CS 4530: Fundamentals of Software Engineering

Module 06: Concurrency Patterns in Typescript

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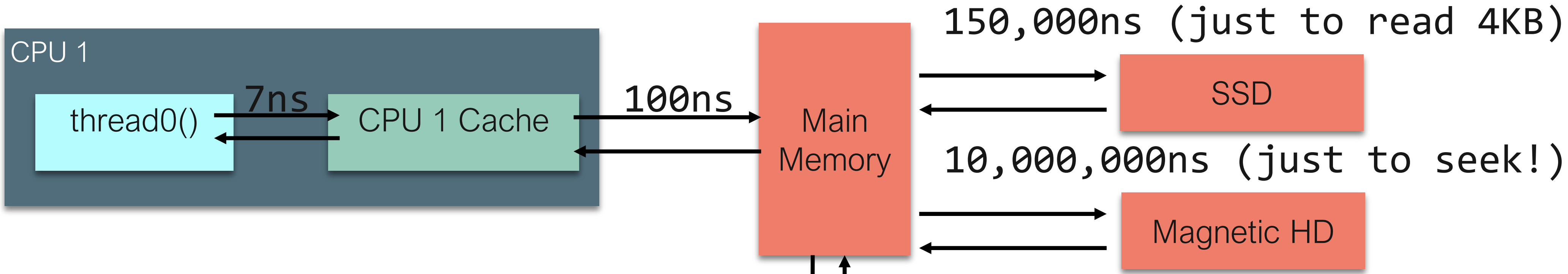
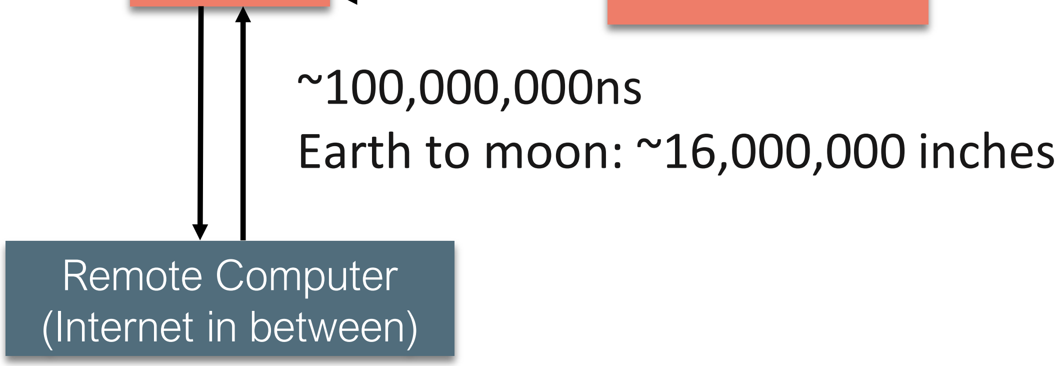
Learning Goals for this Lesson

- At the end of this lesson, you should be prepared to:
  - Explain the difference between JS run-to-completion semantics and interrupt-based semantics.
  - Given a simple program using async/await, work out the order in which the statements in the program will run.
  - Write simple programs that create and manage promises using async/await
  - Write simple programs to mask latency with concurrency by using non-blocking IO and Promise.all in TypeScript.

Our goal is to mask latency with concurrency

- Consider: a 1Ghz CPU executes an instruction every 1 ns
- Almost anything else takes approximately forever





- Utilize this “wasted” time by doing something else
  - Processing data
  - Communicating with remote hosts
  - Timers that countdown while our app is running
  - Echoing user input

We achieve this goal using two techniques:

1. cooperative multiprocessing

2. non-blocking IO

Most OS's use **pre-emptive multiprocessing**

- OS manages multiprocessing with multiple threads of execution
- Processes may be interrupted at unpredictable times
- Inter-process communication by shared memory
- Data races abound
- Really, really hard to get right: need critical sections, semaphores, monitors (all that stuff you learned about in op. sys.)

Javascript/Typescript uses **cooperative multiprocessing**

- Typescript maintains a pool of processes, called **promises**.
- A promise always executes until it hits an `await` or it reaches its end.
- This is called "run-to-completion semantics"
- A promise can create other promises to be added to the pool.
- Promises interact mostly by passing values to one another; data races are minimized.

