NODE.JS UNDER THE HOOD

Understanding the Event Loop, Garbage Collection & Native Modules

(Second Part of the Node.js at Scale Series)

From the Engineers of trace by RisingStack

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CHAPTER ONE: THE EVENT LOOP

The first chapter helps you to understand how the Node.js event loop works, and how you can leverage it to build fast applications. We'll also discuss the most common problems you might encounter, and the solutions for them.

THE PROBLEM

Most of the backends behind websites don't need to do complicated computations. Our programs spend most of their time waiting for the disk to read & write , or waiting for the wire to transmit our message and send back the answer.

IO operations can be orders of magnitude slower than data processing. Take this for example: SSD-s can have a read speed of 200-730 MB/s - at least a high-end one. Reading just one kilobyte of data would take 1.4 microseconds, but during this time a CPU clocked at 2GHz could have performed 28 000 of instruction-processing cycles.

For network communications it can be even worse, just try and ping google.com

```
$ ping google.com
64 bytes from 172.217.16.174: icmp_seq=0 ttl=52
time=33.017 ms
64 bytes from 172.217.16.174: icmp_seq=1 ttl=52
time=83.376 ms
64 bytes from 172.217.16.174: icmp_seq=2 ttl=52
time=26.552 ms
64 bytes from 172.217.16.174: icmp_seq=3 ttl=52
time=40.153 ms
64 bytes from 172.217.16.174: icmp_seq=4 ttl=52
time=37.291 ms
64 bytes from 172.217.16.174: icmp_seq=5 ttl=52
time=58.692 ms
64 bytes from 172.217.16.174: icmp_seq=6 ttl=52
time=45.245 ms
64 bytes from 172.217.16.174: icmp_seq=7 ttl=52
time=27.846 ms
```

The average latency is about 44 milliseconds. Just while waiting for a packet to make a round-trip on the wire, the previously mentioned processor can perform 88 millions of cycles.

THE SOLUTION

Most operational systems provide some kind of an Asynchronous IO interface, which allows you to start processing data that does not require the result of the communication, meanwhile the communication still goes on..

This can be achieved in several ways. Nowadays it is mostly done by leveraging the possibilities of multithreading at the cost of extra software complexity. For example reading a file in Java or Python is a blocking operation. Your program cannot do anything else while it is waiting for the network / disk communication to finish. All you can do - at least in Java - is to fire up a different thread then notify your main thread when the operation has finished.

It is tedious, complicated, but gets the job done. But what about Node? Well, we are surely facing some problems as Node.js - or more like V8 - is single-threaded. Our code can only run in one thread.

SIDE NOTE: This is not entirely true. Both Java and Python have async interfaces, but using them is definitely more difficult than in Node.js.

You might have heard that in a browser, setting `setTimeout(someFunction, 0)` can sometimes fix things magically. But why does setting a timeout to 0, deferring execution by 0 milliseconds fix anything? Isn't it the same as simply calling `someFunction` immediately? Not really.

First of all, let's take a look at the call stack, or simply, "stack". I am going to make things simple, as we only need to understand the very basics of the call stack. In case you are familiar how it works, feel free to jump to the next section.

THE STACK

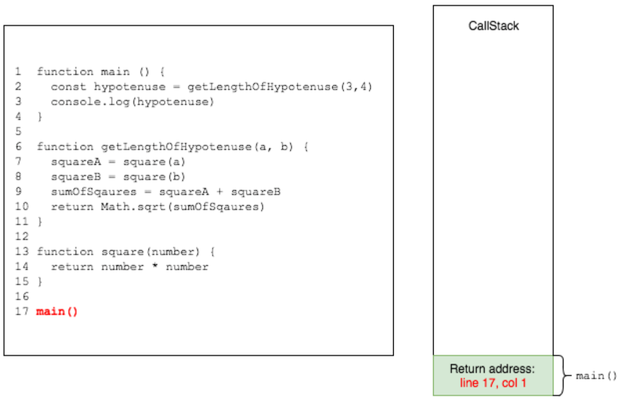
Whenever you call a functions return address, parameters and local variables will be pushed to the stack. If you call another function from the currently running function, its contents will be pushed on top in the same manner as the previous one - with its return address.

For the sake of simplicity I will say that 'a function is pushed' to the top of the stack from now on, even though it is not exactly correct.

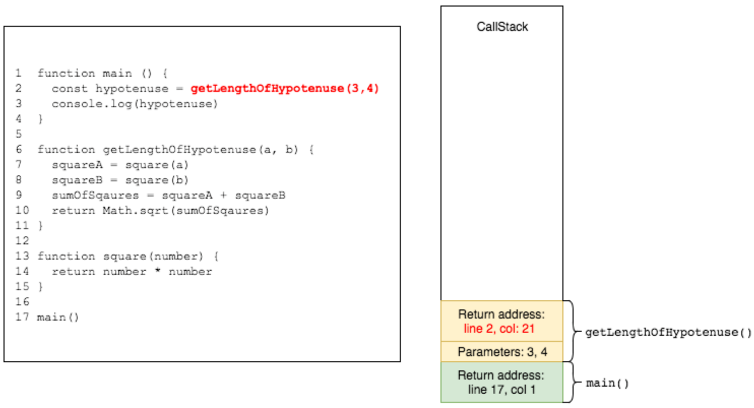
Let's take a look!

```
function main () {
  const hypotenuse = getLengthOfHypotenuse(3, 4)
  console.log(hypotenuse)
}

function getLengthOfHypotenuse(a, b) {
   const squareA = square(a)
   const squareB = square(b)
   const sumOfSquares = squareA + squareB
   return Math.sqrt(sumOfSquares)
}

function square(number) {
   return number * number
}

main()
```

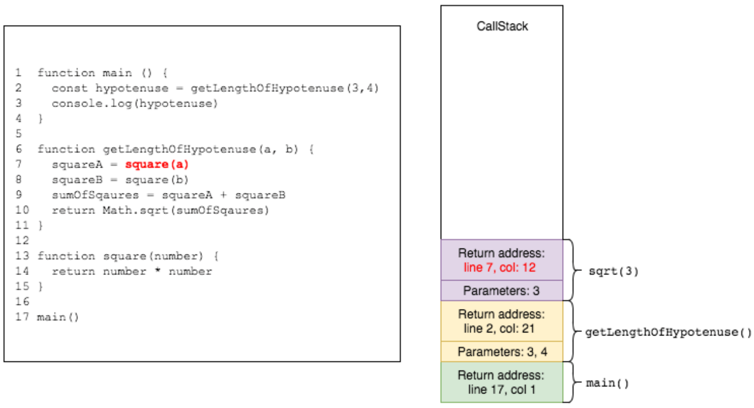
`main` is called first:



