GUI
10         const QMutexLocker locker(&m_mutex);
11         m_cancel = true;
12     }
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14 private:
15     bool isCanceled() const { // called by run()
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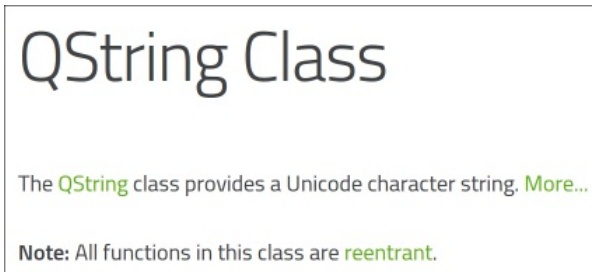
For classes, the above definitions apply to non-static member functions when invoked on the same instance. (In other words, considering the `this` pointer as an argument.)

Examples

- **Thread safe**:
  - `QMutex`
  - `QObject::connect()`
  - `QCoreApplication::postEvent()`
- **Reentrant**:
  - `QString`
  - `QVector`
  - `QImage`
  - value classes in general
- **Non-reentrant**:
  - `QWidget` (including all of its subclasses)
  - `QQuickItem`
  - `QPixmap`
  - in general, GUI classes are usable only from the main thread

Thread safety for Qt classes/functions

The documentation of each class / function in Qt has notes about its thread safety:



Unless otherwise specified, classes and functions are **non-reentrant**.

QObject: thread affinity

What about QObject?

QObject: thread affinity

What about QObject?

- `QObject` itself is thread-aware.
- Every `QObject` instance holds a reference to the thread it was created into (`QObject::thread()`)
  - We say that the object *lives in*, or *has affinity with* that thread
- We can move an instance to another thread by calling `QObject::moveToThread(QThread *)`

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- You can only call `moveToThread()` on a `QObject` from the same thread the object has affinity with (`moveToThread()` is non-reentrant)

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In practice: **it's easier to think of `QObject` as non-reentrant**, as it will make you avoid many mistakes.

QObject: queued connections

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- Qt has a solution: **cross-thread signals and slots**
- You can emit a signal from one thread, and have the slot invoked by another thread
  - Not just any thread: the thread the receiver object is living in

QObject: queued connections

- If the receiver object of a connection lives in a different thread than the thread the signal was emitted in, the slot invocation will be **queued**.

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  - The event will then get dispatched to the object *by the right thread*
  - Handling such metacall events means invoking the slot

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  - The event will then get dispatched to the object *by the right thread*
  - Handling such metacall events means invoking the slot
- This requires that the receiver object is living in a thread with a running event loop!
- Also, `qRegisterMetaType()` is required for the argument types passed
- We can force any connection to be queued:

```
connect(sender, &Sender::signal, receiver, &Receiver::slot, Qt::QueuedConnection);
```

QObject: queued connections example

KDAB

```
1  class MyThread : public QThread {
2      Producer *m_producer;
3  public:
4      explicit MyThread(Producer *p, QObject *parent = nullptr)
5          : QThread(parent), m_producer(p) {}
6
7      void run() override {
8          Consumer consumer;
9          connect(m_producer, &Producer::unitProduced,
10                 &consumer, &Consumer::consume);
11         exec();
12     }
13 };
14
15 // in main thread:
16 auto producer = new Producer;
17 auto thread = new MyThread(producer);
18 thread->start();
19 producer->startProduction();
20
21 // Producer::unitProduced gets emitted some time later from the main thread,
22 // Consumer::consume gets run in the secondary thread
```

QObject: queued connections example (2)


```
1  // Same as before, but without the race
2
3  auto producer = new Producer;
4  auto consumer = new Consumer;
5  auto thread = new QThread;
6
7  connect(m_producer, &Producer::unitProduced,
8          consumer, &Consumer::consume);
9  connect(thread, &QThread::finished,
10         consumer, &QObject::deleteLater);
11
12 consumer->moveToThread(thread);
13
14 thread->start();
15
16 // Producer::unitProduced gets emitted some time later from the main thread,
17 // Consumer::consume gets run in the secondary thread
```

QObject: queued connections example (3)

KDAB

```
1  class MyThread : public QThread {
2  public:
3      explicit MyThread(QObject *parent = nullptr)
4          : QThread(parent) {}
5
6  private:
7      void run() override {
8          emit mySignal();
9      }
10
11 signals:
12     void mySignal();
13 };
14
15 // in main thread:
16 auto thread = new MyThread;
17 connect(thread, &MyThread::mySignal, receiver, &Receiver::someSlot);
18 thread->start();
```

QObject: queued connections example (3)


```
1  class MyThread : public QThread {
2  public:
3      explicit MyThread(QObject *parent = nullptr)
4          : QThread(parent) {}
5
6  private:
7      void run() override {
8          emit mySignal();
9      }
10
11 signals:
12     void mySignal();
13 };
14
15 // in main thread:
16 auto thread = new MyThread;
17 connect(thread, &MyThread::mySignal, receiver, &Receiver::someSlot);
18 thread->start();
```

- It is perfectly OK to add signals to `QThread`
- The connection is queued: the thread that emits the signal is not the thread the receiver has affinity with
- `someSlot()` gets invoked by the main thread's event loop

QObject: queued connections example (4)


```
1  class MyThread : public QThread {
2      Socket *m_socket;
3  public:
4      explicit MyThread(QObject *parent = nullptr)
5          : QThread(parent) {}
6
7  private:
8      void run() override {
9          m_socket = new Socket;
10         connect(m_socket, &Socket::connected, this, &MyThread::onConnected);
11         m_socket->connectToHost(...);
12         exec();
13     }
14
15 private slots:
16     void onConnected() { qDebug() << "Data received:" << m_socket->data(); }
17 };
```

QObject: queued connections example (4)


```
1  class MyThread : public QThread {
2      Socket *m_socket;
3  public:
4      explicit MyThread(QObject *parent = nullptr)
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7  private:
8      void run() override {
9          m_socket = new Socket;
10         connect(m_socket, &Socket::connected, this, &MyThread::onConnected);
11         m_socket->connectToHost(...);
12         exec();
13     }
14
15 private slots:
16     void onConnected() { qDebug() << "Data received:" << m_socket->data(); }
17 };
```

- `QThread` is a `QObject` and as such has its own thread affinity (it's the thread that created the `MyThread` instance, *not itself!*)
- The connection is queued: the thread that emits the signal is not the thread the receiver has affinity with
  - *This is not what we wanted!*
- Huge recommendation: **avoid adding slots to QThread**