CS 4530: Fundamentals of Software Engineering

Module 06: Concurrency Patterns in Typescript

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Asynchronous Programming: we've been teaching it all wrong (again)

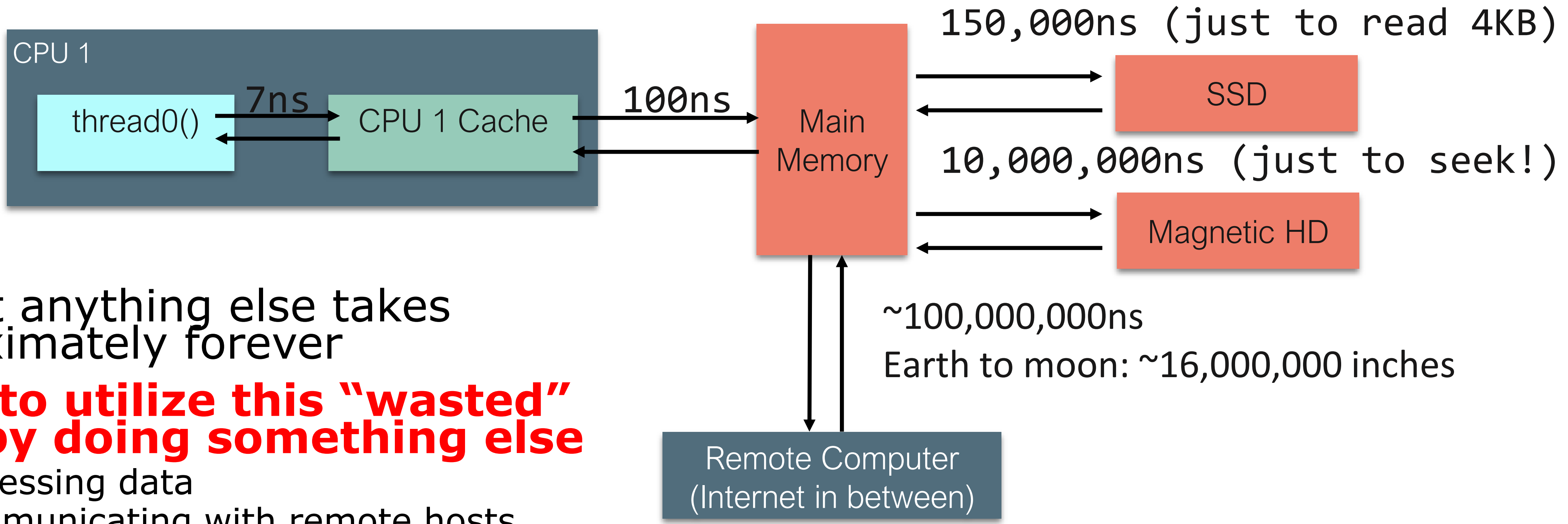
- This slide is me explaining what's going on in this deck; it is not for distribution to students.
- I finally that trying to explain async programming in terms of promises is like explaining typescript in terms of assembly language: it's just the *wrong level*
- Among other things, it fails to emphasize that you can determine the points at which your execution can be interrupted is *statically determinable".
- These slides *start* by explaining what the uninterruptible segments of your program are.
- So we take "run to completion" as a fundamental concept (explaining that it's a misnomer), and go on from there.
- See if you think this could work!!

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.

Your app probably spends most of its time waiting

- Consider: a 1Ghz CPU executes an instruction every 1 ns



- Almost anything else takes approximately forever
- **Want to 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**

- In cooperative multiprocessing, only one process is executed at a time.
- Each process pauses when it is convenient to allow other processes to make progress.
- To make this practical (and avoid cheating!), we need a programming model that encourages this behavior

async/await: a programming model for cooperative multiprocessing

- In async/await, the program is organized into a set of "async functions".
- An async function is like an ordinary function, except that it will pause at two well-defined points in its execution.
- When one program pauses, the runtime can choose to resume executing any process that is ready to run.

A typical async function

```
async function someFunction(i: number) {
    const j = i + 1;
    // ...
    const k = await someOtherAsyncFunction(j);
    // ...
    const m = k + 100
    return m;
}
```

An async function can pause in exactly two places

```
async function someFunction(i: number) {
    const j = i + 1;
    // ...
    const k = await someOtherAsyncFunction(j);
    // ...
    const m = k + 100
    return m;
}
```

HERE

AND HERE

Those are the ONLY places an async function can pause.

```
async function someFunction(i: number) {
    const j = i + 1;
    // ...
    const k = await someOtherAsyncFunction(j);
    // ...
    const m = k + 100;
    return m;
}
```

Never in here

Or in here

Terminology: promises and run-to-completion

- The units of work between two pause points is called a "promise"
- The pattern we've just talked about is called "run-to-completion" semantics, because a pause point corresponds exactly to the end of one of these units of work
- You can do lots of different things with promises.
- Let's look some typical patterns.