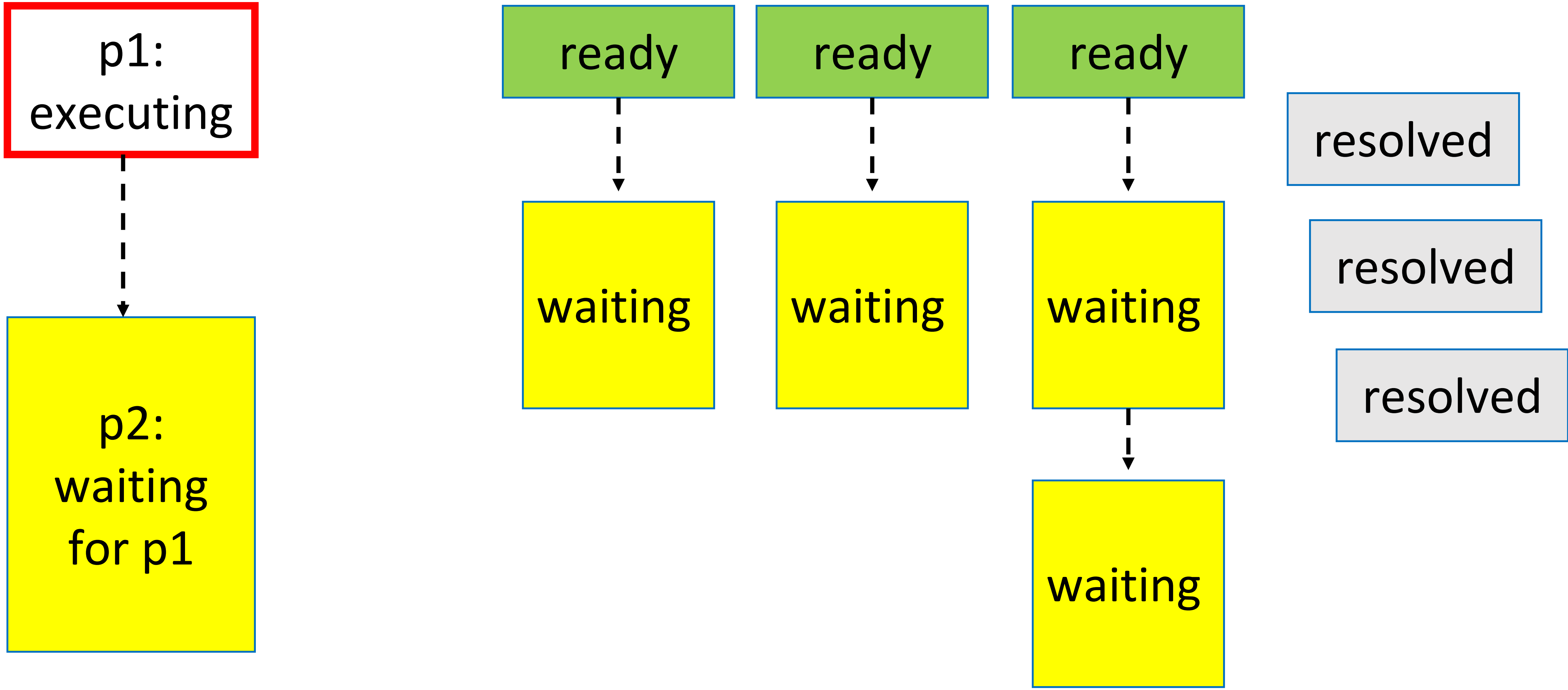
A promise can be in one of exactly 4 states

- **Executing**
  - there is only one of these; we call it the "current promise" or the "current computation", sometimes the "active promise" (We outline this promise in **red**.)
- **Pending** (“waiting”) for some event
  - Either for some other promise to resolve, or for the runtime to select it for execution.
- **Fulfilled** (“resolved”)
  - The asynchronous operation has completed, and the Promise's result is a value .
- **Rejected**
  - The asynchronous operation failed, and the Promise's result is an error.

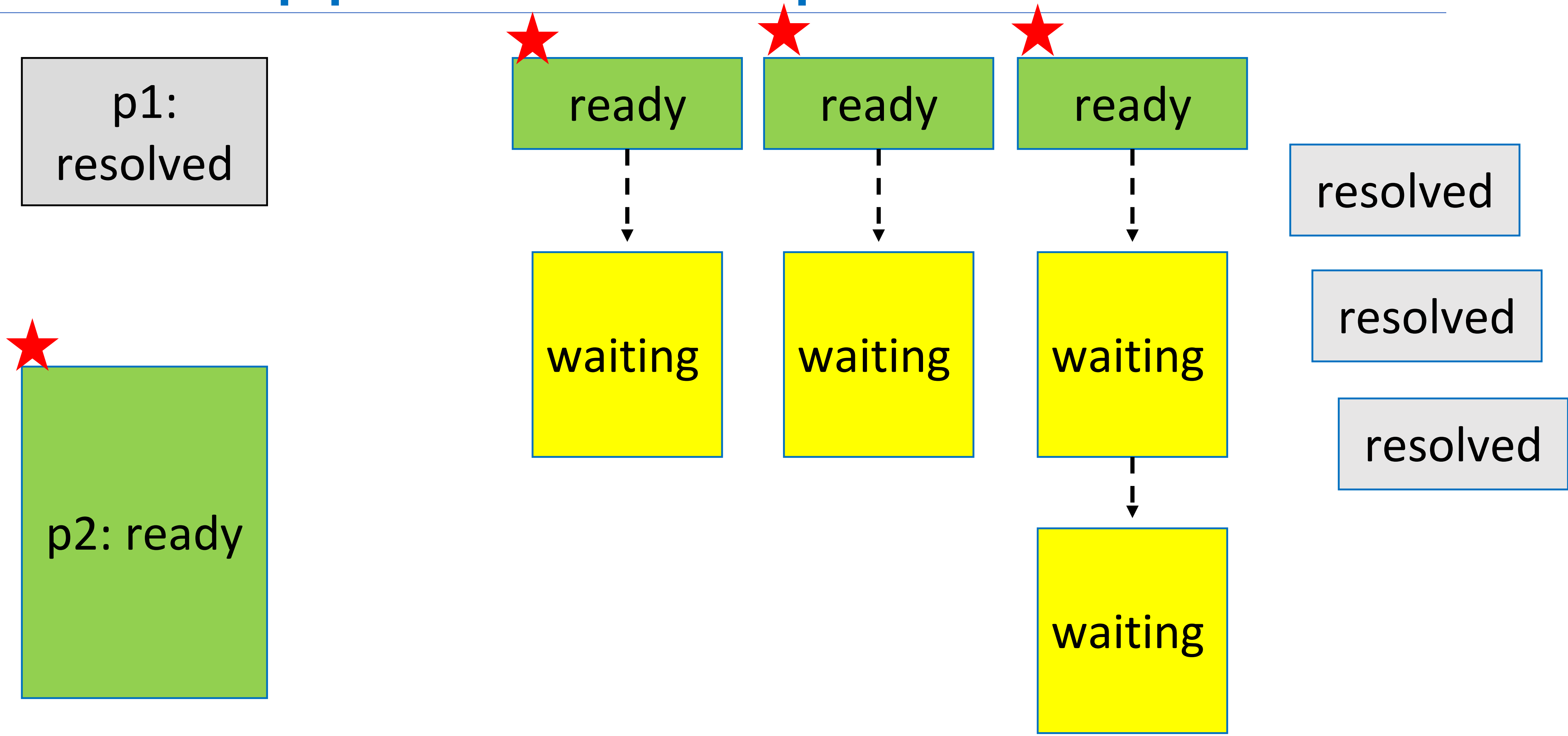
We divide pending promises into two classes

