Work-Stealing without the Baggage

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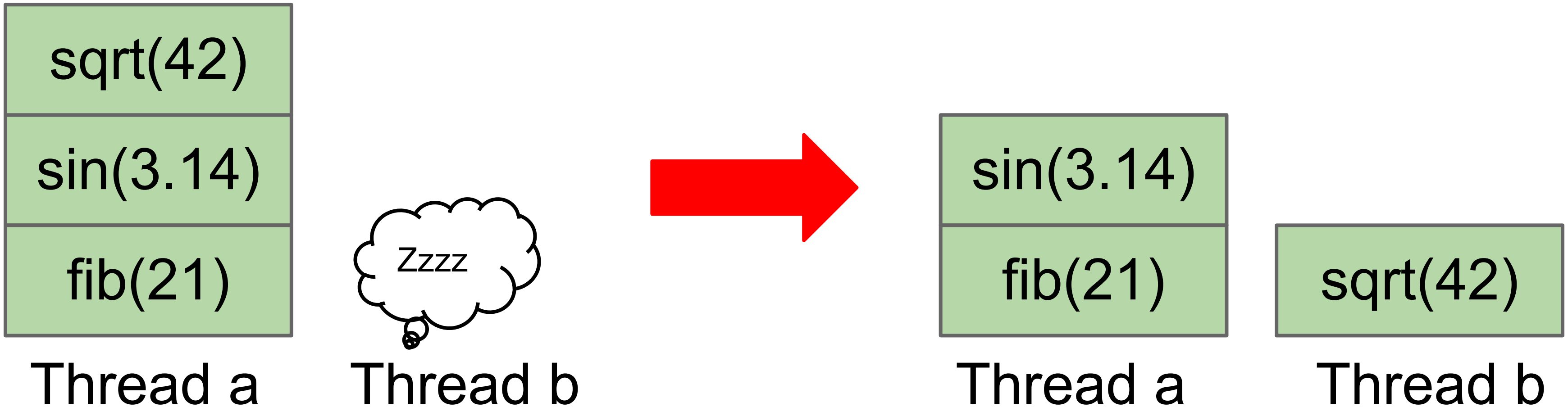
Presentation by Roman Schmocker

Work stealing: Idea

- Work queue for each thread
  - No dependencies allowed between work jobs
- Idle threads steal jobs from busy threads



sqrt(42)
sin(3.14)
fib(21)
Thread a

Thread b

sin(3.14)
fib(21)
Thread a

sqrt(42)
Thread b

X10

- Research language by IBM
  - Object-oriented, Java-like
  - Translated to Java
  - Strong focus on parallel programming

- Async-Finish construct in X10:

```
finish {
   async a = sqrt (42); // May run concurrently
   b = fib (21);
}                           // Thread join point
c = a+b;
```

Async-Finish and Work Stealing

- When encountering async
  - push the *continuation* to work queue
  - execute the *async* immediately

- Continuation
  - The code following an async statement up to the end of finish block

```
finish {
   async a = sqrt (42);
   b = fib (21);
}
```

Translation to Java

- Put continuation into separate method
    - called *continuation method*

- All variables accessed within continuation method are heap-allocated
    - i.e. generate frame classes and instantiate *frame objects* that hold these variables

- Work queue entries:
    - continuation method
    - frame object (as its argument)

Finish block semantics

- Worker retrieves job from queue
    - No steal -> No waiting necessary

- Worker retrieves **null**
    - continuation stolen!
    - How to check if thief has finished execution?

- Atomic integer for each finish block
    - Denotes number of active threads
    - Increment when stealing
    - Decrement when completing job
    - Worker: proceed when zero

Performance analysis

- Authors interested in *sequential overhead*
    - Compare performance between:
        - Work-stealing with only one thread
        - Sequential version (no async-finish statements)

- Several benchmarks
    - e.g. Fibonacci number, LU-Decomposition

- Results
    - Sequential overhead is huge!
    - up to 16x slower than sequential version
    - Best result has still overhead of 1.5

Performance analysis

- Some operations very costly
  - Synchronization of work queue
  - Allocation (and deallocation) of frame objects
- Method splitting prevents optimizations
  - plus overhead of additional call
- This applies even when there's no steal!
- Moreover, further analysis has shown that steals are very rare
  - usually 1 steal among 1'000'000 tasks
  - at most 1 in 10