Example:

src/XXXXX/oneRequest.ts

```
// fakeRequest(n) is an async that waits for 1 second and then
// resolves with the number n+10
import { fakeRequest } from "./fakeRequest";
import { timeIt } from "./timeIt";

async function main() {
    console.log('main started');
    const request = 32
    const res = await fakeRequest(request);
    console.log(`fakeRequest(${request}) return
    console.log('main done');
}

timeIt(main)
```

```
$ npx ts-node oneRequest.ts
main started
fakeRequest received request: 32
time passes....
fakeRequest(32) returned: 42
main done
1015.98 msec
```

Use Promise.all to execute several requests concurrently

```
async function main() {
    console.log('starting main');
    const promises = [fakeRequest(1),
                      fakeRequest(2),
                      fakeRequest(3)];
    const results = await Promise.all(promises);
    console.log('results:', results);
    console.log('main done');
}

timeIt(main)
```

```
$ npx ts-node
threeRequestsConcurrently.ts
starting main
fakeRequest received request: 1
time passes....
fakeRequest received request: 2
time passes....
fakeRequest received request: 3
time passes....
results: [ 11, 12, 13 ]
main done
1018.81 msec
```

If you add awaits, the requests will be processed sequentially

```
async function main() {
    console.log('starting main');
    const res1 = await fakeRequest(1);
    console.log(`fakeRequest(1) returned: ${res1
    const res2 = await fakeRequest(2);
    console.log(`fakeRequest(2) returned: ${res2
    const res3 = await fakeRequest(2);
    console.log(`fakeRequest(2) returned: ${res3
    console.log('main done');


}

timeIt(main)
```

```
$ npx ts-node
threeRequestsSequentially.ts
starting main
fakeRequest received request: 1
time passes....
fakeRequest(1) returned: 11
fakeRequest received request: 2
time passes....
fakeRequest(2) returned: 12
fakeRequest received request: 3
time passes....
fakeRequest(3) returned: 13
main done
3024.03 msec
```

src/XXXXX/threeRequestsSequentially.ts

…but it would be much slower

```
$ npx ts-node timeComparison.ts
After 100 runs of length 10
makeRequestsConcurrently: min = 23  avg = 34 max = 190 milliseconds
makeRequestsSerially    : min = 210  avg = 237 max = 812 milliseconds
```

Need to redo with this semester's examples

Why is that?
Visualizing Promise.all

Sequential (await)

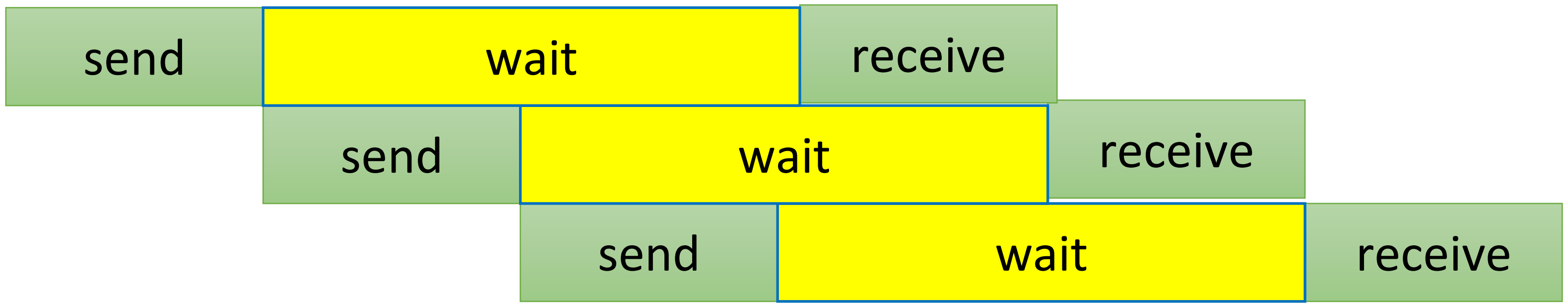
“Don’t make another request until you got the last response back”

237 msec

Concurrent (Promise.all)

“Make all of the requests now, then wait for all of the responses”

34 msec



Requests can also be chained

```
async function main() {
    console.log('main started');
    const request1 = 32
    const res1 = await fakeRequest(request1);
    console.log(`fakeRequest(${request1}) returned: ${res
    const res2 = await fakeRequest(res1);
    console.log(`fakeRequest(${res1})returned: ${res2}`);
    const res3 = await fakeRequest(res2);
    console.log(`fakeRequest(${res2})returned: ${res3}`);
    console.log([request1, res1, res2, res3]);
    console.log('main done');
}
```

```
$ npx ts-node
threeRequestsChained.ts
main started
fakeRequest received request: 32
time passes....
fakeRequest(32) returned: 42
fakeRequest received request: 42
time passes....
fakeRequest(42)returned: 52
fakeRequest received request: 52
time passes....
fakeRequest(52)returned: 62
[ 32, 42, 52, 62 ]
main done
3080.99 msec
```