- **Ready**
  - This process is not waiting for any other promise, but is merely waiting to be selected for execution.
  - We color these promises green.
- **Waiting**
  - this promise can't be executed until some other process is resolved.
  - We color these promises yellow.

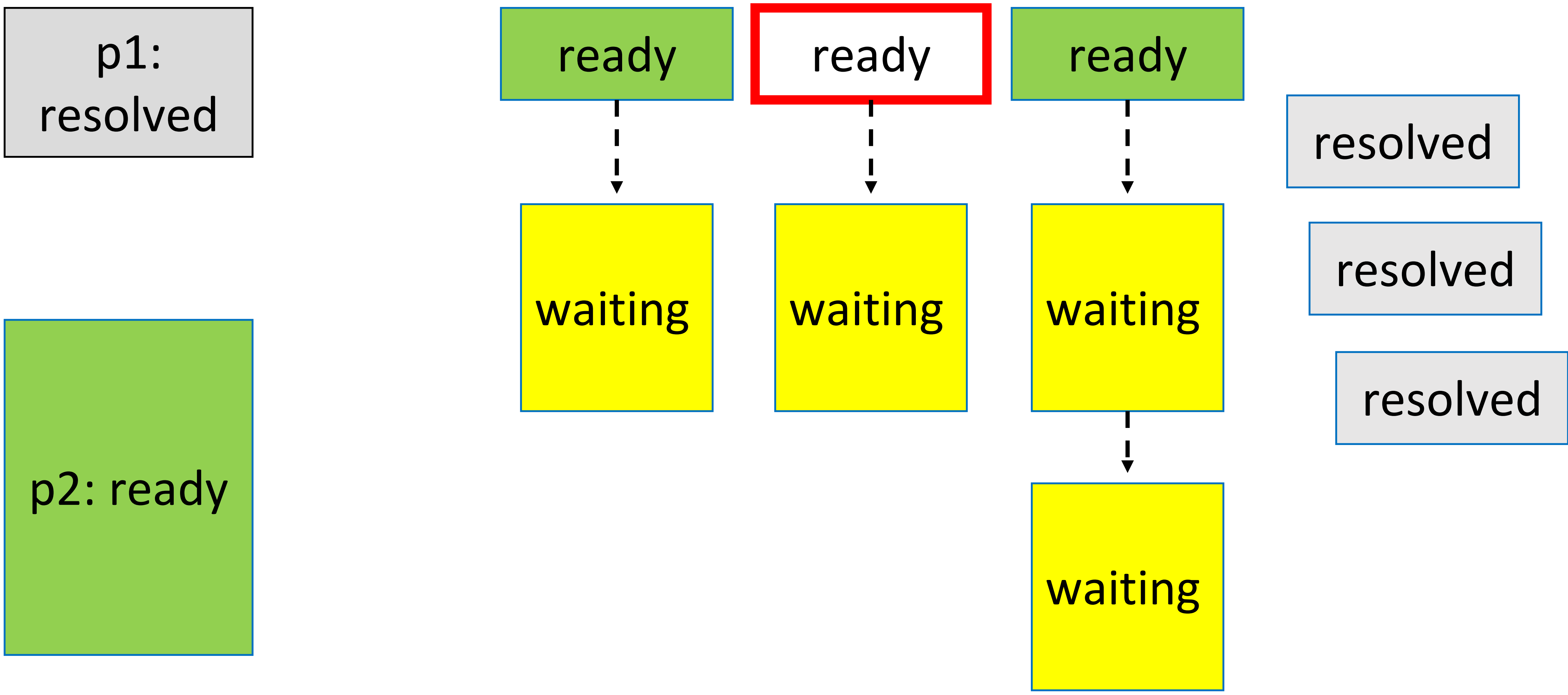
A snapshot of the thread pool



What happens when p1 finishes?