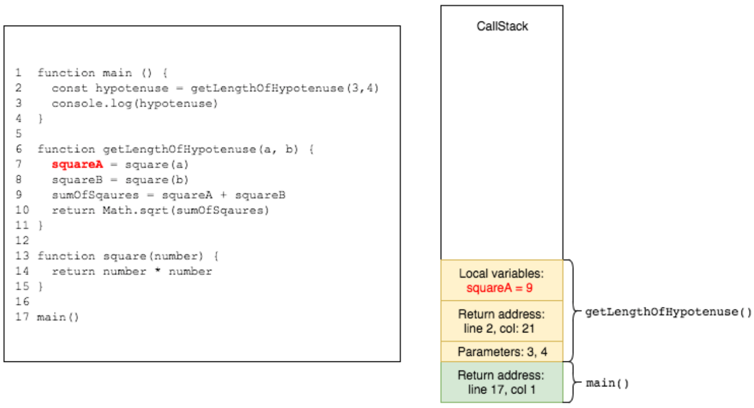
then main calls getLengthOfHypotenuse with 3 and 4 as arguments



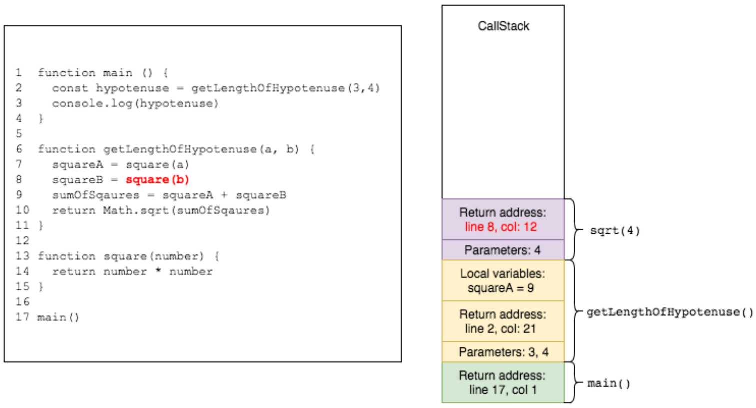
afterwards square is with the value of `a`

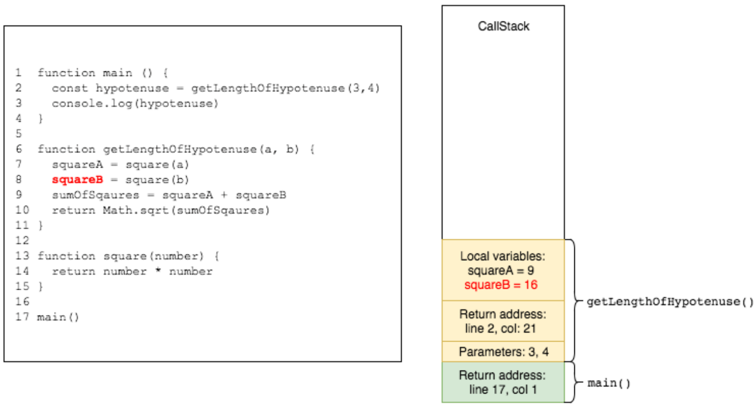


when square returns, it is popped from the stack, and its return value is assigned to `squareA`. squareA is added to the stack frame of `getLengthOfHypotenuse`

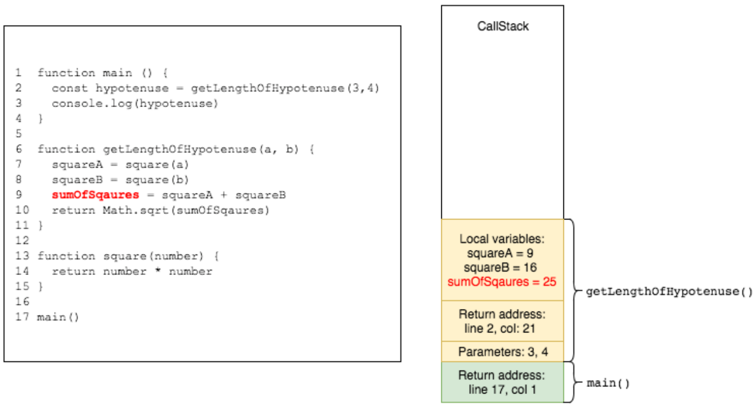


same goes for the next call to square

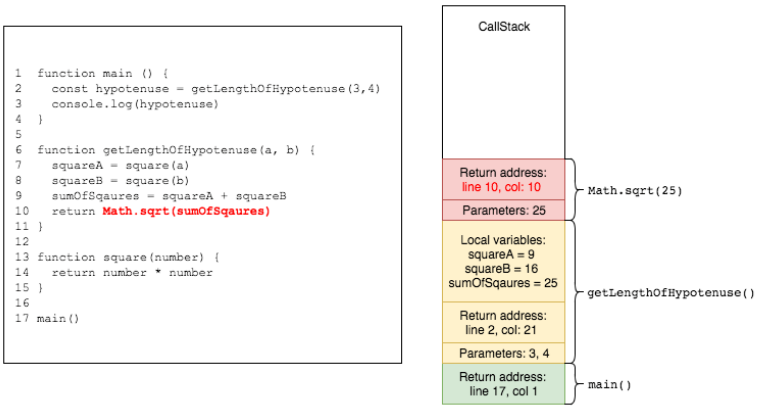




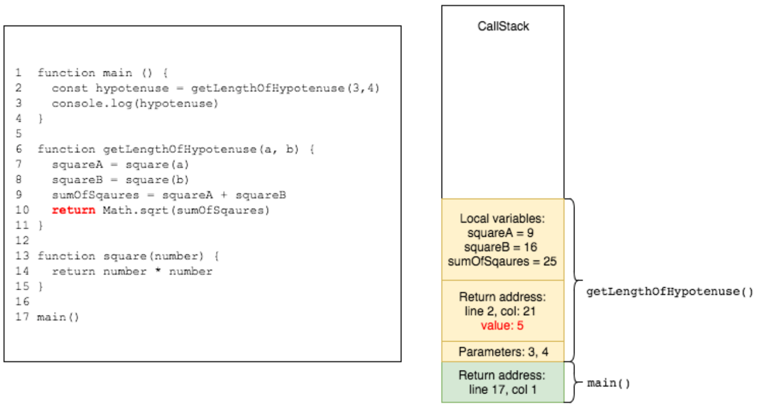
in the next line the expression `squareA + squareB` is evaluated



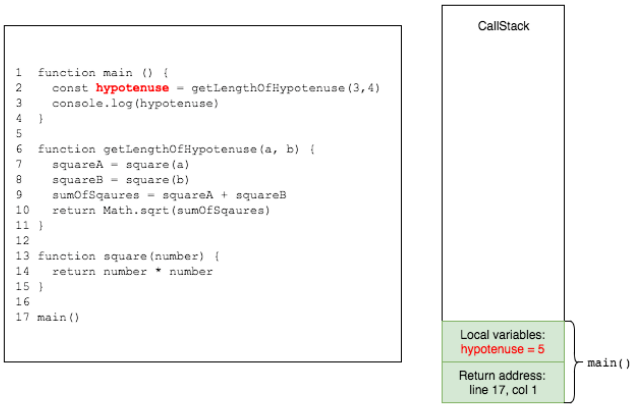
then Math.sqrt is called with sumOfSquares