Recover from errors with try/catch

```
// a request that may fail
async function maybeFailingRequest(req: number): Promise<number> {
    const res = await fakeRequest(req);
    if (res < 0) {
        throw new Error(`Request ${req} failed because response ${res} < 0`);
    } else {
        return res;
    }
}
```

try/catch, continued

```
async function main() {
    console.log('main started');
    const req1 = -32
    let res: number;
    try {
        res = await maybeFailingRequest(req1);
        console.log(`fakeRequest(${req1}) returned: ${res}`);
    } catch (err) {
        console.error(`Error occurred for request ${req1}`);
        res = 0
    }
    console.log('main done with res =',
}

timeIt(main);
```

```
$ npx ts-node tryCatchExample.ts
main started
fakeRequest received request: -32
time passes....
Error occurred for request -32
main done with res = 0
1007.52 msec
```

Pattern for testing an async function

```
test('fakeRequest should return its argument + 10', async () => {
    expect.assertions(1)
    await expect(fakeRequest(33)).resolves.toEqual(43)
})

// this will succeed, because it does not await the promise
test('bogus test', async () => {
    // expect.assertions(1)
    expect(fakeRequest(33)).resolves.toEqual(99)
})
```

src/XXX/jest-example.test.ts

src/XXXXX/oneRequestNoAwait.ts

AntiPattern 1: un**await**ed promise

```typescript
// fakeRequest(n) is an async that waits for 1 second and then
// resolves with the number n+10
import { fakeRequest } from "./fakeRequest";
import { timeIt } from "./timeIt";

async function main() {
    console.log('main started');
    const request = 32
    const res = fakeRequest(request);
    console.log(`fakeRequest(${request}) returned: ${res}`);
    console.log('main done');
}

timeIt(main)
```

```
$ npx ts-node oneRequestNoAwait.ts
main started
fakeRequest(32) returned: [object Promise]
main done
2.64 msec
fakeRequest received request: 32
time passes....
```

What just happened?

```
$ npx ts-node oneRequestNoAwait.ts
main started
fakeRequest(32) returned: [object Promise]
main done
2.64 msec
fakeRequest received request: 32
time passes....
```

1. main() called fakeRequest(32).
2. fakeRequest(32) created a unit of work (a Promise), and told the runtime to run it sometime or other.
3. Normally, we wouldn't see the actual value returned by fakeRequest(32), because we'd just wait for the unit of work to run before proceeding.
4. But here, we didn't wait-- we just took the value returned by fakeRequest(32)-- the Promise-- and printed it.
5. We finished our current unit of work, printing "main done", which informed the runtime that we were done.
6. The runtime then looked around for another unit of work to do. In this case, it found the unit of work created by fakeRequest(32), and ran it, printing the last two lines

Wow! That was complicated!

- We try to make our code easy to understand.
- That's why it's an antipattern.
- Luckily, in real code we don't need to do this very often

AntiPattern1a: async with no await

```
async function main() {
    console.log('main started');
    const request = 32
    const res = fakeRequest(request);
    console.log(`fakeRequest(${request}) returned: ${res}`);
    console.log('main done');
}
```