Here's one possibility



Computations always run until they are completed.

- Along the way, it may create promises that can be run anytime after the current computation is completed (i.e. they are in the "ready" state)
- It may also create promises that are in the "waiting" state-- waiting for some event, at which time they become "ready".
- When the current computation is completed (that is, it reaches an await or its end), the operating system (e.g. node.js) chooses some "ready" process to become the next current computation.

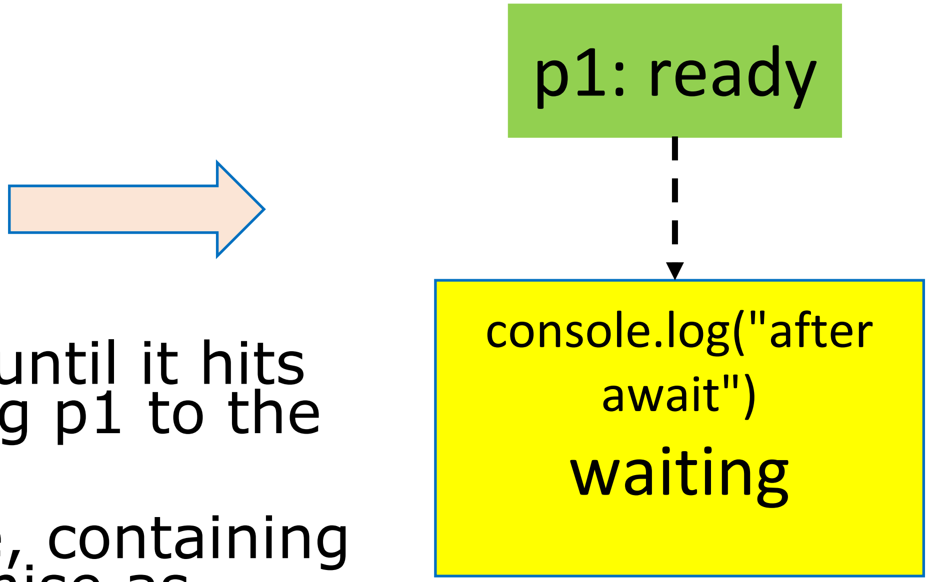
Where do promises come from?

- Typescript has primitives that create promises.
  - But you will never do this
- Some typescript libraries have API procedures that return promises
  - this is the usual way you'll get promises.
- Most of the time, you'll be building new promises out of the ones that are given to you.
- This is what async/await does…

src/async-await/asyncExample.ts

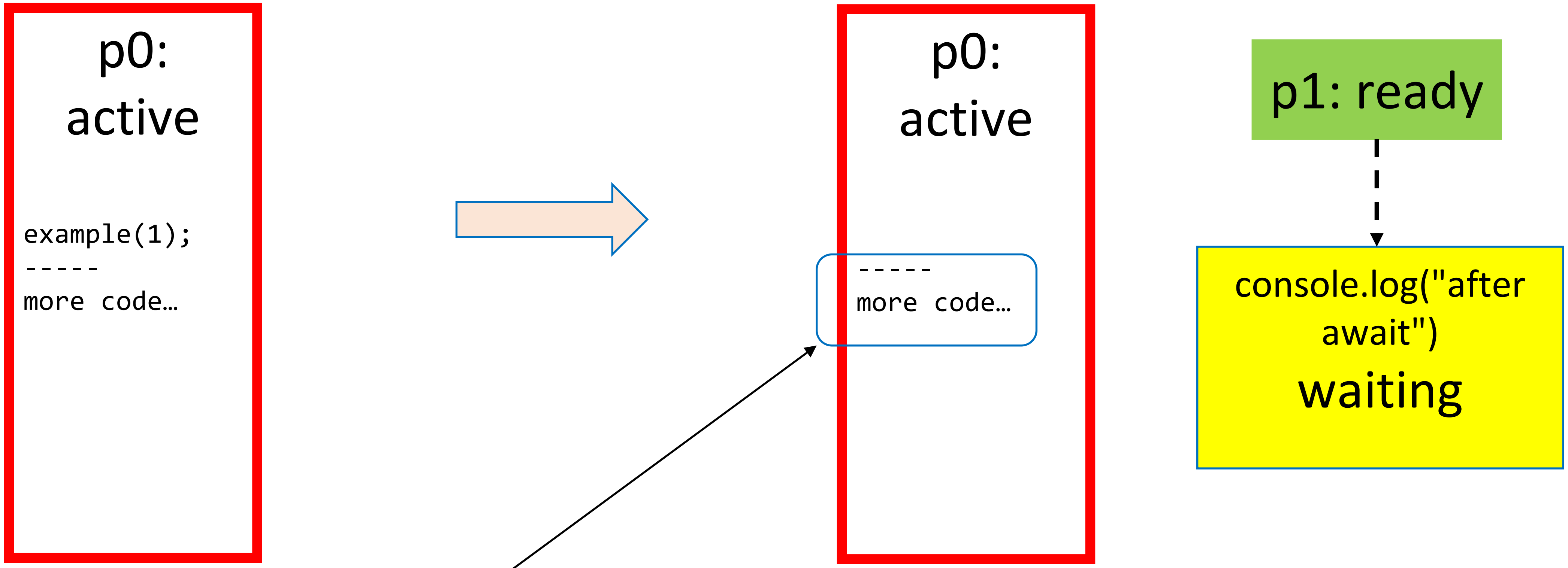
async/await creates a pair of promises.

```
export async function example (n:number) {
    console.log("doThisNow", n);
    const p1 = somePromise();
    const response = await p1
    console.log("doThisLater", n);
}
```



