CS 4530: Fundamentals of Software Engineering

Module 6: Concurrency Patterns in Typescript

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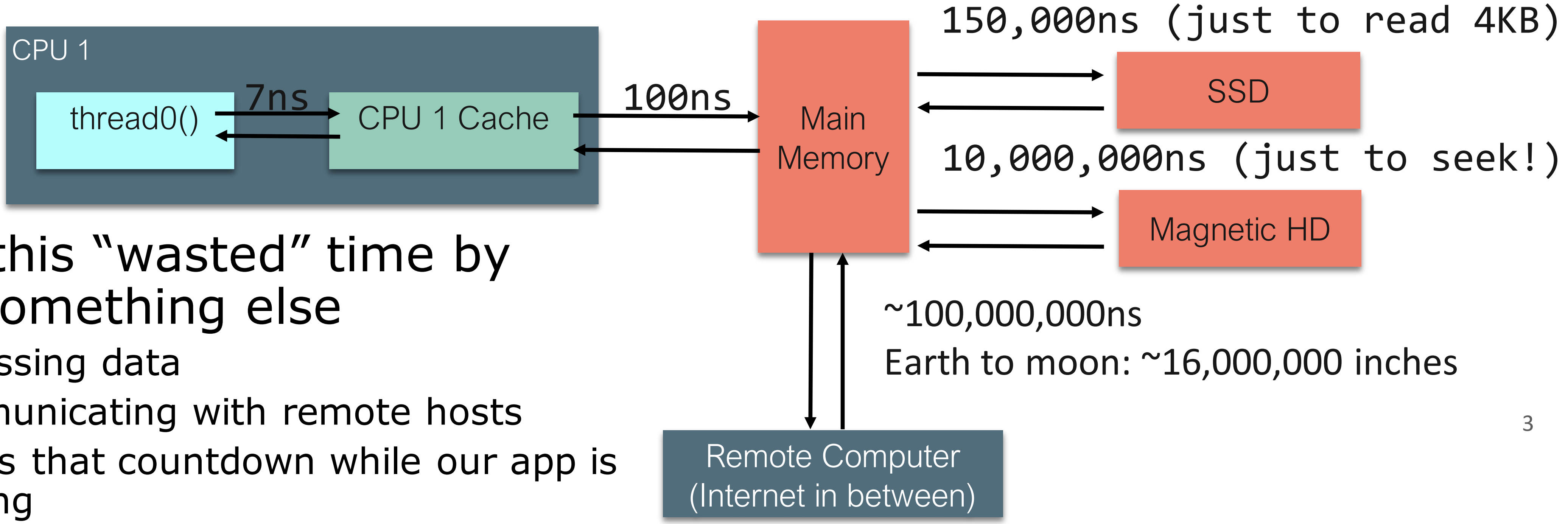
Learning Goals for this Lesson

- At the end of this lesson, you should be prepared to:
  - Explain how to achieve concurrency through asynchronous operations and Promise.all in TypeScript.
  - Write asynchronous and concurrent code in TypeScript using async/await and Promise.all.
  - Explain the difference between JS run-to-completion semantics and interrupt-based semantics.

Masking Latency with Concurrency

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


CPU 1
thread0()
7ns
CPU 1 Cache
100ns
Main Memory
150,000ns (just to read 4KB)
SSD
10,000,000ns (just to seek!)
Magnetic HD
~100,000,000ns
Earth to moon: ~16,000,000 inches
Remote Computer (Internet in between)

- Utilize this “wasted” time by doing something else
  - Processing data
  - Communicating with remote hosts
  - Timers that countdown while our app is running
  - Waiting for users to provide input

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.)

An alternative model: cooperative multiprocessing

- OS manages multiprocessing with multiple threads of execution
- In Typescript, these “threads” are called **promises**.
- Each thread decides when it should ***yield*** to let other threads execute
- Typically, via a **yield** or **await** operation

A computation is not suspended until it hits an ‘await’ or finishes.

- A computation is suspended when it hits an ‘await’. The runtime system (node.js, for us) chooses what to do next.
- This means that a computation runs **continuously** until it is either suspended or completed.

This is known as “Run to Completion”

JavaScript is **Single-threaded** language (with one call stack and one memory heap) and it uses **WebAPI** to run **asynchronous** tasks

But where does the concurrency come from?