AntiPattern 2: Side-effect before **await**

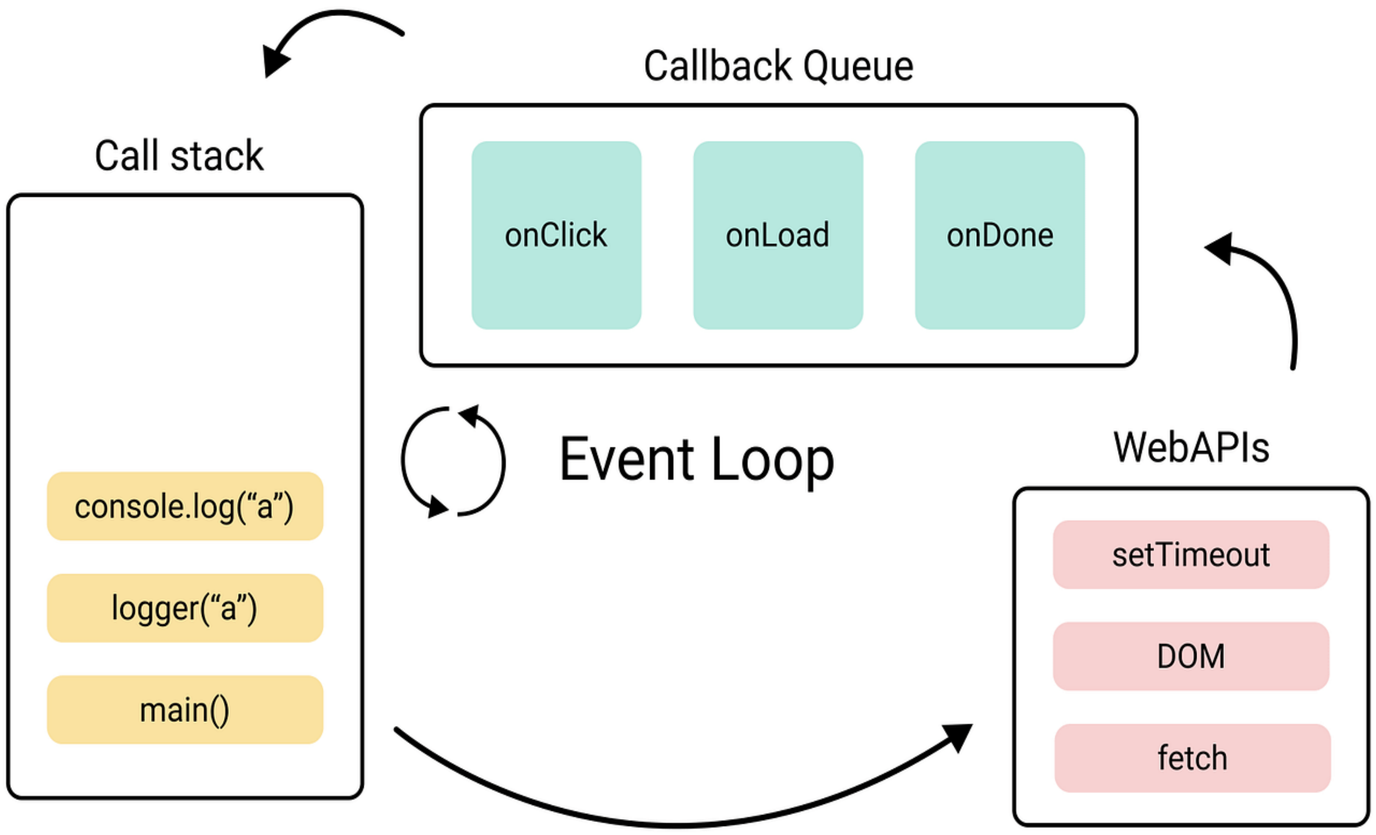
```
async function f() {
    console.log('f started');
    await g();
    console.log('f done');
}

async function g() {
    console.log('g started');
    const res = await fakeRequest(32);
    console.log(`fakeRequest(32) returned:
${res}`);
}
```

These two are actually part of the *same* critical section

How does JS Engine make this happen?

- One Event Loop means that we have single thread of execution
- WebAPI are used for asynchronous tasks
- Queues are used for “await”-ing tasks
- When call stack gets empty, event loop picks up tasks from Callback Queue



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

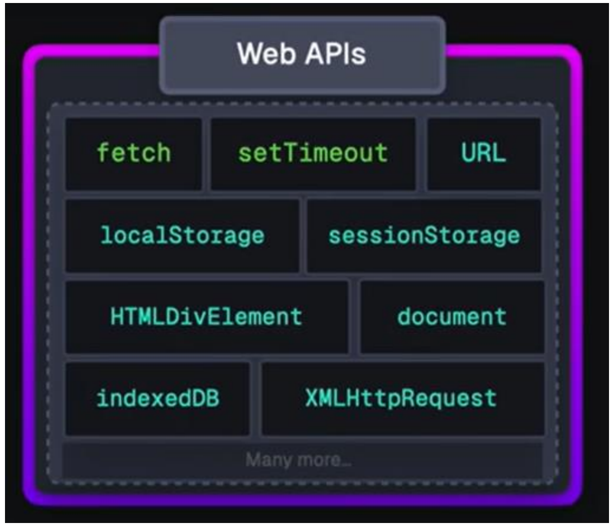
- These are things like http requests, I/O operations, or timers.
- Each of these returns a promise that you can **await**. The promise runs while it is pending, and produces the response from the http request, or the contents of the file, etc.
- You will hardly ever call one of these primitives yourself; 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.