1. When called, this procedure executes normally until it hits the **await**, printing out "doThisNow" and binding p1 to the value of **somePromise()**.
2. When it hits the await, it creates a new promise, containing everything after the await, and marks that promise as waiting for p1.
3. It puts p1 (now with the yellow promise attached) into the promise pool. The yellow code is blocked.
4. The call to example(n) returns with the value of p1 (a promise)
5. The caller of example(n) then continues its execution

A bigger picture



"more code" is executed next ("Run to Completion");
meanwhile, p1 is waiting to be selected.

Simplest example

```
export async function
example(n:number) {
   console.log("doThisNow", n);
    const p1 = somePromise();
    const response = await p1
    console.log("doThisLater", n);
}
```

```
import { example } from "./asyncExample"

function main () {
    console.log("calling example(1)")
    example(1)
    console.log("main finished\n")
}

main()
```

```
$ npx ts-node example1.ts
calling example(1)
doThisNow 1
main finished

doThisLater 1
```

src/async-await/example1.ts

You can start multiple threads

src/async-await/example2.ts

```
import { example }
   from "./asyncExample";

async function main() {
    example(1)
    example(2)
    example(3)
    console.log("main finished\n")
}

main()
```

```
$ npx ts-node example2.ts
doThisNow 1
doThisNow 2
doThisNow 3
main finished

doThisLater 1
doThisLater 2
doThisLater 3
```

Use await to make promises execute sequentially

src/async-await/example3.ts

```
import { example }
  from "./asyncExample";

async function main() {
    await example(1)
    await example(2)
    await example(3)
    console.log("main finished\n")
}

main()
```

```
$ npx ts-node example3.ts
doThisNow 1
doThisLater 1
doThisNow 2
doThisLater 2
doThisNow 3
doThisLater 3
main finished
```

Use Promise.all to synchronize on the completion of several promises

```
async function forkJoin() {
    console.log("forkJoin started")
    const promises
     = [example(1), example(2), example(3)]
    console.log(promises)
    await Promise.all(promises)
    console.log("forkJoin finished\n")
}

async function main() {
    forkJoin()
    console.log("main finished\n")
}
```

```
$ npx ts-node example4.ts
forkJoin started
doThisNow 1
doThisNow 2
doThisNow 3
[ Promise { <pending> }, Promise {
<pending> }, Promise { <pending> } ]
main finished

doThisLater 1
doThisLater 2
doThisLater 3
forkJoin finished
```

src/async-await/example4.ts

But where does the non-blocking IO come from?

We achieve this goal using two techniques:

1. cooperative multiprocessing

2. non-blocking IO

Answer: JS/TS has some primitives for starting a non-blocking computation

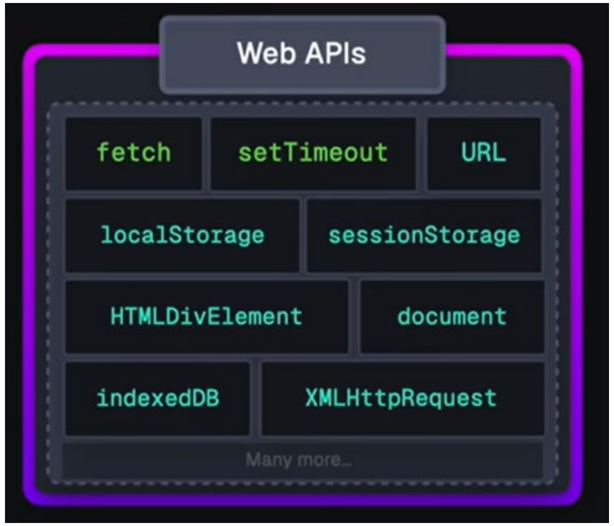
- These are things like http requests, I/O operations, or timers.
- We often use WebAPIs for these which allows us to run them on browser asynchronously
- Each of these returns a promise that you can **await**. The promise runs while it is pending, and produces the response from the http request, or the contents of the file, etc.
- You will hardly ever call one of these primitives yourself; usually they are wrapped in a convenient procedure, e.g., we write

```
axios.get('https://rest-example.covey.town’)
```

to make an http request, or

```
fs.readFile(filename)
```

to read the contents of a file.