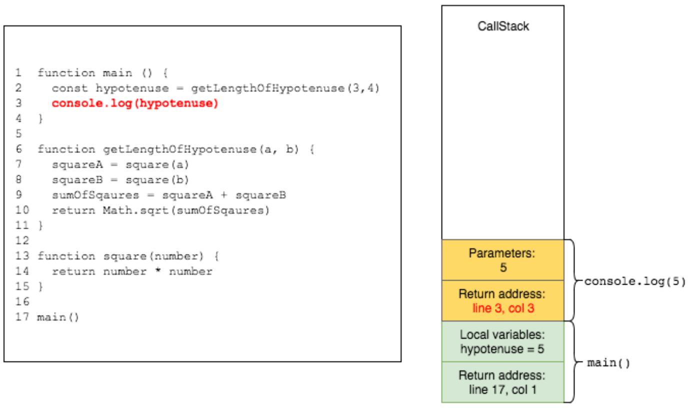
now all is left for `getLengthOfHypotenuse` is to return the final value of its calculation



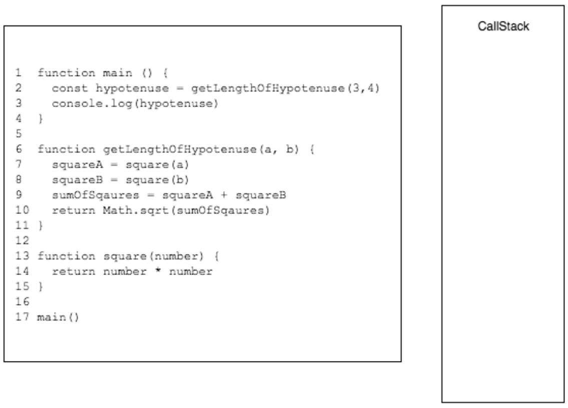
the returned value gets assigned to `hypotenuse` in `main`



the value of `hypotenuse` is logged to console



finally, `main` returns without any value, gets popped from the stack leaving it empty



SIDE NOTE: You saw that local variables are popped from the stack when the functions execution finishes. It happens only when you work with simple values such as numbers, strings and booleans. Values of objects, arrays and such are stored in the heap and your variable is merely a pointer to them. If you pass on this variable, you will only pass the said pointer, making these values mutable in different stack frames. When the function is popped from the stack, only the pointer to the Object gets popped with leaving the actual value in the heap. The garbage collector is the guy who takes care of freeing up space once the objects outlived their usefulness.

ENTER NODE.JS EVENT LOOP

So what happens when we call something like `setTimeout`, `http.get`, `process.nextTick`, or `fs.readFile`? Neither of these things can be found in V8's code, but they are available in the Chrome WebApi and the C++ API in case of Node.js. To understand this, we will have to understand the order of execution a little bit better.

Let's take a look at a more common Node.js application - a server listening on `localhost:3000/`. Upon getting a request, the server will call `wttr.in/<city>` to get the weather, print some kind messages to the console, and it forwards responses to the caller after recieving them.

```
'use strict'
const express = require('express')
const superagent = require('superagent')
const app = express()

app.get('/', sendWeatherOfRandomCity)

function sendWeatherOfRandomCity (request, response) {
  getWeatherOfRandomCity(request, response)
  sayHi()
}

const CITIES = [
  'london',
  'newyork',
  'paris',
  'budapest',
  'warsaw',
  'rome',
  'madrid',
  'moscow',
  'beijing',
  'capetown',
]

function getWeatherOfRandomCity (request, response) {
  const city = CITIES[Math.floor(Math.random() * CITIES.length)]
  superagent.get(`wttr.in/${city}`)
    .end((err, res) => {
      if (err) {
        console.log('O snap')
        return response.status(500).send('There was an error getting
        the weather, try looking out the window')
      }
      const responseText = res.text
      response.send(responseText)
      console.log('Got the weather')
    })

  console.log('Fetching the weather, please be patient')
}

function sayHi () {
  console.log('Hi')
}

app.listen(3000)
```

What will be printed out aside from getting the weather when a request is sent to `localhost:3000`?

If you have some experience with Node, you shouldn't be surprised that even though `console.log('Fetching the weather, please be patient')` is called after `console.log('Got the weather')` in the code, the former will print first resulting in:

```
Fetching the weather, please be patient
Hi
Got the weather
```

What happened? Even though V8 is single-threaded, the underlying C++ API of Node isn't. It means that whenever we call something that is a non-blocking operation, Node will call some code that will run concurrently with our javascript code under the hood. Once this hiding thread receives the value it awaits for or throws an error, the provided callback will be called with the necessary parameters.

SIDE NOTE: The 'some code' we mentioned is actually part of libuv. libuv is the open source library that handles the thread-pool, doing signaling and all other magic that is needed to make the asynchronous tasks work. It was originally developed for Node.js but a lot of other projects use of it by now.

To peek under the hood, we need to introduce two new concepts: the event loop and the task queue.

TASK QUEUE

Javascript is a single-threaded, event-driven language. This means that we can attach listeners to events, and when a said event fires, the listener executes the callback we provided.

Whenever you call `setTimeout`, `http.get` or `fs.readFile`, Node.js sends these operations to a different thread allowing V8 to keep executing our code. Node also calls the callback when the counter has run down or the IO / http operation has finished.

These callbacks can enqueue other tasks and those functions can enqueue others and so on. This way you can read a file while processing a request in your server, and then make an http call based on the read contents without blocking other requests from being handled.

However, we only have one main thread and one call-stack, so in case there is another request being served when the said file is read, its callback will need to wait for the stack to become empty. The limbo where callbacks are waiting for their turn to be executed is called the task queue (or event queue, or message queue). Callbacks are being called in an infinite loop whenever the main thread has finished its previous task, hence the name 'event loop'.

In our previous example it would look something like this:

1. express registers a handler for the 'request' event that will be called when request arrives to '/'
2. skips the functions and starts listening on port 3000
3. the stack is empty, waiting for 'request' event to fire
4. upon incoming request, the long awaited event fires, express calls the provided handler `sendWeatherOfRandomCity`
5. `sendWeatherOfRandomCity` is pushed to the stack
6. `getWeatherOfRandomCity` is called and pushed to the stack
7. `Math.floor` and `Math.random` are called, pushed to the stack and popped, a from `cities` is assigned to `city`
8. `superagent.get` is called with `'wttr.in/${city}'`, the handler is set for the `end` event.
9. the http request to `http://wttr.in/${city}` is send to a background thread, and the execution continues
10. `'Fetching the weather, please be patient'` is logged to the console, `getWeatherOfRandomCity` returns
11. `sayHi` is called, `'Hi'` is printed to the console
12. `sendWeatherOfRandomCity` returns, gets popped from the stack leaving it empty
13. waiting for `http://wttr.in/${city}` to send it's response once the response has arrived, the `end` event is fired.
14. the `anonymous handler` we passed to `.end()` is called, gets pushed to the stack with all variables in its closure, meaning it can see and modify the values of `express, superagent, app, CITIES, request, response, city` and all the functions we have defined
15. `response.send()` gets called either with `200` or `500` statusCode, but again it is sent to a background thread, so the response stream is not blocking our execution, `anonymous handler` is popped from the stack.