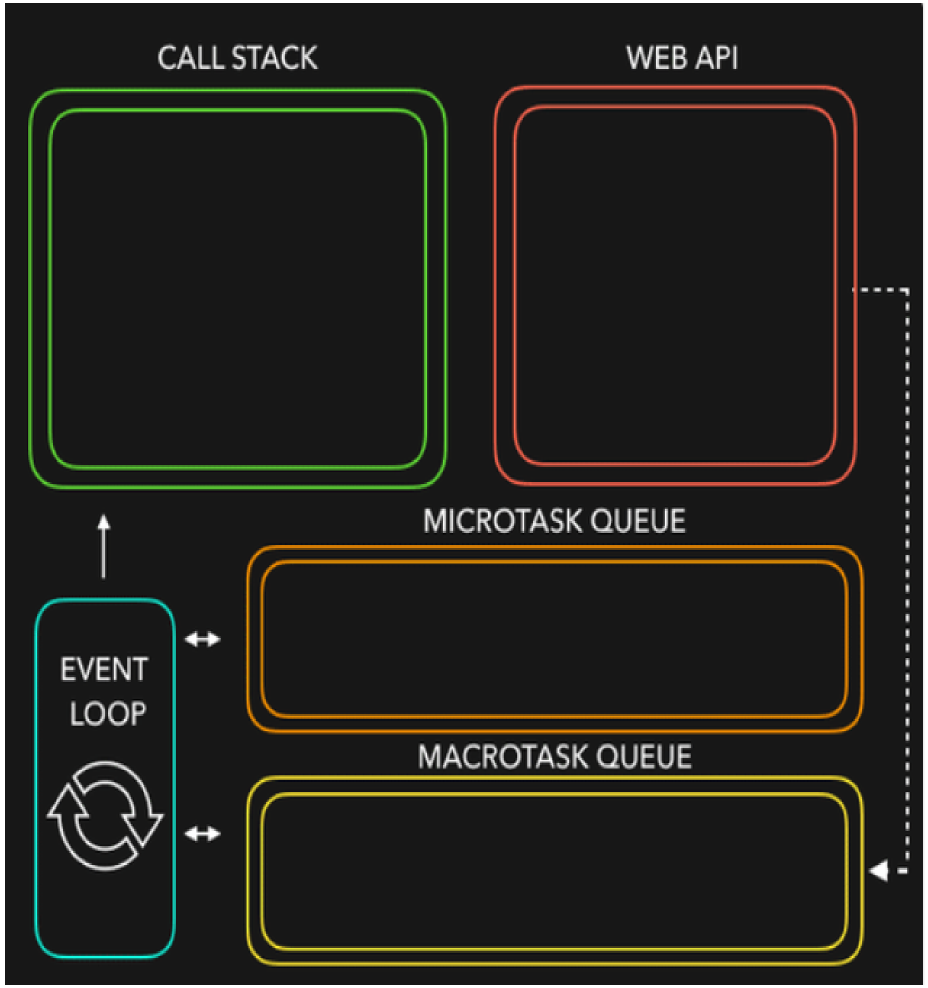
Pattern for starting a concurrent computation using non-blocking I/O

```
export async function makeRequest(requestNumber:number) {
    console.log(`starting makeRequest(${requestNumber})`);
    const response = await axios.get('https://rest-example.covey.town');
    console.log('request:', requestNumber, '\nresponse:', response.data);
}
```

1. The first console.log is printed
2. The http request is sent, using non-blocking i/o
3. A promise is created to run the second console.log *after* the axios.get returns
4. The makeRequest() returns to its caller.

Let’s put it all together

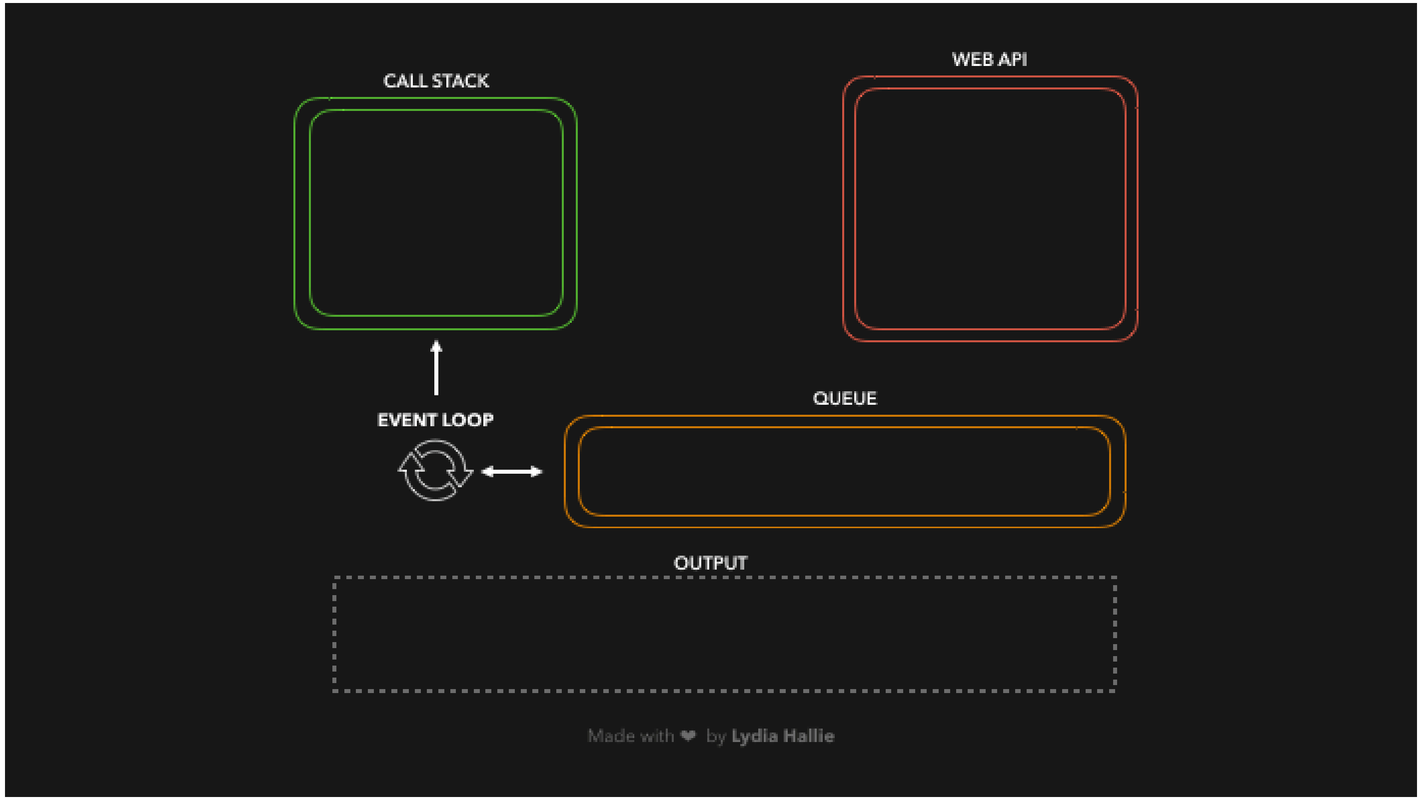
- JS/TS has single event loop
- We outsource most of the non-blocking IO work (to WebAPIs) for asynchronous work
- Upon completion, they are placed in queues (Microtask queue has priority over Macrotask queue)
- Event loop picks them up from queue when call stack is empty!