Pattern for starting a concurrent computation

```
async function makeRequest(requestNumber:number) {
    // some code (to be executed now)
    const response =
      await axios.get('https://rest-example.covey.town')
    // more code (to be executed after the .get() returns.
}
```

- The http request is sent immediately.
- A promise is created to run the `more code` *after* the http call returns (i.e., the code after "awaits" is blocked)
- Control returns to the caller of `makeRequest.`
- The promises containing the green and yellow code are left in the promise pool.

The pattern in action

src/requests/example1.ts

```
export async function makeRequest(requestNumber:number) {
    console.log(`makeRequest is about to start request ${requestNumber}`);
    const response = await axios.get('https://rest-exa
    console.log(`makeRequest resumes request ${requestN
    console.log(`makeRequest reports that for request
response.data);
}

console.log("main thread is about to call makeRequest"
makeRequest(1000);
console.log("main thread continues after makeRequest re
console.log("end of main thread")
```

1. Axios.get starts the http request in the background, and
2. Creates a promise to do the code after the await.
3. The call to makeRequest returns.

```
$ npx ts-node example1
main thread is about to call makeRequest
makeRequest is about to start request 1000
main thread continues after makeRequest returns
end of main thread
makeRequest resumes request 1000
makeRequest reports that for request '1000', server replied:  This is GET number 200 on the current server
```

4. The main thread finishes.
5. The computation resumes the promise

Running several requests concurrently

src/requests/example2.ts

```
import makeRequest from './makeRequest';
import timeIt from './timeIt'

async function makeThreeSimpleRequests() {
    makeRequest(1);
    makeRequest(2);
    makeRequest(3);
    console.log("Three requests made; main thread finishes")
}

timeIt("main thread", makeThreeSimpleRequests)
```

Requests are made in order

But the response for request 3 arrived at the server before request 1.

```
$ npx ts-node example2
makeRequest is about to start request 1
makeRequest is about to start request 2
makeRequest is about to start request 3
Three requests made; main thread finishes
Elapsed time for main thread: 41.064 milliseconds
makeRequest reports that for request '3', server replied:  This is GET number 223
on the current server
makeRequest reports that for request '1', server replied:  This is GET number 224
on the current server
makeRequest reports that for request '2', server replied:  This is GET number 225
on the current server
```

```typescript
import makeRequest from './makeRequest';
import timeIt from './timeIt'

async function makeThreeSerialRequests() {
    await makeRequest(1);
    await makeRequest(2);
    await makeRequest(3);
    console.log("Three requests made; main thread finishes")
}

timeIt("main thread", makeThreeSerialRequests)
```

src/requests/example3.ts

await makes your code more sequential

```
$ npx ts-node example3
makeRequest is about to start request 1
makeRequest reports that for request '1', server rep
number 232 on the current server
makeRequest is about to start request 2
makeRequest reports that for request '2', server replied:  This is GET
number 233 on the current server
makeRequest is about to start request 3
makeRequest reports that for request '3', server replied:  This is GET
number 234 on the current server
Three requests made; main thread finishes
Elapsed time for main thread: 800.270 milliseconds
```

Second request doesn't start until to first request returns

Promise.all waits for all of the promises in a list to finish

```typescript
async function makeThreeConcurrentRequests() {
    const p1 : Promise<void> = makeRequest(1);
    const p2 : Promise<void> = makeRequest(2);
    const p3 : Promise<void> = makeRequest(3);
    const thePromises = [p1,p2,p3]
    await Promise.all(thePromises)
    console.log(`main thread reports: thePromises = [${thePromises}]`)
    console.log(`main thread finishes`)
}

timeIt("main thread", makeThreeConcurrentRequests)
```

src/requests/example4.ts

```
$ npx ts-node example5
makeRequest is about to start request 1
makeRequest is about to start request 2
makeRequest is about to start request 3
makeRequest reports that for request '2', server replied:  This is GET number 259 on the current server
makeRequest reports that for request '1', server replied:  This is GET number 260 on the current server
makeRequest reports that for request '3', server replied:  This is GET number 261 on the current server
main thread reports: thePromises = [[object Promise],[object Promise],[object Promise]]
main thread finishes
Elapsed time for main thread: 256.518 milliseconds
```

Main thread doesn't resume until ALL of the promises are satisfied

Visualizing Promise.all (1)

Sequential version: ~206 msec

```
async function makeThreeSerialRequests():
Promise<void> {
    await makeOneGetRequest(1);
    await makeOneGetRequest(2);
    await makeOneGetRequest(3);
    console.log('Heard back from all of the
requests')
}
```

"Don't make another request until you got the last response back"

Concurrent version: ~80 msec

```
async function makeThreeConcurrentRequests():
Promise<void> {
    await Promise.all([
        makeOneGetRequest(1),
        makeOneGetRequest(2),
        makeOneGetRequest(3)
    ])
    console.log('Heard back from all of the requests')
}
```

"Make all of the requests now, then wait for all of the responses"