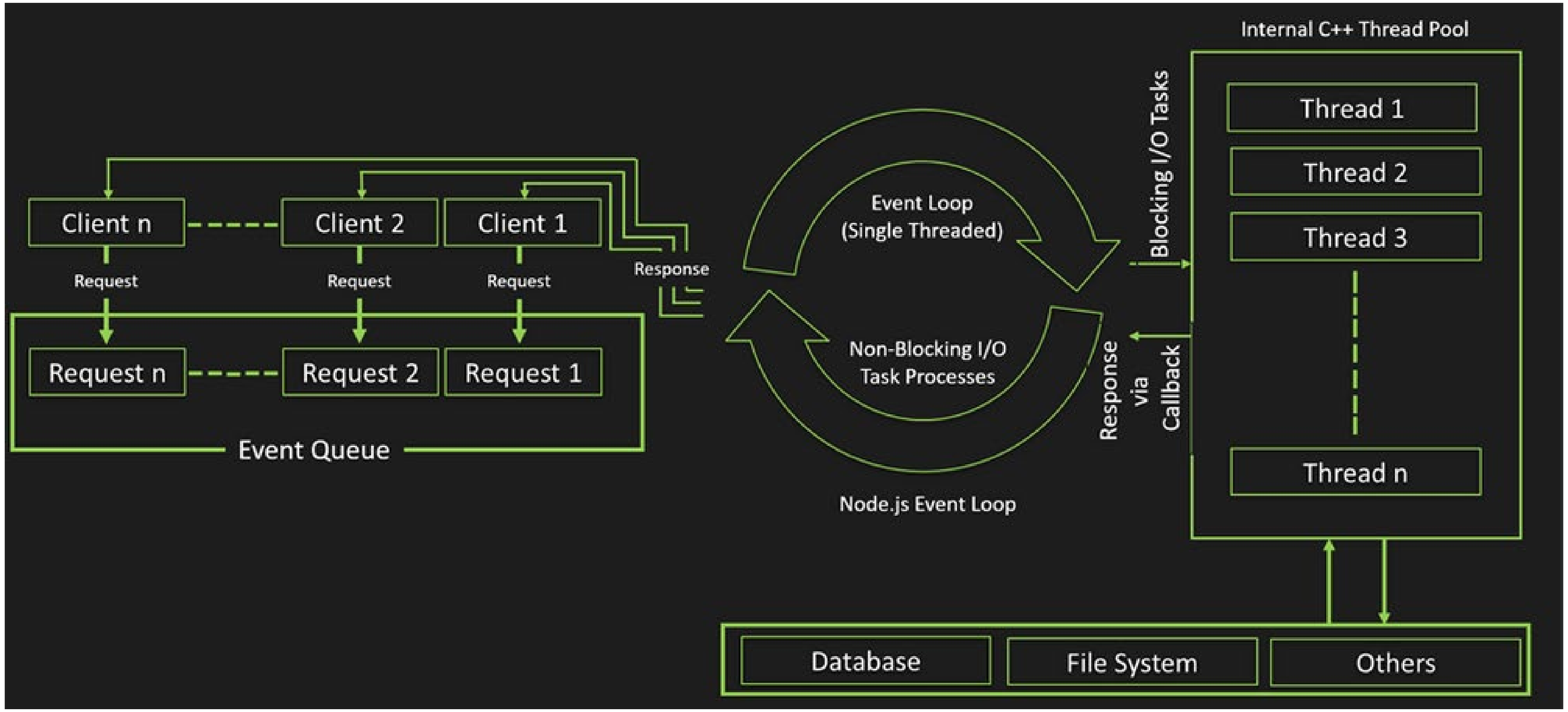


Diagram courtesy of c-sharpcorner.com

Answer: JS/TS has some primitives for starting a concurrent computation

- These are things like http requests, I/O operations, or timers.
- 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.

Defining a concurrent computation

```
async function makeOneGetRequest(requestNumber:number) {
    const response = await axios.get('https://rest-example.covey.town');
    console.log(`For request ${requestNumber}, server replied: `, 
response.data);
}
```

This is the address of a server that returns the number of calls that have been made to this server.

- An async function is a function that creates a concurrent computation. Calling the function will tell the OS to start the computation.
- 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)
- The call to makeOneGetRequest returns immediately.

One concurrent computation can wait for the result of another one.

```
async function makeOneGetRequest(requestNumber:number) {
    const response = await axios.get('https://rest-example.covey.town');
    console.log(`For request ${requestNumber}, server replied: `,
response.data);
}
```

- Axios.get is also an async function, so it returns a promise (let’s call it **p**)
- The **await** suspends the current computation until the response is received (or the promise **p** is resolved or rejected).
- While the current computation is suspended, other computations (including **p**) can run.

example1.ts

The pattern in action

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

This makes it simple to run several concurrent 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
```

example3.ts

```
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)
```

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

Promises are values; async functions return promises

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

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

example4.ts

So, you can make lists of them!