X10 (Try-Catch)

- New way to translate async-finish
  - main contribution of the paper

- Goal: No sequential overhead
  - Preparing for a potential steal is too expensive
  - Use call stack as implicit queue
  - Copy values only during an actual steal operation

- Control Flow modelled with Java exceptions
  - First step: wrap async-finish into try-catch

X10

```
def fib (n:Int):Int {
    val a:Int; val b:Int;
    if (n < 2) return n;

    finish {
        async a = fib(n-1);
        b = fib (n-2);
    }

    return a + b;
}
```

Java

```
int fib (int n) {
    int a,b;
    if (n < 2) return n;
    try {
        try {
            a = fib (n-1);
        }
        catch (...) {}
        b = fib (n-2);
    }
    catch(...) {}

    return a + b;
}
```

Informing thieves

```
int fib (int n) {
    int a,b; if (n < 2) return n;
    try {
        try {
            // Atomically set a flag indicating that work can be stolen
            // WS is a class with some static support methods
            WS.setFlag();
            a = fib (n-1);
        }
        catch (...) {}
        b = fib (n-2);
    }
    catch(...) {}
    return a + b;
}
```

Performing a steal

- Thief forcibly stops worker
  - using Java VM functionality
- Copy call stack of worker
  - and update flag
- Restart worker thread
- Dive into execution by throwing Continuation exception
  - Requires catch clause for thief!

```
int fib (int n) {
    int a,b; if (n < 2) return n;
    try {
        try {
            WS.setFlag();
            a = fib (n-1);
        }
        catch (Continuation c) {
            // Empty catch clause.
            // Thief will start here after throwing Continuation exception!
        }
        b = fib (n-2);
    }
    catch(...) {}
    return a + b;
}
```

Control flow

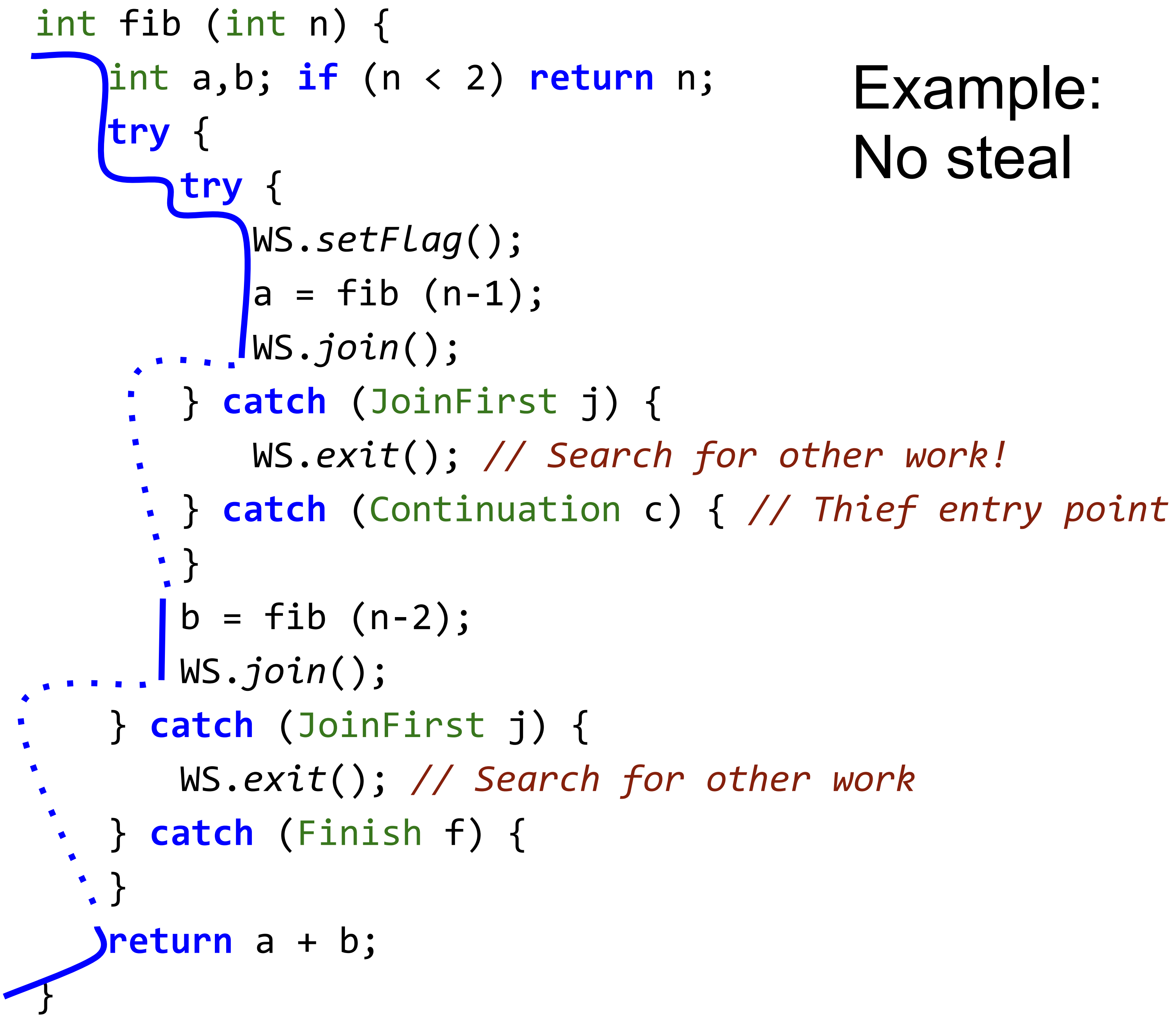
- Goals
  - Worker must not execute stolen continuation
  - None shall leave finish{} while the other is running
  - Exactly one must proceed after finish{}
- Guard exit
  - join() method at end of try blocks
  - Correct control flow through exceptions
- Finish node
  - Available in join()
  - Created lazily during steal
  - Atomic integer, represents active threads (initially 2)