So now we can understand why the previously mentioned `setTimeout` hack works. Even though we set the counter to zero, it defers the execution until the current stack and the task queue is empty, allowing the browser to redraw the UI, or Node to serve other requests.

MICROTASKS AND MACROTASKS

If this wasn't enough, we actually have more then one task queue. One for microtasks and another for macrotasks.

examples of microtasks:

- `process.nextTick`
- `promises`
- `Object.observe`

examples of macrotasks:

- `setTimeout`
- `setInterval`
- `setImmediate`
- `I/O`

Let's take a look at the following code (on the next page) :

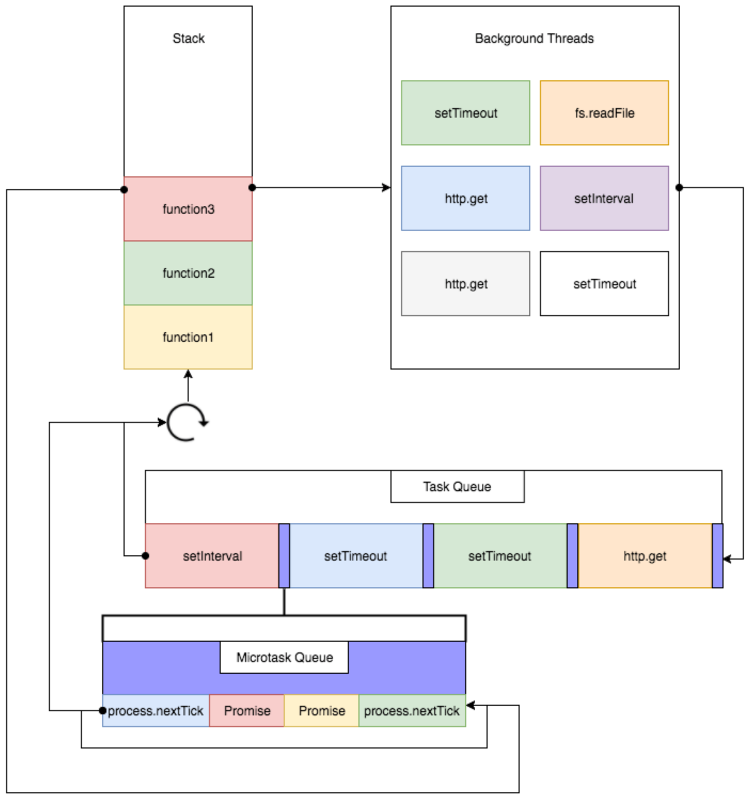
```
console.log('script start')

const interval = setInterval(() => {
  console.log('setInterval')
}, 0)

setTimeout(() => {
  console.log('setTimeout 1')
  Promise.resolve().then(() => {
    console.log('promise 3')
  }).then(() => {
    console.log('promise 4')
  }).then(() => {
    setTimeout(() => {
      console.log('setTimeout 2')
      Promise.resolve().then(() => {
        console.log('promise 5')
      }).then(() => {
        console.log('promise 6')
      }).then(() => {
        clearInterval(interval)
      })
    }, 0)
  })
}, 0)

Promise.resolve().then(() => {
  console.log('promise 1')
}).then(() => {
  console.log('promise 2')
})
```

this will log to the console:

```
script start
promise1
promise2
setInterval
setTimeout1
promise3
promise4
setInterval
setTimeout2
setInterval
promise5
promise6
```

According to the WHATVG specification, exactly one (macro)task should get processed from the macrotask queue in one cycle of the event loop. After said macrotask has finished, all of the available microtasks will be processed within the same cycle. While these microtasks are being processed, they can queue more microtasks, which will all be run one by one, until the microtask queue is exhausted.

This diagram tries to make the picture a bit clearer:



In our case (on the next page):

--- CYCLE 1 ---

1. \`setInterval\` is scheduled as task
2. \`setTimeout 1\` is scheduled as task
3. in \`Promise.resolve 1\` both \`then\`s are scheduled as microtasks
4. the stack is empty, microtasks are run

Task queue: `setInterval`, `setTimeout 1`

--- CYCLE 2 ---

5. the microtask queue is empty, \`setInteval\`'s handler can be run, another \`setInterval\` is scheduled as a task, right behind \`setTimeout 1\`

Task queue: `setTimeout 1`, `setInterval`

--- CYCLE 3 ---

6. the microtask queue is empty, \`setTimeout 1\`'s handler can be run, \`promise 3\` and \`promise 4\` are scheduled as microtasks,
7. handlers of \`promise 3\` and \`promise 4\` are run \`setTimeout 2\` is scheduled as task

Task queue: `setInterval`, `setTimeout 2`

--- CYCLE 4 ---

8. the microtask queue is empty, \`setInteval\`'s handler can be run, another \`setInterval\` is scheduled as a task, right behind \`setTimeout\`

Task queue: `setTimeout 2`, `setInteval`

9. \`setTimeout 2\`'s handler run, \`promise 5\` and \`promise 6\` are scheduled as microtasks

Now handlers of `promise 5` and `promise 6` should be run clearing our interval, but for some strange reason `setInterval` is run again. However, if you run this code in Chrome, you will get the expected behavior.

We can fix this in Node too with process.nextTick and some mind-boggling callback hell.

```
console.log('script start')

const interval = setInterval(() => {
  console.log('setInterval')
}, 0)

setTimeout(() => {
  console.log('setTimeout 1')
  process.nextTick(() => {
    console.log('nextTick 3')
    process.nextTick(() => {
      console.log('nextTick 4')
      setTimeout(() => {
        console.log('setTimeout 2')
        process.nextTick(() => {
          console.log('nextTick 5')
          process.nextTick(() => {
            console.log('nextTick 6')
            clearInterval(interval)
          })
        })
      }, 0)
    })
  })
})

process.nextTick(() => {
  console.log('nextTick 1')
  process.nextTick(() => {
    console.log('nextTick 2')
  })
})
```

This is the exact same logic as our beloved promises use, only a little bit more hideous. At least it gets the job done the way we expected.

TAME THE ASYNC BEAST!

As we saw, we need to manage and pay attention to both task queues, and to the event loop when we write an app in Node.js - in case we wish to leverage all its power, and if we want to keep our long running tasks from blocking the main thread.

The event loop might be a slippery concept to grasp at first, but once you get the hang of it, you won't be able to imagine that there is life without it. The continuation passing style that can lead to a callback hell might look ugly, but we have Promises, and soon we will have async-await in our hands... and while we are (a)waiting, you can simulate async-await using co and/or koa.

