

CS 4530: Fundamentals of Software Engineering

Module 06: Concurrency Patterns in Typescript

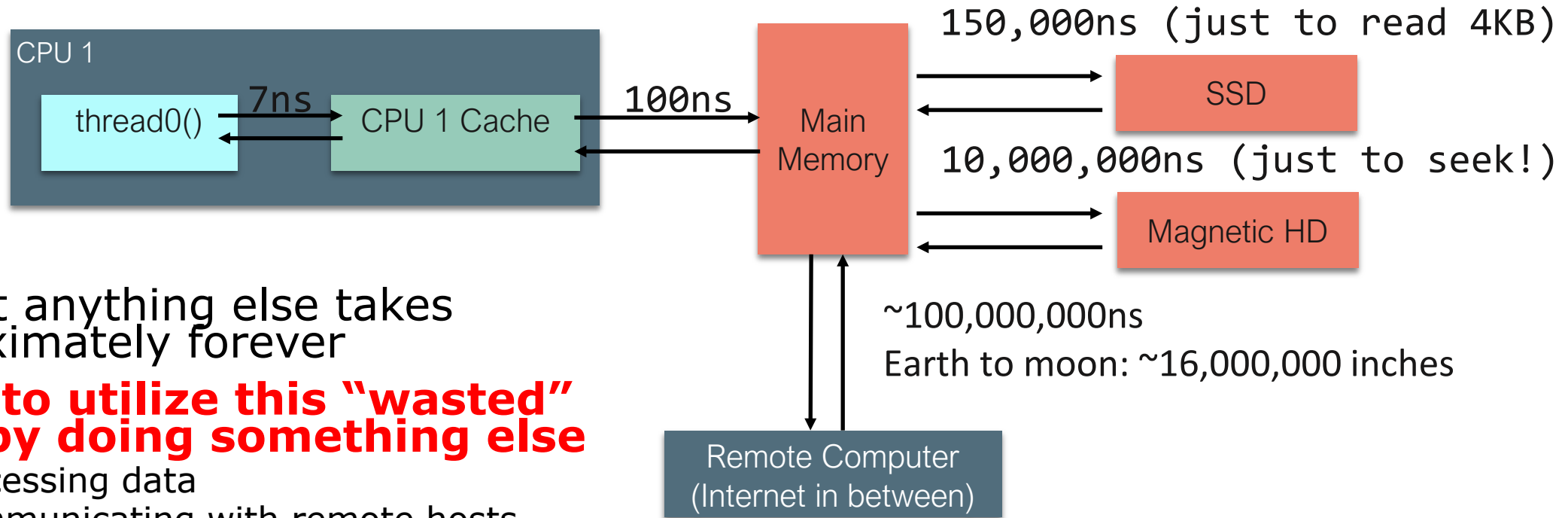
Adeel Bhutta, Joydeep Mitra and Mitch Wand
Khoury College of Computer Sciences

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 well-defined points in its execution. We will show you those with an example.
- 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 only pause in two places

```
async function someFunction(i: number) {
```

```
  const j = i + 1;  
  // ...
```

```
  const k = await someOtherAsyncFunction(j);
```

```
  // ...  
  const m = k + 100;  
  return m;
```

```
}
```

It will never
pause in here

Or in here

What happens at those pause points?

```
async function someFunction(i: number) {
```

```
  const j = i + 1;  
  // ...
```

```
  const k = await someOtherAsyncFunction(j);
```

```
  // ...  
  const m = k + 100;  
  return m;
```

```
}
```

Pause points



Java vs. JS/TS

```
async function asyncPrintA() {  
    await waitRandom(1);  
    console.log('A');  
}
```

```
async function asyncPrintBC() {  
    await waitRandom(2);  
    console.log('B');  
    console.log('C');  
}
```

```
async function run() {  
    await Promise.all([asyncPrintA(), asyncPrintBC()])  
}
```

- In Java, you could get an interrupt between the print B and the print C.
- So the output could be ABC, BAC, BCA
- In TS/JS, the print B and print C are in the same critical section, so BAC is impossible!