Join method

```
// in class WS

static void join () {
    if (WS.getFlag() == false) { // A steal has occured
        int active = finish_node.count.decrementAndGet();
        if (active == 0)
            // I'm the last thread
            throw new Finish();
        } else {
            // The other thread hasn't finished
            throw new JoinFirst();
        }
    }
}
```

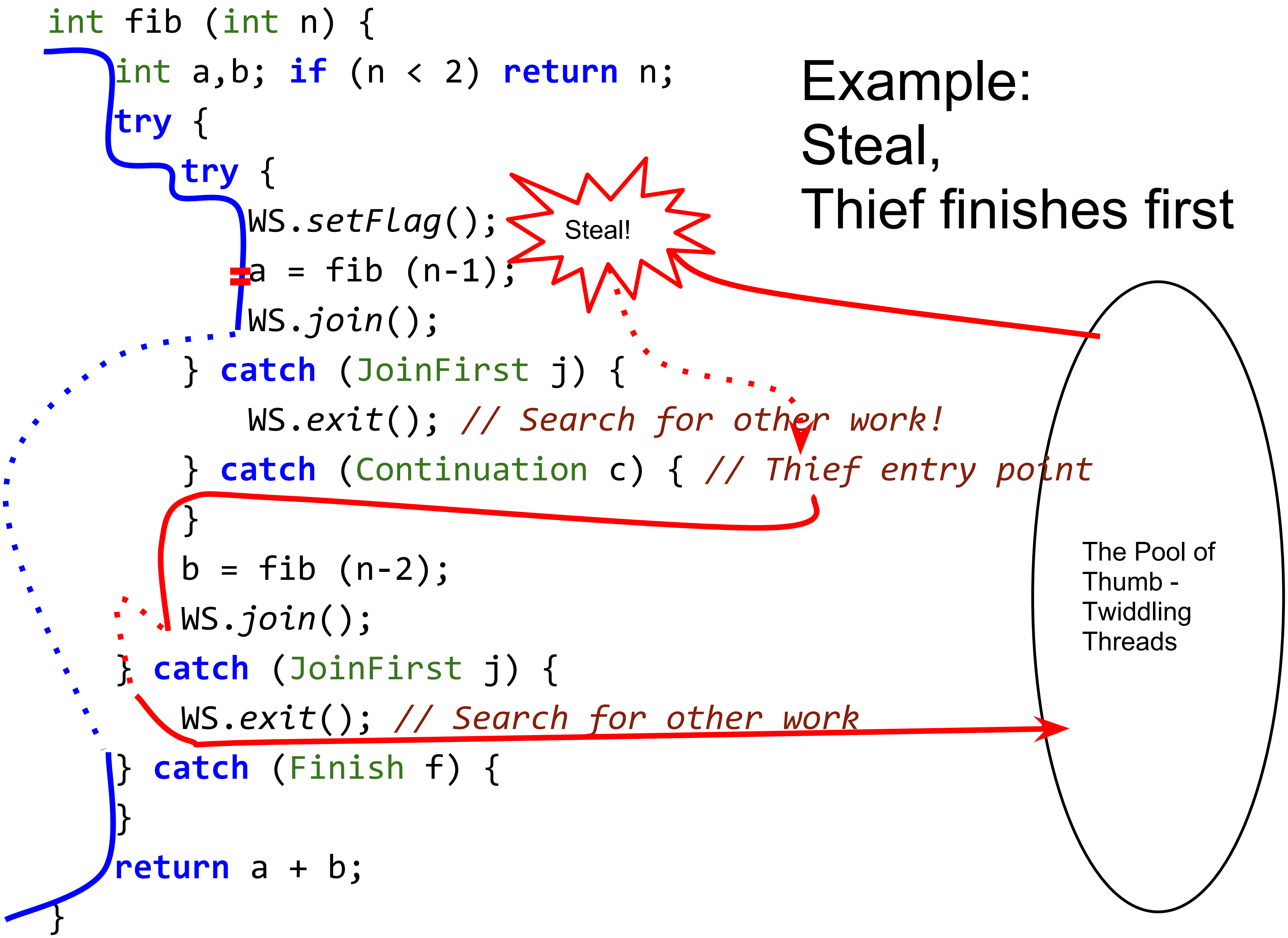
```
int fib (int n) {
    int a,b; if (n < 2) return n;
    try {
        try {
            WS.setFlag();
            a = fib (n-1);
            WS.join();
        } catch (JoinFirst j) {
            WS.exit(); // Search for other work!
        } catch (Continuation c) { // Thief entry point
        }
        b = fib (n-2);
        WS.join();
    } catch (JoinFirst j) {
        WS.exit(); // Search for other work
    } catch (Finish f) {
    }
    return a + b;
}
```