One last parting advice:

Knowing how Node.js and V8 handles long running executions, you can start using it for your own good. You might have heard before that you should send your long running loops to the task queue. You can do it by hand or make use of async.js.

Happy coding!

The book continues with Chapter Two on the next page!

CHAPTER TWO: GARBAGE COLLECTION

In this chapter, you are going to learn how Node.js garbage collection works, what happens in the background when you write code and how memory is freed up for you.

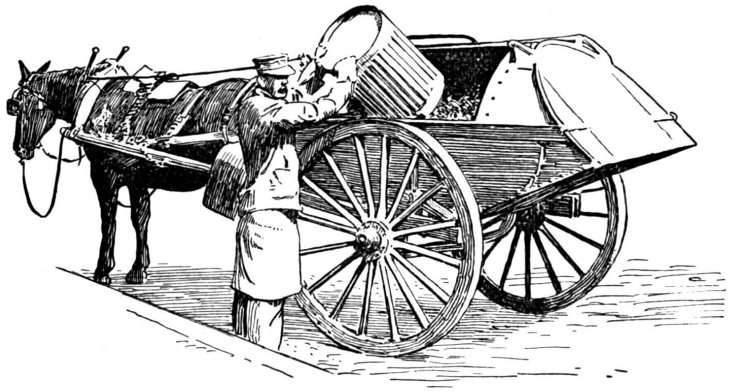


FIG. 109. — A GARBAGE COLLECTOR.

MEMORY MANAGEMENT IN NODE.JS APPLICATIONS

Every application needs memory to work properly. Memory management provides ways to dynamically allocate memory chunks for programs when they request it, and free them when they are no longer needed - so that they can be reused.

Application-level memory management can be manual or automatic. The automatic memory management usually involves a garbage collector.

The following code snippet shows how memory can be allocated in `C`, using manual memory management (cont. next page) :

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main() {

   char name[20];
   char *description;

   strcpy(name, “RisingStack”);

   // memory allocation
   description = malloc( 30 * sizeof(char) );

   if( description == NULL ) {
      fprintf(stderr, “Error - unable to
      allocate required memory\n”);
   } else {
      strcpy( description, “Trace by
      RisingStack is an APM.”);
   }

   printf(“Company name = %s\n”, name );
   printf(“Description: %s\n”, description );

   // release memory
   free(description);
}
```

In **manual memory management**, it is the responsibility of the developer to free up the unused memory portions. Managing your memory this way can introduce several major bugs to your applications:

- **Memory leaks** when the used memory space is never freed up.
- **Wild/dangling pointers** appear when an object is deleted, but the pointer is reused. Serious security issues can be introduced when other data structures are overwritten or sensitive information is read.

Luckily for you, Node.js comes with a garbage collector, and you don’t need to manually manage memory allocation.

THE CONCEPT OF THE GARBAGE COLLECTOR

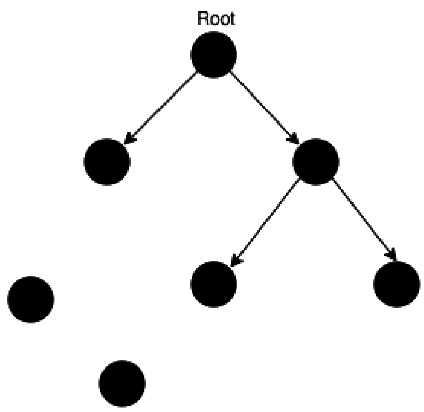
Garbage collection is a way of managing application memory automatically. The job of the garbage collector *(GC)* is to reclaim memory occupied by unused objects *(garbage)*. It was first used in

LISP in 1959, invented by John McCarthy.

The way how the GC knows that objects are no longer in use is that no other object has references to them.

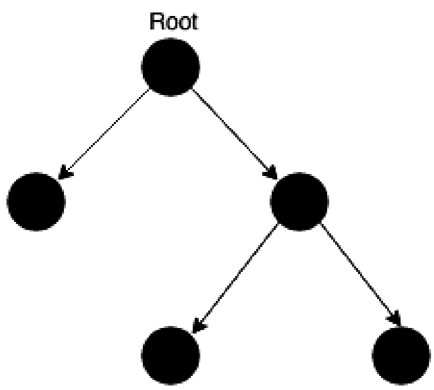
MEMORY BEFORE THE GARBAGE COLLECTION

The following diagram shows how the memory can look like if you have objects with references to each other, and with some objects that have no reference to any objects. These are the objects that can be collected by a garbage collector run.



MEMORY AFTER THE GARBAGE COLLECTION

Once the garbage collector is run, the objects that are unreachable gets deleted, and the memory space is freed up.



THE ADVANTAGES OF USING A GARBAGE COLLECTOR

- it prevents **wild/dangling pointers** bugs,
- it won't try to free up space that was already freed up,
- it will **protect** you **from** some types of **memory leaks**.

Of course, using a garbage collector doesn't solve all of your problems, and it's not a silver bullet for memory management. Let's take a look at things that you should keep in mind!

Things to Keep in Mind When Using a Garbage Collector:

- **performance impact** - in order to decide what can be freed up, the GC consumes computing power
- **unpredictable stalls** - modern GC implementations try to avoid "stop-the-world" collections

GARBAGE COLLECTION & MEMORY MANAGEMENT IN PRACTICE

The easiest way of learning is by doing - so I am going to show you what happens in the memory with different code snippets.

The Stack

The stack contains local variables and pointers to objects on the heap or pointers defining the control flow of the application.

In the following example, both `a` and `b` will be placed on the stack.

```
function add (a, b) {
  return a + b
}

add(4, 5)
```

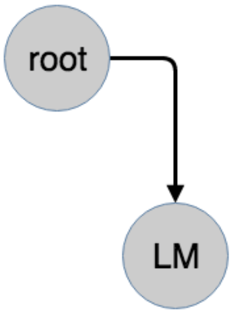
The Heap

The heap is dedicated to store reference type objects, like strings or objects.

The `Car` object created in the following snippet is placed on the heap.

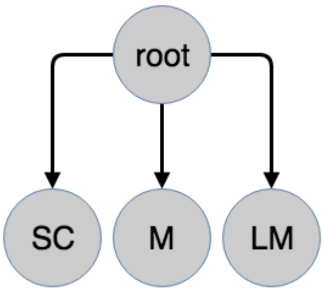
```
function Car (opts) {
  this.name = opts.name
}

const LightningMcQueen = new Car({name:
'Lightning McQueen'})
```

After this, the memory would look something like this:



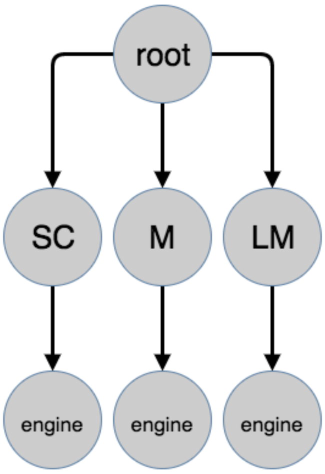
Let's add more cars, and see how our memory would look like!