Terminology: promises and run-to-completion

- Each uninterruptible unit of work 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:

```
// 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}) returned: ${res}`);
  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
```

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. The browser goes about its business
4. Eventually, the axios.get returns.
5. Some time after that, the console.log is printed and the makeRequest concludes.
6. Any promises that are waiting for the result of this makeRequest become eligible for execution.

Use Promise.all to execute several requests concurrently

src/Slides/threeRequestsConcurrently.ts

```
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
```

Running 3 concurrent get requests

```
import axios from 'axios';
```

```
export async function makeRequest(  
  console.log(`starting makeRequest`);  
  const response = await axios.get(request);  
  console.log(`request:${request}`);  
}
```

```
function make3ConcurrentRequests(  
  console.log('starting make3ConcurrentRequests');  
  makeRequest(100);  
  makeRequest(200);  
  makeRequest(300);  
  console.log('make3ConcurrentRequests finished');  
}
```

```
make3ConcurrentRequests()
```

```
$ npx ts-node makeThreeConcurrentRequests.ts  
starting make3ConcurrentRequests  
starting makeRequest(100)  
starting makeRequest(200)  
starting makeRequest(300)  
make3ConcurrentRequests finished  
request 300 returned  
request 100 returned  
request 200 returned
```


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/Slides/threeRequestsSequentially.ts

...but it would be much slower

```
$ tsx timeComparison.ts  
After 100 runs of length 10 with delay 100ms  
makeRequestsConcurrently: min = 107   avg = 109 max = 115 msec  
makeRequestsSerially      : min = 1085  avg = 1093 max = 1103 msec
```

Why is that?

Visualizing Promise.all

Sequential (await)

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

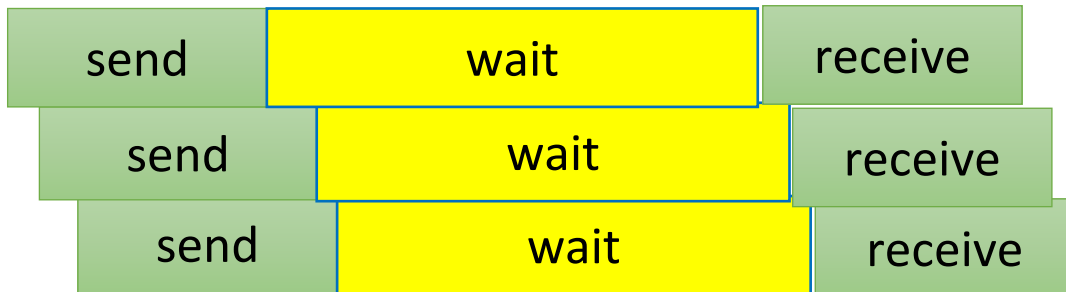
237 msec



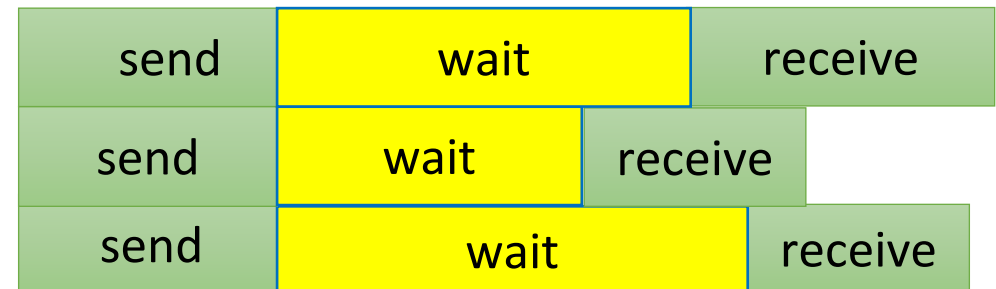
Concurrent (Promise.all)

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

34 msec



or



Requests can also be chained (if they are serial)

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

src/Slides/threeRequestsChained.ts

```
$ 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;
  }
}
```

src/Slides/tryCatchExample.ts

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/Slides/jest-example.test.ts

AntiPattern 1: unawaited promise

```
// 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})`);  
  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 **anti**pattern.
- Luckily, in real code we don't need to do this very often

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}`);  
}
```