Example: No steal

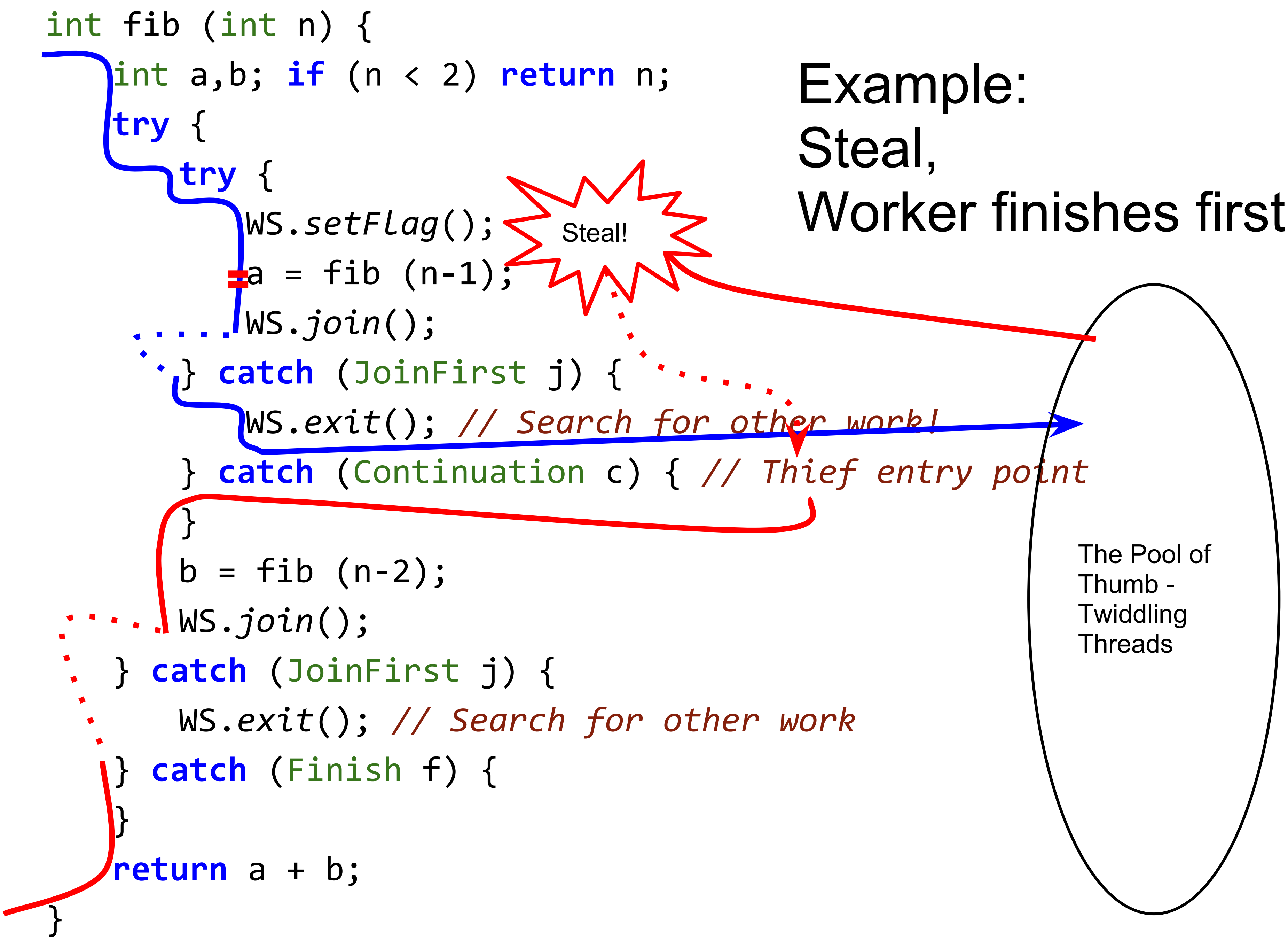
```
int fib (int n) {
    int a,b; if (n < 2) return n;
    try {
        try {
            WS.setFlag();
            a = fib (n-1);
            WS.join();
        } catch (JoinFirst j) {
            WS.exit(); // Search for other work!
        } catch (Continuation c) { // Thief entry point
        }
        b = fib (n-2);
        WS.join();
    } catch (JoinFirst j) {
        WS.exit(); // Search for other work
    } catch (Finish f) {
    }
    return a + b;
}
```

Example:
Steal,
Thief finishes first



```
int fib (int n) {
    int a,b; if (n < 2) return n;
    try {
        try {
            WS.setFlag();
            a = fib (n-1);
            WS.join();
        } catch (JoinFirst j) {
            WS.exit(); // Search for other work!
        } catch (Continuation c) { // Thief entry point
        }
        b = fib (n-2);
        WS.join();
    } catch (JoinFirst j) {
        WS.exit(); // Search for other work
    } catch (Finish f) {
    }
    return a + b;
}
```

Example:
Steal,
Worker finishes first



```
int fib (int n) {
  int a,b; if (n < 2) return n;
  try {
    try {
      WS.setFlag();
      a = fib (n-1);
      WS.join();
    } catch (JoinFirst j) {
      WS.exit(); // Search for other work!
    } catch (Continuation c) { // Thief entry point
    }
    b = fib (n-2);
    WS.join();
  } catch (JoinFirst j) {
    WS.exit(); // Search for other work
  } catch (Finish f) {
  }
  return a + b;
}
```

State management

- Computed variables in two different stacks!
- Move values to correct stack
  - depends on who finishes last
- First thread stores its values to the finish node
  - in JoinFirst catch blocks
- Last thread retrieves values from finish node
  - in Finish catch block

Improvements

- `WS.join()` only needed when steal occurs

- Generate two versions of method
  - Slow version: as seen previously
  - Fast version: join() replaced with NOP
  - Default to fast version
  - Stack frame layout and jump offsets remain the same!

- Thief switches worker to slow version when stealing

Performance Evaluation

- Sequential overhead
  - Usually a lot smaller than previous solution
  - Between 1.15 and 1.5
  - (one outlier has little more than 2)

- Speedup
  - compared to purely sequential version
  - very good for fine-grained concurrency (e.g. Fibonacci), up to 7x speedup for 12 threads
  - at least on par with old solution on other benchmarks

Conclusion

- Interesting approach
- Requires managed runtime (Java VM)
- Impressive results
- Possible improvements
  - Reduce worker downtime
  - Translate X10 arrays correctly