Here is a quick demo for you

```
const foo = () => console.log("First");
const bar = () => setTimeout(() => console.log("Second"), 500);
const baz = () => console.log("Third");

bar();
foo();
baz();
```



Courtesy of https://dev.to/lydiahallie/javascript-visualized-event-loop-3dif

Everything after here is old

- We'll consider what changes should be made (if any!)
- I don't like being dependent on a transcript server that we don't control.

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**

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 here also gives other processes a chance to run.

src/transcripts/simple.ts

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

src/transcripts/simple.ts

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
```

Odds and Ends You Should Know About

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(){
    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()

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

Download the activity (includes instructions in README.md):
Linked from course webpage for Module 6

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.

Javascript/Typescript uses **cooperative multiprocessing //old..**

- Typescript maintains a pool of processes, called **promises**.
- A promise *always* executes until it reaches its end (i.e., *a promise cannot be interrupted*).
- 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 3 states

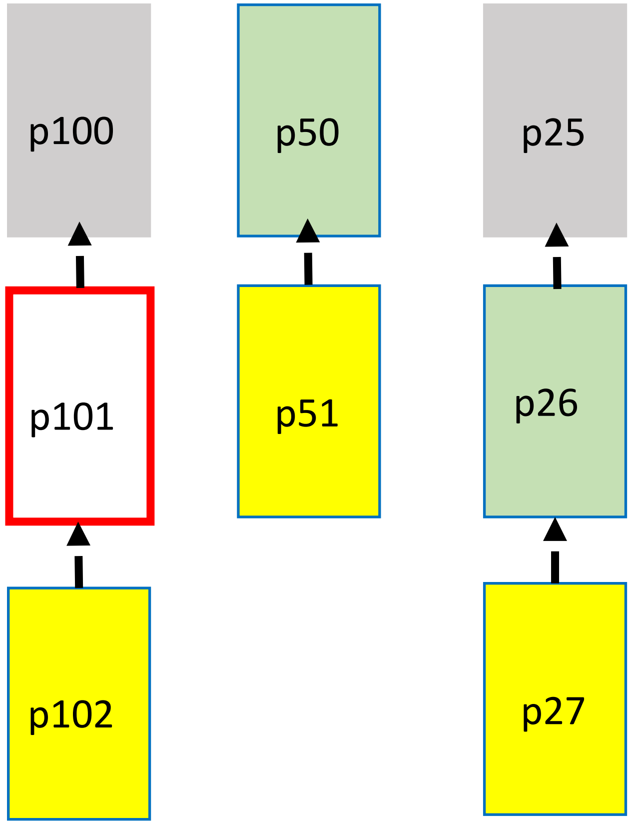
- A JavaScript promise can be in one of three states: pending, fulfilled, or rejected.
- Pending is the initial state where the promise is ***waiting*** for an operation to complete;