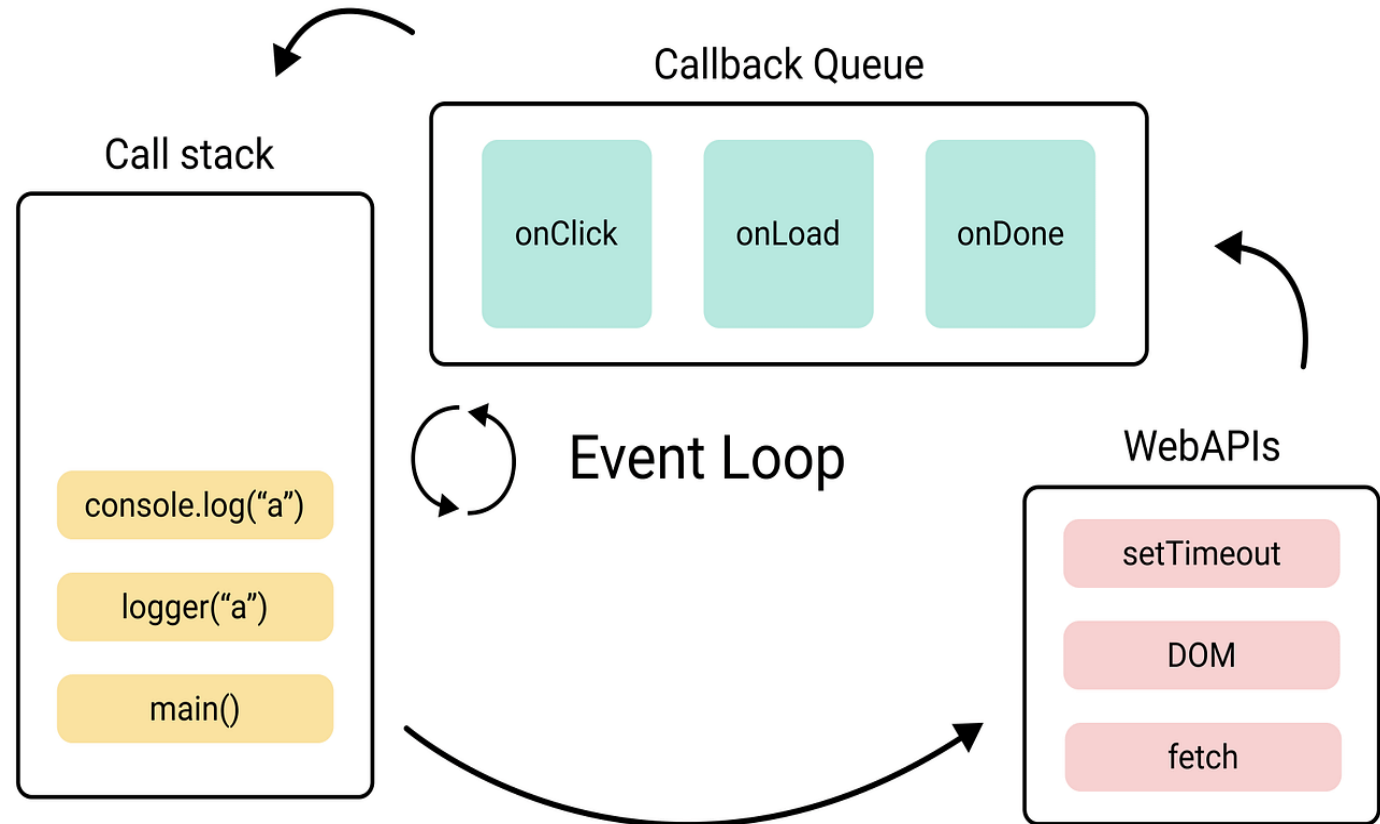
Critical Section
#1: no
interruption
between 'f
started' and 'g
started'