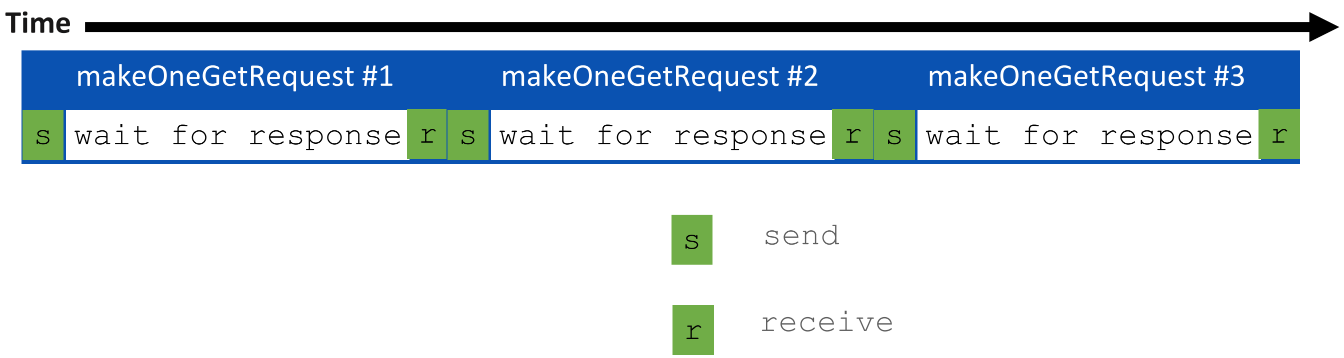
Visualizing Promise.all (2)

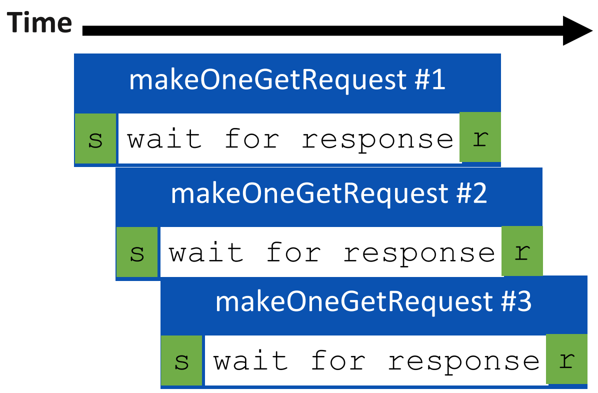
Sequential version: ~206 msec

```
async function makeThreeSerialRequests():
Promise<void> {
    await makeOneGetRequest(1);
    await makeOneGetRequest(2);
    await makeOneGetRequest(3);
    console.log('Heard back from all of the
requests')
}
```

Concurrent version: ~80 msec

```
async function makeThreeConcurrentRequests():
Promise<void> {
    await Promise.all([
        makeOneGetRequest(1),
        makeOneGetRequest(2),
        makeOneGetRequest(3)
    ])
    console.log('Heard back from all of the requests')
}
```





An Example Task Using the Transcript Server

- Given an array of StudentIDs:
  - Request each student’s transcript, and save it to disk so that we have a copy, and calculate its size
  - Once all of the pages are downloaded and saved, print out the total size of all of the files that were saved

Generating a promise for each student

```
async function asyncGetStudentData(studentID: number) {
    const returnValue =
     await axios.get(`https://rest-example.covey.town/transcripts/${studentID}`)
    return returnValue
}

async function asyncProcessStudent(studentID: number) : Promise<number> {
    // wait to get the student data
    const response = await asyncGetStudentData(studentID)
    // asynchronously write the file
    await fsPromises.writeFile(
        dataFileName(studentID),
        JSON.stringify(response.data))
    // last, extract its size
    const stats = await fsPromises.stat(dataFileName(studentID))
    const size : number = stats.size
    return size
}
```

Calling await also gives other processes a chance to run.

src/transcripts/simple.ts

Running the student processes concurrently

src/transcripts/simple.ts

```
async function runClientAsync(studentIDs:number[]) {
    console.log(`Generating Promises for ${studentIDs}`);
    const studentPromises =
      studentIDs.map(studentID => asyncProcessStudent(studentID)) ;
    console.log('Promises Created!');
    console.log('Satisfying Promises Concurrently')
    const sizes = await Promise.all(studentPromises);
    console.log(sizes)
    const totalSize = sum(sizes)
    console.log(`Finished calculating size: ${totalSize}`);
    console.log('Done');
  }
```

Map-promises pattern: take a list of elements and generate a list of promises, one per element

Output

```
runClientAsync([411,412,423])
```

```
$ npx ts-node simple.ts
Generating Promises for 411,412,423
Promises Created!
Satisfying Promises Concurrently
[ 151, 92, 145 ]
Finished calculating size: 388
Done
```

But what if there’s an error?

```
runClientAsync([411,412,87065,423,23044])
```

```
$ npx ts-node transcripts/simple.ts
Generating Promises for 411,412,87065,423,23044
Promises Created!
Satisfying Promises Concurrently

<blah blah blah>\node_modules\axios\lib\core\createError.js:16
  var error = new Error(message);
              ^
Error: Request failed with status code 404
```

Oops!