- Resolved: either fulfilled or rejected.
  - fulfilled means the operation was successful,
  - rejected indicates that the operation failed.

Subcategories of Pending Promises

- Waiting: pending, and some of the operations it was waiting for have not yet completed
- Ready for Execution: pending, but all the operations it was waiting for have completed
- Executing: pending (not resolved), but the code of the promise is currently being executed

- There can be at most **one** executing promise at any time

A snapshot of the promise pool



The grey promises are fulfilled

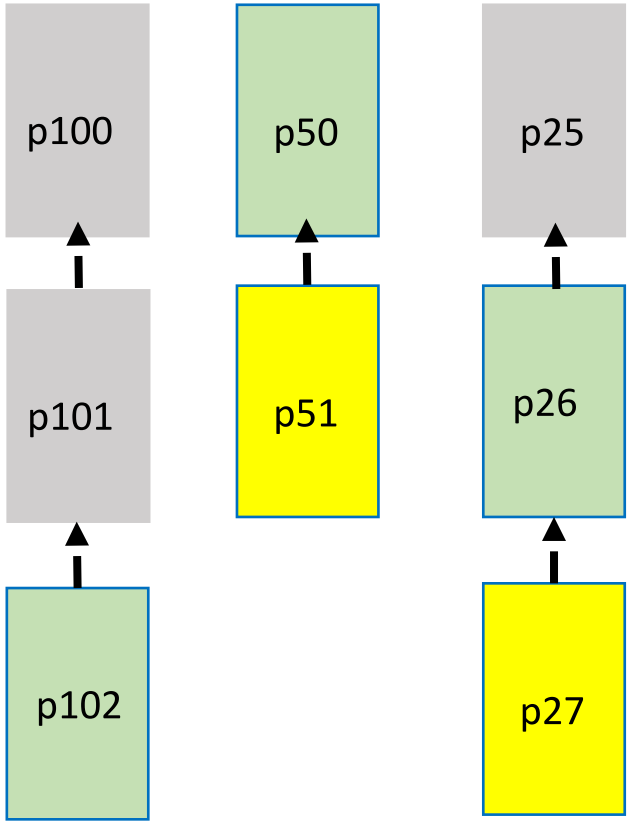
The green promises are pending and ready

The yellow promises are waiting.

The white promise is the currently executing promise

The arrows indicate that one promise is waiting for another

When the currently executing promise succeeds, the pool will look like this:



The grey promises are fulfilled

The green promises are pending and ready

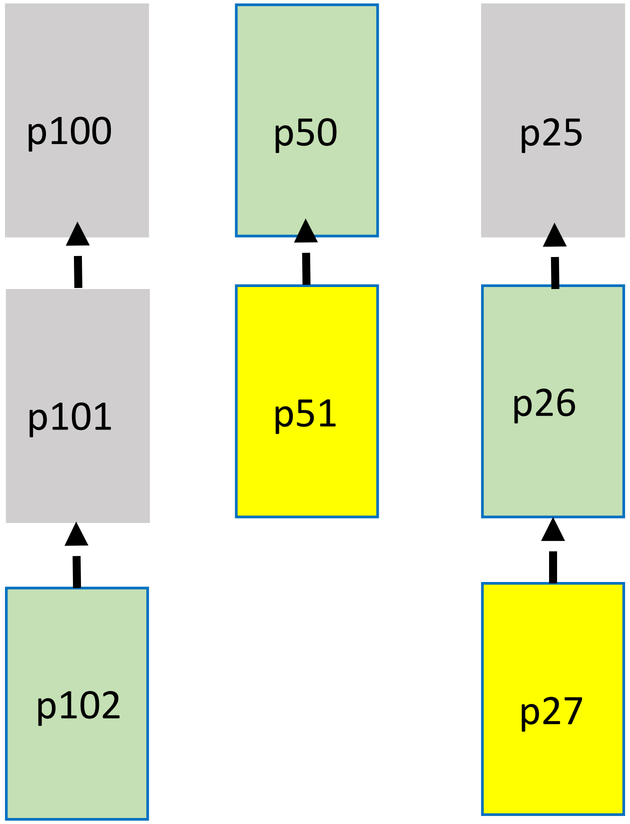
The yellow promises are waiting

The white promise is the currently executing promise

The currently executing promise may have created some new promises, not shown here. Some of them might be ready, too.

The arrows indicate that one promise is waiting for another

Any ready promise can be chosen as the next promise to be executed



The grey promises are fulfilled

The green promises are pending and ready

The yellow promises are waiting

The white promise is the currently executing promise

The arrows indicate that one promise is waiting for another

Computations always run until they are completed.

- Execution of a promise cannot be interrupted. That's what we mean by "**run to completion**".