Critical Section
#2

Critical Section
#3

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

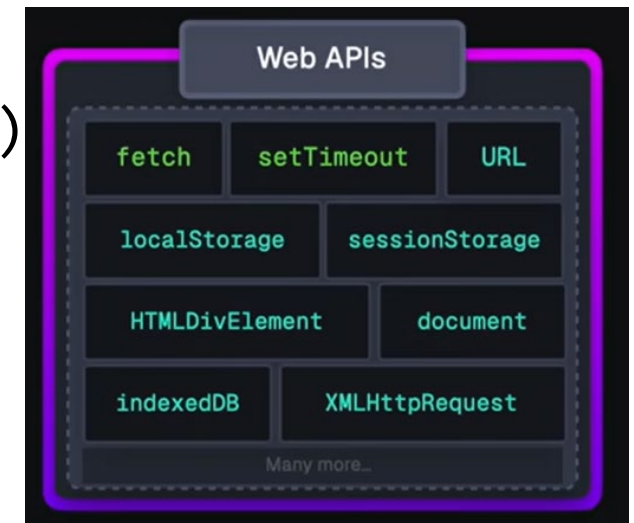
- These are things like http requests, I/O operations, or timers.
- Each of these returns a promise that you can **await**. The promise runs while it is pending, and produces the response from the http request, or the contents of the file, etc.
- You will hardly ever call one of these primitives yourself;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

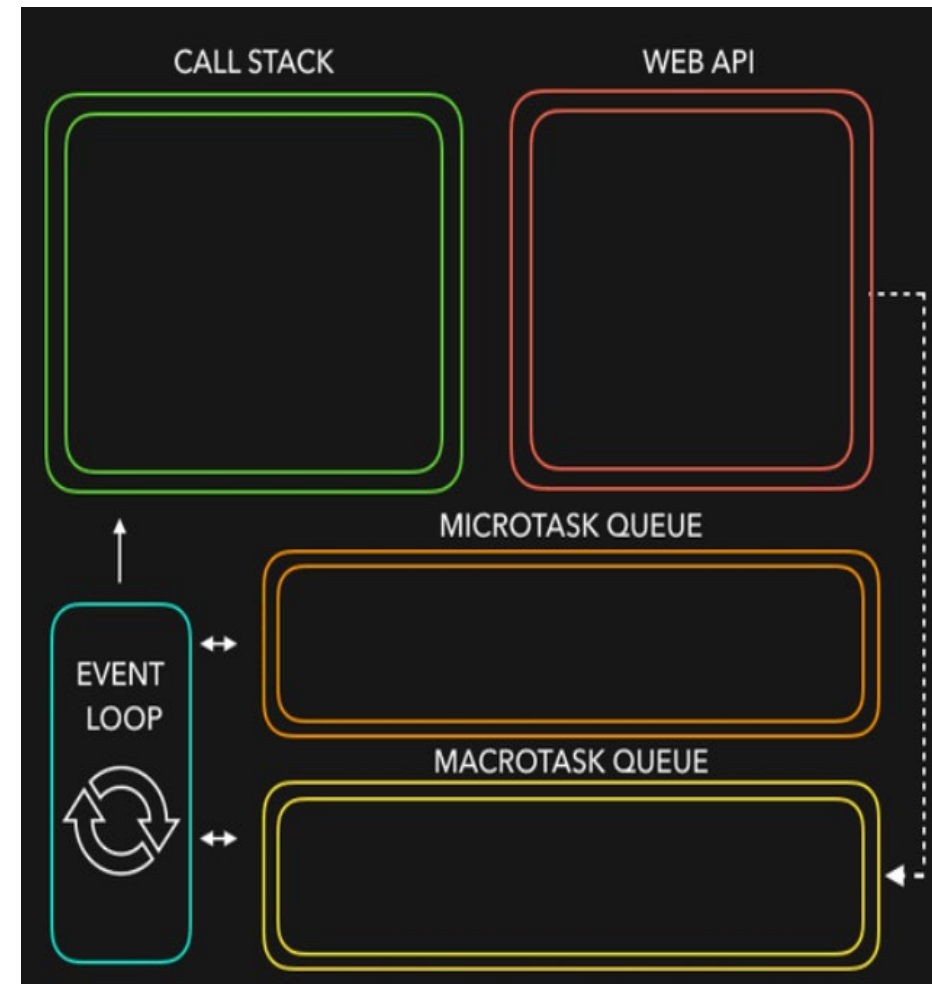
```
fs.readFile(filename)
```

to read the contents of a file.