```
function Car (opts) {
  this.name = opts.name
}

const LightningMcQueen = new Car({name: 'Lightning McQueen'})
const SallyCarrera = new Car({name: 'Sally Carrera'})
const Mater = new Car({name: 'Mater'})
```

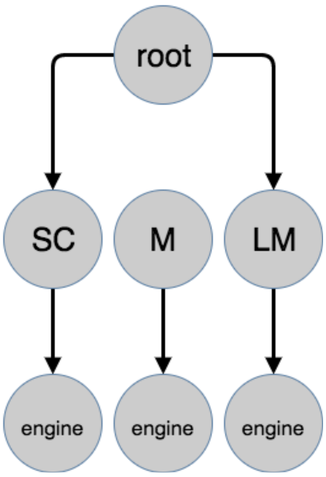


If the GC would run now, nothing could be freed up, as the root has a reference to every object. Let's make it a little bit more interesting, and add some parts to our cars!

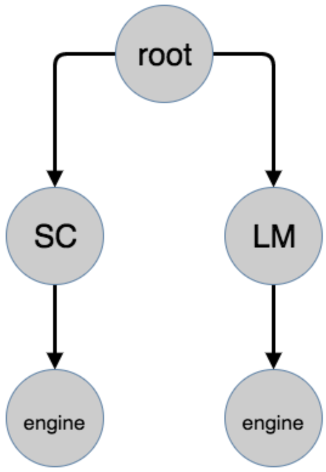
```
function Engine (power) {
  this.power = power
}

function Car (opts) {
  this.name = opts.name
  this.engine = new Engine(opts.power)
}

let LightningMcQueen = new Car({name: 'Lightning
McQueen', power: 900})
let SallyCarrera = new Car({name: 'Sally Carrera',
power: 500})
let Mater = new Car({name: 'Mater', power: 100})
```



What would happen, if we no longer use `Mater`, but redefine it and assign some other value, like `Mater = undefined`?



As a result, the original `Mater` object cannot be reached from the root object, so on the next garbage collector run it will be freed up:



Now as we understand the basics of what's the expected behaviour of the garbage collector, let's take a look on how it is implemented in V8!

GARBAGE COLLECTION METHODS

In one of our previous articles we dealt with how the Node.js garbage collection methods work, so I strongly recommend reading that article. Here are the most important things you'll learn there:

New Space and Old Space

The heap has two main segments, the New Space and the Old Space. The New Space is where new allocations are happening; it is fast to collect garbage here and has a size of ~1-8MBs. Objects living in the New Space are called Young Generation.

The Old Space where the objects that survived the collector in the New Space are promoted into - they are called the Old Generation. Allocation in the Old Space is fast, however collection is expensive so it is infrequently performed .

Young Generation

Usually, ~20% of the Young Generation survives into the Old Generation. Collection in the Old Space will only commence once it is getting exhausted. To do so the V8 engine uses two different collection algorithms.

Scavenge and Mark-Sweep collection

Scavenge collection is fast and runs on the Young Generation, however the slower Mark-Sweep collection runs on the Old Generation.

A REAL-LIFE EXAMPLE - THE METEOR CASE-STUDY

In 2013, the creators of Meteor announced their findings about a memory leak they ran into. The problematic code snippet was the following:

```
var theThing = null
var replaceThing = function () {
  var originalThing = theThing
  var unused = function () {
    if (originalThing)
      console.log("hi")
  }
  theThing = {
    longStr: new Array(1000000).join('*'),
    someMethod: function () {
      console.log(someMessage)
    }
  };
};
setInterval(replaceThing, 1000)
```

Well, the typical way that closures are implemented is that every function object has a link to a dictionary-style object representing its lexical scope. If both functions defined inside replaceThing actually used originalThing, it would be important that they both get the same object, even if originalThing gets assigned to over and over, so both functions share the same lexical environment. Now, Chrome's V8 JavaScript engine is apparently smart enough to keep variables out of the lexical environment if they aren't used by any closures - from the Meteor blog.

Further reading:
- Finding a memory leak in Node.js
- JavaScript Garbage Collection Improvements - Orinoco
- memorymanagement.org

CHAPTER THREE: NATIVE MODULES

There are times when the performance of JavaScript is not enough, so you have to depend more on native Node.js modules.

While native extensions are definitely not a beginner topic, we recommend this chapter for every Node.js developer to get a bit of knowledge on how they work.

COMMON USE CASES OF NATIVE NODE.JS MODULES

The knowledge on native modules comes handy when you're adding a native extension as a dependency, which you could have done already!

Just take a look at the list of a few popular modules using native extensions. **You're using at least one of them, right?**

- https://github.com/wadey/node-microtime
- https://github.com/node-inspector
- https://github.com/node-inspector/v8-profiler
- http://www.nodegit.org/

There are a few reasons why one would consider writing native Node.js modules, these include but not limited to:

- Performance-critical applications: Let's be honest, Node.js is great for doing asynchronous I/O operations, but when it comes to real number-crunching, it's not that great of a choice.

- Hooking into lower level (e.g.: operating-system) APIs

- Creating a bridge between C or C++ libraries and Node.js

WHAT ARE THE NATIVE MODULES?

Node.js Addons are dynamically-linked shared objects, written in C or C++, that can be loaded into Node.js using the require() function, and used just as if they were an ordinary Node.js module.
- From the Node.js documentation

This means that (if done right) the quirks of C/C++ can be hidden from the module's consumer. What they will see instead is that your module is a Node.js module - just like if you had written it in JavaScript.

As we've learned from the previous chapters, Node.js runs on the V8 JavaScript Engine, which is a C program on its own. We can write code that interacts directly with this C program in its own language, which is great because we can avoid a lot of expensive serialization and communication overhead.

Also, in the previous chapter we've learnt about the cost of the Node.js Garbage Collector. Although Garbage Collection can be completely avoided if you decide to manage memory yourself (because C/C++ have no GC concept), you'll create memory issues much easier.

Writing native extensions requires knowledge on one or more of the following topics:

- Libuv
- V8
- Node.js internals

All of those have excellent documentation. If you're getting into this field, I'd recommend to read them.

Without further ado, let's begin:

PREREQUISITES

Linux:

- python (v2.7 recommended, v3.x.x is not supported)
- make
- A proper C/C++ compiler toolchain, like GCC

Mac:

- Xcode installed: make sure you not only install it, but you start it at least once and accept its terms and conditions - otherwise it won't work!

Windows

- Run `cmd.exe` as administrator and type `npm install --global --production windows-build-tools` - which will install everything for you.

OR

- Install Visual Studio (it has all the C/C++ build tools preconfigured)

OR

- Use the Linux subsystem provided by the latest Windows build. With that, follow the LINUX instructions above.

CREATING OUR NATIVE NODE.JS EXTENSION

Let's create our first file for the native extension. We can either use the `.cc` extension that means it's C with classes, or the `.cpp` extension which is the default for C++. The Google Style Guide recommends `.cc`, so I'm going to stick with it.

First, let's see the file in whole, and after that, I'm going to explain it to you line-by-line!

(Code snippet on the next page!)