```
$ npx ts-node example4
makeRequest is about to start request 1
makeRequest is about to start request 2
makeRequest is about to start request 3
main thread reports: thePromises = [[object Promise],[object Promise],[object Promise]]
main thread finishes
Elapsed time for main thread: 36.501 milliseconds
makeRequest reports that for request '2', server replied:  This is GET number 248 on the current server
makeRequest reports that for request '3', server replied:  This is GET number 247 on the current server
makeRequest reports that for request '1', server replied:  This is GET number 249 on the current server
```

Promise.all allows you to wait for all of the promises in a list to finish

```
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)
```

example5.ts

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

```
$ 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
```

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”

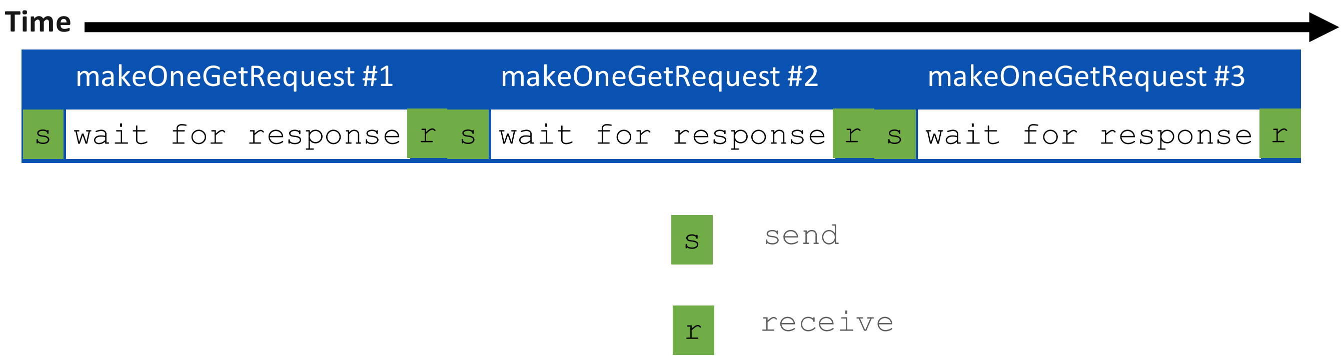
Visualizing Promise.all (2)

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')
}
```



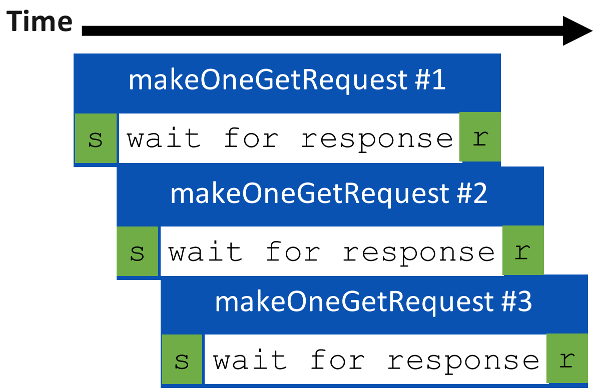
Time

makeOneGetRequest #1 | makeOneGetRequest #2 | makeOneGetRequest #3

s wait for response r s wait for response r s wait for response r

s send

r receive



Time

makeOneGetRequest #1

s wait for response r

makeOneGetRequest #2

s wait for response r

makeOneGetRequest #3

s wait for response r

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 gives other processes a chance to run.

Running the student processes concurrently

```
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 transcript-v2.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 transcript-v2.simple.ts
Generating Promises for 411,412,87065,423,23044
Promises Created!
Satisfying Promises Concurrently

C:\Users\wand\OneDrive\Documents\Work\Courses\CS 4530
Future\My Modules Workspace\Module 05 Concurrency
Patterns\Examples\Lecture05-
Async\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.

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.

New output

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

```
$ npx ts-node transcript-v2.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")
})
```

General Rules for Writing Asynchronous Code

- You can’t return a value from an async procedure to an ordinary procedure.
  - 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**

Odds and Ends You Should Know About

Async/await code is compiled into promise/then code

```
async function makeThreeSerialRequests(){
    console.log('Making first request’);
    await makeOneGetRequest();
    console.log('Making second request’);
    await makeOneGetRequest();
    console.log('Making third request’);
    await makeOneGetRequest();
    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()

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)
}
```

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)
}
```

The Self-Ticking Clock

- To make the clock self-ticking, add the following line to your clock:

```
constructor () {
  setInterval(() => {this.tick()},50)
}
```

Async/Await Programming Activity

- Your task is to write a new async function, importGrades, which takes in input of the type ImportTranscript[].
- importGrades should create a student record for each ImportTranscript, and then post the grades for each of those students.
- After posting the grades, it should fetch the transcripts for each student and return an array of transcripts.

Download the activity (includes instructions in README.md):
Linked from course webpage for Module 5

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  - Explain the difference between JS run-to-completion semantics and interrupt-based semantics.