Let's put it all together

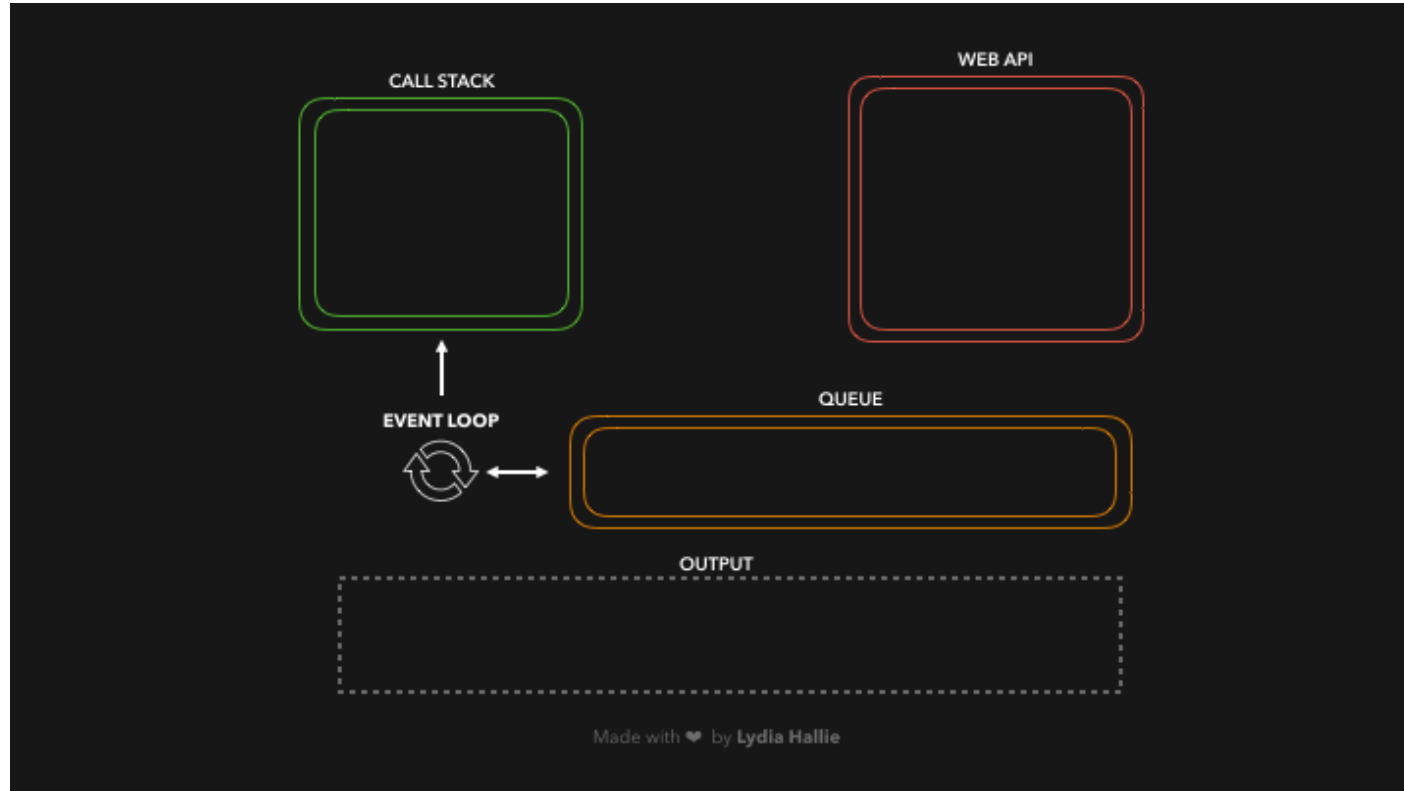
- JS/TS has single event loop
- We outsource most of the non-blocking IO work (to WebAPIs) for asynchronous work
- Upon completion, they are placed in queues (Microtask queue has priority over Macrotask queue)
- Event loop picks them up from queue when call stack is empty!



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>

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 (or **Promise.allSettled**, if needed).
- Check for errors with **try/catch**

Odds and Ends You Should Know

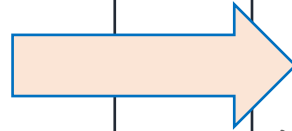
Promises Enforce Ordering Through “Then”

```
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 not run until 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()`
- Each **then** is a pause point.

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!');
});
```

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)  
}
```

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.