```
#include <node.h>

const int maxValue = 10;
int numberOfCalls = 0;

void WhoAmI(const v8::FunctionCallbackInfo<v8::Value>& args) {
  v8::Isolate* isolate = args.GetIsolate();
  auto message = v8::String::NewFromUtf8(isolate, "I'm a Node Hero!");
  args.GetReturnValue().Set(message);
}

void Increment(const v8::FunctionCallbackInfo<v8::Value>& args) {
  v8::Isolate* isolate = args.GetIsolate();

  if (!args[0]->IsNumber()) {
    isolate->ThrowException(v8::Exception::TypeError(
          v8::String::NewFromUtf8(isolate, "Argument must be a
number")));
    return;
  }

  double argsValue = args[0]->NumberValue();
  if (numberOfCalls + argsValue > maxValue) {
    isolate->ThrowException(v8::Exception::Error(
          v8::String::NewFromUtf8(isolate, "Counter went through the
roof!")));
    return;
  }

  numberOfCalls += argsValue;

  auto currentNumberOfCalls =
    v8::Number::New(isolate, static_cast<double>(numberOfCalls));

  args.GetReturnValue().Set(currentNumberOfCalls);
}

void Initialize(v8::Local<v8::Object> exports) {
  NODE_SET_METHOD(exports, "whoami", WhoAmI);
  NODE_SET_METHOD(exports, "increment", Increment);
}

NODE_MODULE(module_name, Initialize)
```

Now let's go through the file line-by-line!

`#include <node.h>`

Include in C++ is like `require()` in JavaScript. It will pull everything from the given file, but instead of linking directly to the source, in C++ we have the concept of header files.

We can declare the exact interface in the header files without implementation and then we can include the implementations by their header file. The C++ linker will take care of linking these two together. Think of it as a documentation file that describes contents of it, that can be reused from your code.

```
void WhoAmI(const v8::FunctionCallbackInfo<v8::Value>& args) {
  v8::Isolate* isolate = args.GetIsolate();
  auto message = v8::String::NewFromUtf8(isolate, “I’m a Node Hero!”);
  args.GetReturnValue().Set(message);
}
```

Because this is going to be a native extension, the v8 namespace is available to use. Note the `v8::` notation - which is used to access the v8’s interface. If you don’t want to include `v8::` before using any of the v8’s provided types, you can add `using v8;` to the top of the file. Then you can omit all the `v8::` namespace specifiers from your types, but this can introduce name collisions in the code, so be careful using these. To be 100% clear, I’m going to use `v8::` notation for all of the v8 types in my code.

In our example code, we have access to the arguments the function was called with (from JavaScript), via the `args` object that also provides us with all of the call related information.

With `v8::Isolate*` we’re gaining access to the current JavaScript scope for our function. Scopes work just like in JavaScript: we can assign variables and tie them into the lifetime of that specific code. We don’t have to worry about deallocating these chunks of memory, because we allocate them as if we’d do in JavaScript, and the Garbage Collector will automatically take care of them.

```
function () {
 var a = 1;
} // SCOPE
```

Via `args.GetReturnValue()` we get access to the return value of our function. We can set it to anything we’d like as long as it is from `v8::` namespace.

C++ has built-in types for storing integers and strings, but JavaScript only understands it’s own `v8::` type objects. As long as we are in the scope of the C++ world, we are free to use the ones built into C++, but when we’re dealing with JavaScript objects and interoperability with JavaScript code, we have to transform C++ types into ones that are understood by the JavaScript context. These are the types that are exposed in the v8:: namespace like `v8::String` or `v8::Object`.

```
void WhoAmI(const v8::FunctionCallbackInfo<v8::Value>& args) {
  v8::Isolate* isolate = args.GetIsolate();
  auto message = v8::String::NewFromUtf8(isolate, "I'm a Node Hero!");
  args.GetReturnValue().Set(message);
}
```

Let's look at the second method in our file that increments a counter by a provided argument until an upper cap of 10.

This function also accepts a parameter from JavaScript. When you're accepting parameters from JavaScript, you have to be careful because they are loosely typed objects. (You're probably already used to this in JavaScript.)

The arguments array contains `v8::Objects` so they are all JavaScript objects, but be careful with these, because in this context we can never be sure what they might contain. We have to explicitly check for the types of these objects. Fortunately, there are helper methods added to these classes to determine their type before typecasting.

To maintain compatibility with existing JavaScript code, we have to throw some error if the arguments type is wrong. To throw a type error, we have to create an Error object with the `v8::Exception::TypeError()` constructor. The following block will throw a `TypeError` if the first argument is not a number.

```
if (!args[0]->IsNumber()) {
    isolate->ThrowException(v8::Exception::TypeError(
          v8::String::NewFromUtf8(isolate, "Argument must be a 
number")));
    return;
}
```

In JavaScript that snippet would look like:

```
If (typeof arguments[0] !== 'number') {
  throw new TypeError('Argument must be a number')
}
```

We also have to handle if our counter goes out of bounds. We can create a custom exception just like we would do in JavaScript: `new Error(error message')`.

In C++ with the v8 api it looks like: `v8::Exception:Error(v8::String::NewFromUtf8(isolate, “Counter went through the roof!”)));` where the isolate is the current scope that we have to first get the reference via the `v8::Isolate* isolate = args.GetIsolate();`.

```
double argsValue = args[0]->NumberValue();
if (numberOfCalls + argsValue > maxValue) {
  isolate->ThrowException(v8::Exception::Error(
        v8::String::NewFromUtf8(isolate, “Counter went through the
roof!”)));
  return;
}
```

After we handled everything that could go wrong, we add the argument to the counter variable that’s available in our C++ scope. That looks like as if it was JavaScript code. To return the new value to JavaScript code, first we have to make the conversion from `integer` in C++ to `v8::Number` that we can access from JavaScript. First we have to cast our integer to double with `static_cast<double>()` and we can pass its result to the `v8::Number` constructor.

```
auto currentNumberOfCalls =
  v8::Number::New(isolate, static_cast<double>(numberOfCalls));
```

`NODE_SET_METHOD` is a macro that we use to assign a method on the exports object. This is the very same exports object that we’re used to in JavaScript. That is the equivalent of:

```
exports.whoami = WhoAmI
```

In fact, all Node.js addons must export an initialization function following this pattern:

```
void Initialize(v8::Local<v8::Object> exports);
NODE_MODULE(module_name, Initialize)
```

All C++ modules have to register themselves into the node module system. Without these lines, you won’t be able to access your module from JavaScript. If you accidentally forget to register your module, it will still compile, but when you’re trying to access it from JavaScript you’ll get the following exception:

```
module.js:597
  return process.dlopen(module, path._makeLong(filename));
               ^

Error: Module did not self-register.
```

From now on when you see this error you'll know what to do.

COMPILING OUR NATIVE NODE.JS MODULE

Now we have a skeleton of a C++ Node.js module ready, so let's compile it! The compiler we have to use is called `node-gyp` and it comes with `npm` by default. All we have to do is add a `binding.gyp` file which looks like this:

```
{
  "targets": [
    {
      "target_name": "addon",
      "sources": [ "example.cc" ]
    }
  ]
}
```

`npm install` will take care of the rest. You can also use `node-gyp` in itself by installing it globally on your system with `npm install node-gyp -g`.

Now that we have the C++ part ready, the only thing remaining is to get it working from within our Node.js code. Calling these addons are seamless thanks to the `node-gyp` compiler.
It's just a `require` away.