Need to catch the error

```
type StudentData = {isOK: boolean, id: number, payload?: any }

/** asynchronously retrieves student data,  */
async function asyncGetStudentData(studentID: number): Promise<StudentData> {
    try {
        const returnValue =
          await axios.get(`https://rest-example.covey.town/transcripts/${studentID}`)
        return { isOK: true, id: studentID, payload: returnValue }
    } catch (e) {
        return { isOK: false, id: studentID }
    }
}
```

Catch the error and transmit it in a form the rest of the caller can handle.

src/transcripts/handle-errors.ts

And recover from the error…

```
async function asyncProcessStudent(studentID: number): Promise<number> {
    // wait to get the student data
    const response = await asyncGetStudentData(studentID)
    if (!(response.isOK)) {
        console.error(`bad student ID ${studentID}`)
        return 0
    } else {
        await fsPromises.writeFile(
            dataFileName(studentID),
            JSON.stringify(response.payload.data))
        // last, extract its size
        const stats = await fsPromises.stat(dataFileName(studentID))
        const size: number = stats.size
        return size
    }
}
```

Design decision: if we have a bad student ID, we'll print out an error message, and count that as 0 towards the total.

src/transcripts/handle-errors.ts

New output

```
runClientAsync([411,32789,412,423,10202040])
```

```
$ npx ts-node transcripts/handle-errors.ts
Generating Promises for 411,32789,412,423,10202040
Promises Created!
Wait for all promises to be satisfied
bad student ID 32789
bad student ID 10202040
[ 151, 0, 92, 145, 0 ]
Finished calculating size: 388
Done
```

Pattern for testing an async function

```
import axios from 'axios'

async function echo(str: string) : Promise<string> {
    const res =
        await axios.get(`https://httpbin.org/get?answer=${str}`)
    return res.data.args.answer
}

test('request should return its argument', async () => {
    expect.assertions(1)
    await expect(echo("33")).resolves.toEqual("33")
})
```

src/jest/jest-example.test.ts

General Rules for Writing Asynchronous Code

- You can't return a value from a promise to an ordinary procedure.
  - You can only send the value to another promise that is awaiting it.
- Call async procedures only from other async functions or from the top level.
- Break up any long-running computation into **async/await** segments so other processes will have a chance to run.
- Leverage concurrency when possible
  - Use **promise.all** if you need to wait for multiple promises to return.
- Check for errors with **try/catch**

Optional Material

src/data-races/dataRace.ts

This is not Java!

```
let x : number = 10

async function asyncDouble() {
    // start an asynchronous computation and wait for the result
    await makeOneGetRequest(1);
    x = x * 2  // statement 1
}


async function asyncIncrementTwice() {
    // start an asynchronous computation and wait for the result
    await makeOneGetRequest(2);
    x = x + 1;   // statement 2
    // nothing can happen between these two statements!!
    x = x + 1;   // statement 3
}

async function run() {
    await Promise.all([asyncDouble(), asyncIncrementTwice()])
    console.log(x)
}
```

- In Java, you could get an interrupt between statement 2 and statement 3.
- In TS/JS statement 3 is guaranteed to be executed *immediately* after statement 2!
- No interrupt is possible.

src/data-races/dataRace.ts

But you can still have a data race

```
let x : number = 10

async function asyncDouble() {
    // start an asynchronous computation and wait for the result
    await makeOneGetRequest(1);
    x = x * 2  // statement 1
}


async function asyncIncrementTwice() {
    // start an asynchronous computation and wait for the result
    await makeOneGetRequest(2);
    x = x + 1;   // statement 2
    x = x + 1;   // statement 3
}

async function run() {
    await Promise.all([asyncDouble(), asyncIncrementTwice()])
    console.log(x)
}
```

Async/await code is compiled into promise/then code

```
async function
makeThreeSerialRequests(){
1.   console.log('Making first
request’);
2.   await makeOneGetRequest();
3.   console.log('Making second
request’);
4.   await makeOneGetRequest();
5.   console.log('Making third
request’);
6.   await makeOneGetRequest();
7.   console.log('All done!');
}
makeThreeSerialRequests();
```

```
console.log('Making first request');
makeOneGetRequest().then( () =>{
  console.log('Making second request');
  return makeOneGetRequest();
}).then(() => {
  console.log('Making third request');
  return makeOneGetRequest();
}).then(()=>{
  console.log('All done!');
});
```

Promises Enforce Ordering Through “Then”

```
1. console.log('Making requests');
2. axios.get('https://rest-example.covey.town/')
    .then((response) =>{
        console.log('Heard back from server');
        console.log(response.data);
   });
3. axios.get('https://www.google.com/')
      .then((response) =>{
       console.log('Heard back from Google');
      });
4. axios.get('https://www.facebook.com/')
      .then((response) =>{
        console.log('Heard back from Facebook');
      });
5. console.log('Requests sent!');
```

- **axios.get** returns a promise.
- **p.then** mutates that promise so that the then block is run immediately after the original promise returns.
- The resulting promise isn’t completed until the then block finishes.
- You can chain .**then**’s, to get things that look like p.then().then().then()

Async/Await Programming Activity

- We have an activity that extends the transcript example we showed in this module.
- Details are linked from the Module 6 web page.

Review

- You should now be prepared to:
  - Explain the difference between JS run-to-completion semantics and interrupt-based semantics.
  - Given a simple program using async/await, work out the order in which the statements in the program will run.
  - Write simple programs that create and manage promises using async/await
  - Write simple programs to mask latency with concurrency by using non-blocking IO and Promise.all in TypeScript.