- Along the way, it may create promises that can be run anytime after the current computation is completed (i.e. they will be in the "waiting" state).
  - We'll see that async/await provides an easy way to do that.
- A computation is completed when it returns from a procedure, but there are no procedures for it to return to (i.e. it returns to the "top level")
- When the current computation is completed, the operating system (e.g. node.js) chooses some "ready" promise to become the next current computation.

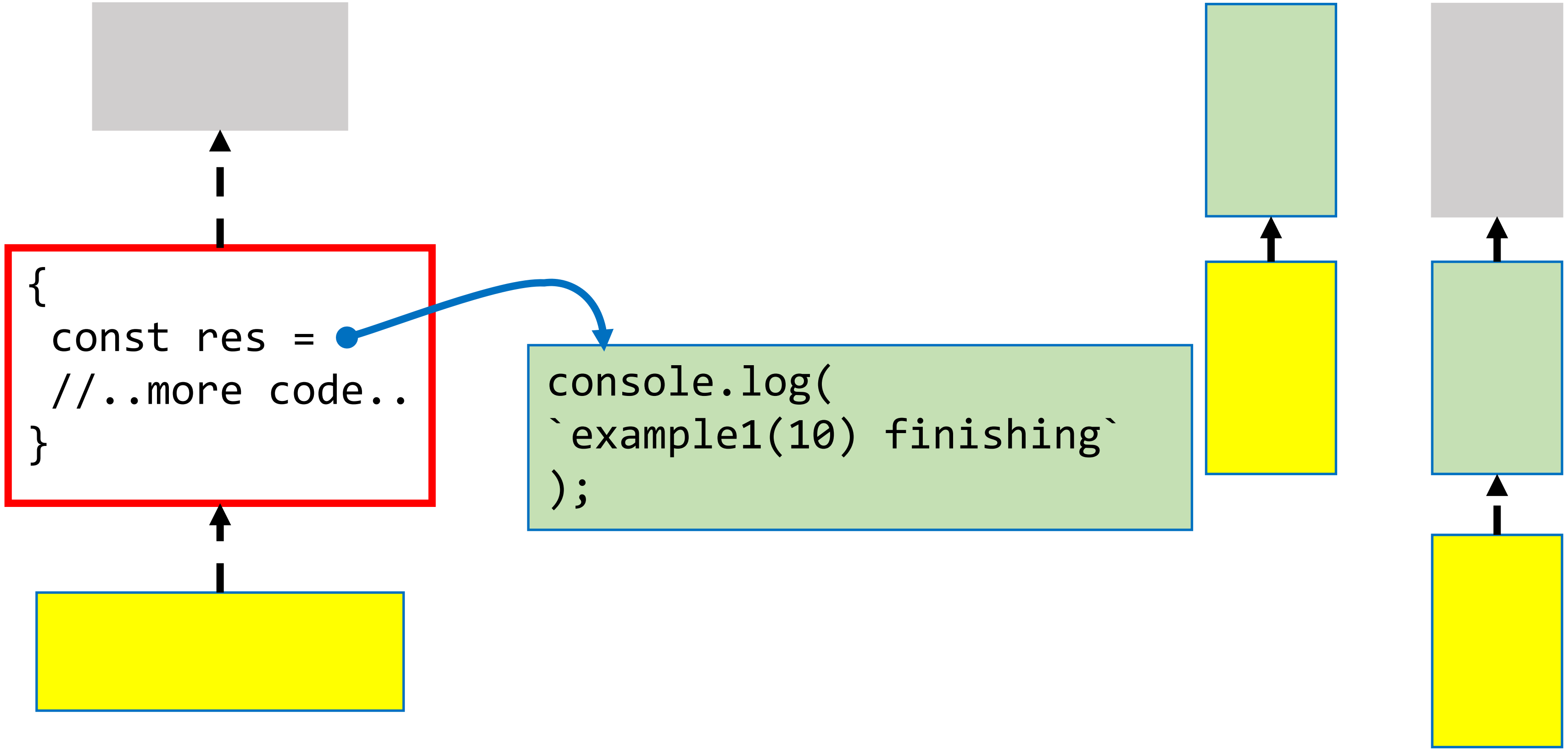
async/await: from the inside out

```
export async function example1(n: number): Promise<void> {
  console.log(`example1(${n}) starting`);
  const p1 = promiseToPrint(`p1 is printing`);
  await p1;
  console.log(`example1(${n}) finishing`);
}
```

1. This function executes normally until it hits the **await**, printing out "example1(1) starting" and binding p1 to the value of `promiseToPrint('p1 is printing')`
2. When it hits the await, it takes all the code following the await and creates a new promise that can only be executed **after** p1 is completed.
3. The new promise becomes the value of example(n).
4. The caller of example(n) then continues its execution.
5. If example(n) has no caller, then the runtime system chooses some ready promise to execute.

The promise pool before before calling example1()

The promise pool after calling example1()



example1(10) starting
p1 is printing

Important:
The console.log can't run until after the 'more code' finishes

Async functions: from the outside in

- What can async functions do?
- What are the typical patterns for applying them?