```
const myAddon = require('./build/Release/addon')
console.log(myAddon.whoami())
```

This approach works, but it can get a little bit tedious to specify paths every time, and we all know that relative paths are just hard to work with. There is a module to help us deal with this problem.

The `bindings` module is built to make `require` even less work for us. First, let's install the `bindings` module with `npm install bindings --save`, then make a small adjustment in our code snippet right over there.

We can `require` the bindings module, and it will expose all the .node native extensions that we've specified in the `binding.gyp` files `target_name`.

```
const myAddon = require('bindings')('addon')
console.log(myAddon.whoami())
```

These two ways of using the binding is equivalent.

This is how you create native bindings to Node.js and bridge it to JavaScript code. But there is one small problem: Node.js is constantly evolving, and the interface just tends to break a lot! This means that targeting a specific version might not be a good idea because your addon will go out of date fast.

Think ahead and use Native Abstractions for Node.js (NaN).

The NaN library started out as a third party module written by independent individuals, but from late 2015 it became an incubated project of the Node.js foundation.

NaN provides us a layer of abstraction on top of the Node.js API and creates a common interface on top of all versions. It's considered a best practice to use NaN instead of the native Node.js interface, so you can always stay ahead of the curve.

To use NaN, we have to rewrite parts of our application, but first, let's install it with `npm install nan --save`. First, we have to add the following lines into the targets field in our `bindings.gyp`. This will make it possible to include the NaN header file in our program to use NaN's functions.

```
{
  "targets": [
    {
      "include_dirs" : [
        "<!(node -e \"require('nan')\")"
      ],
      "target_name": "addon",
      "sources": [ "example.cc" ]
    }
  ]
}
```

We can replace some of the v8's types with NaN's abstractions in our sample application. It provides us helper methods on the call arguments and makes working with v8 types a much better experience.

The first thing you'll probably notice is that we don't have to have explicit access to the JavaScript's scope, via the `v8::Isolate* isolate = args.GetIsolate();` NaN handles that automatically for us. Its types will hide bindings to the current scope, so we don't have to bother using them.

```
#include <nan.h>

const int maxValue = 10;
int numberOfCalls = 0;

void WhoAmI(const Nan::FunctionCallbackInfo<v8::Value>& args) {
  auto message = Nan::New<v8::String>("I'm a Node Hero!").ToLocalChecked();
  args.GetReturnValue().Set(message);
}

void Increment(const Nan::FunctionCallbackInfo<v8::Value>& args) {
  if (!args[0]->IsNumber()) {
    Nan::ThrowError("Argument must be a number");
    return;
  }

  double argsValue = args[0]->NumberValue();
  if (numberOfCalls + argsValue > maxValue) {
    Nan::ThrowError("Counter went through the roof!");
    return;
  }

  numberOfCalls += argsValue;

  auto currentNumberOfCalls =
    Nan::New<v8::Number>(numberOfCalls);

  args.GetReturnValue().Set(currentNumberOfCalls);
}

void Initialize(v8::Local<v8::Object> exports) {
  exports->Set(Nan::New("whoami").ToLocalChecked(),
      Nan::New<v8::FunctionTemplate>(WhoAmI)->GetFunction());
  exports->Set(Nan::New("increment").ToLocalChecked(),
      Nan::New<v8::FunctionTemplate>(Increment)->GetFunction());
}

NODE_MODULE(addon, Initialize)
```

Now we have a working and also idiomatic example of how a Node.js native extension should look like.

First, we've learned about structuring the code, then about compilation processes, then went through the code itself line by line to understand every small piece of it. At the end, we looked at NaN's provided abstractions over the v8 API.

There is one more small tweak we can make, and that is to use the provided macros of NaN.

Macros are snippets of code that the compiler will expand when compiling the code. More on macros can be found in this documentation. We had already been using one of these macros, `NODE_MODULE`, but NaN has a few others that we can include as well. These macros will save us a bit of time when creating our native extensions.

```
#include <nan.h>

const int maxValue = 10;
int numberOfCalls = 0;

NAN_METHOD(WhoAmI) {
  auto message = Nan::New<v8::String>("I'm a Node Hero!").ToLocalChecked();
  info.GetReturnValue().Set(message);
}

NAN_METHOD(Increment) {
  if (!info[0]->IsNumber()) {
    Nan::ThrowError("Argument must be a number");
    return;
  }

  double infoValue = info[0]->NumberValue();
  if (numberOfCalls + infoValue > maxValue) {
    Nan::ThrowError("Counter went through the roof!");
    return;
  }

  numberOfCalls += infoValue;

  auto currentNumberOfCalls =
    Nan::New<v8::Number>(numberOfCalls);

  info.GetReturnValue().Set(currentNumberOfCalls);
}

NAN_MODULE_INIT(Initialize) {
  NAN_EXPORT(target, WhoAmI);
  NAN_EXPORT(target, Increment);
}

NODE_MODULE(addon, Initialize)
```

The first `NAN_METHOD` will save us the burden of typing the long method signature and will include that for us when the compiler expands this macro. Take note that if you use macros, you'll have to use the naming provided by the macro itself - so now instead of `args` the arguments object will be called `info`, so we have to change that everywhere.

The next macro we used is the `NAN_MODULE_INIT` which provides the initialization function, and instead of exports, it named its argument `target` so we have to change that one as well.

The last macro is `NAN_EXPORT` which will set our modules interface. You can see that we cannot specify the objects keys in this macro, it will assign them with their respective names.

That would look like this in modern JavaScript:

```
module.exports = {
  Increment,
  WhoAmI
}
```

If you’d like to use this with our previous example make sure you change the function names to uppercase, like this:

```
‘use strict’

const addon = require(‘./build/Release/addon.node’)

console.log(`native addon whoami: ${addon.WhoAmI()}`)

for (let i = 0; i < 6; i++) {
  console.log(`native addon increment: ${addon.
Increment(i)}`)
}
```

For further documentation refer to Nan’s Github page.

Example Repository

We’ve created a repository with all the code included in this post. The repository is under GIT version control, and available on GitHub. Each of the steps have their own branch, master is the first example, nan is the second one and the final step’s branch is called macros.

Conclusion

I hope you had as much fun following along, as we’ve had writing this book. We’d highly recommend getting into at least a bit of C/C++ to understand the lower levels of the platform itself. You’ll surely find something of your interest. :)

If you enjoyed this book, we recommend to check out our Node.js Debugging and Monitoring solution called Trace - which helps you to build even better applications!