Server Farm to Table

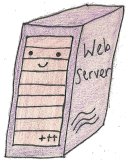
(or, how the Internet works)

Jenna Zeigen
@zeigenvector

So, what *does* happen when you type www.google.com into the browser?

Server Farm to Table

(or, how the Internet works)



nm, u?

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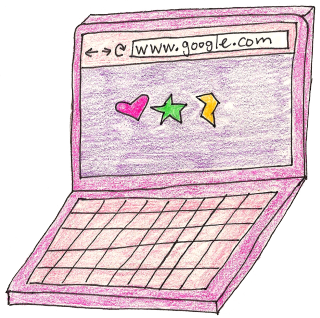

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The OSI model is a really good way of thinking about processes like these. It details seven layers, from Layer 1 which talks about physical bits in the computer, through Layer 7, which is the full application layer, so things like the browser. This talk is going to start at Layer 4, which is transport. We won't be talking about anything lower than that, so no networking, though I'm sure there's plenty of stuff all over the Internet if you want to learn more about those lower layers.

Overview

1. IP Address Lookup
2. Opening a socket
3. Security Stuff
4. HTTP Request
5. Server Things
6. HTTP Response
7. Parsing
8. Rendering

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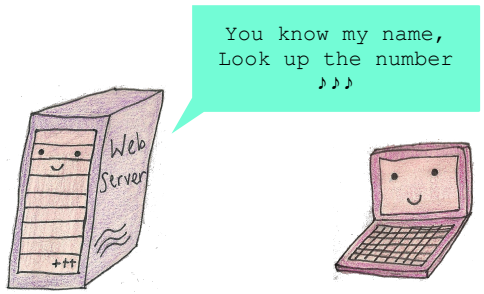
I'm going to go through all of these and talk about optimizations along the way!

IP Address Lookup



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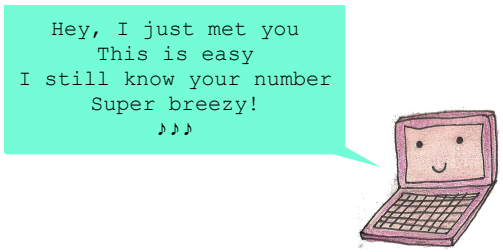
To do anything, we need to map the human readable URL "www.google.com" to the address of a computer to "talk to."

IP Address Lookup



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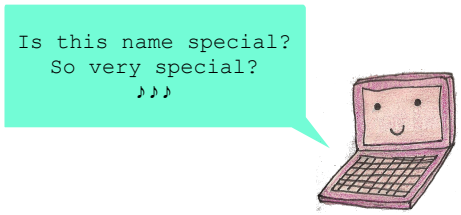
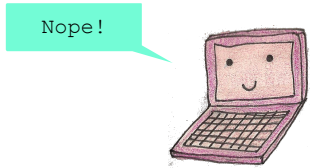
First, the browser checks its cache.

IP Address Lookup



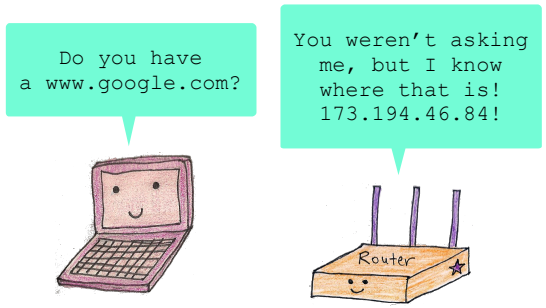
If not found, the browser calls the `gethostbyname` library function, the contents of which vary by OS, to do the lookup. This function checks if the hostname can be resolved by reference in the local hosts file, the location of which also varies by OS. On Macs, it's at `/etc/hosts`. This is how your computer knows what localhost should resolve to. If you wanna check it out, you can type `cat /etc/hosts` into your terminal and see what's in there!

IP Address Lookup

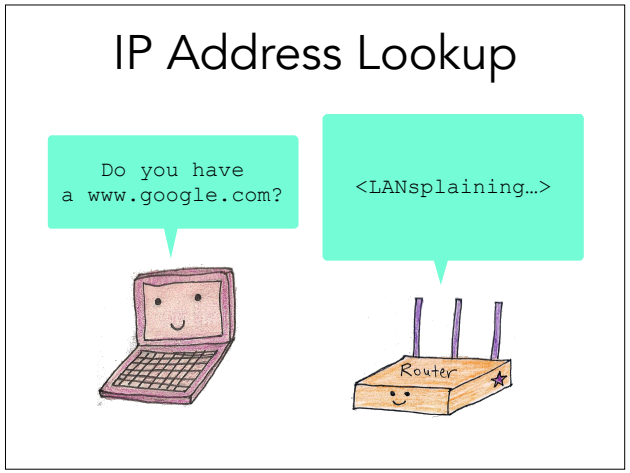


If `gethostbyname` does not have it cached and can't find it in the hosts file, then it makes a request to the DNS server configured in the network stack. This is typically the ISP's caching DNS server, but you could configure your computer to use any DNS server, i.e. Google's (8.8.8.8) if you wanted…

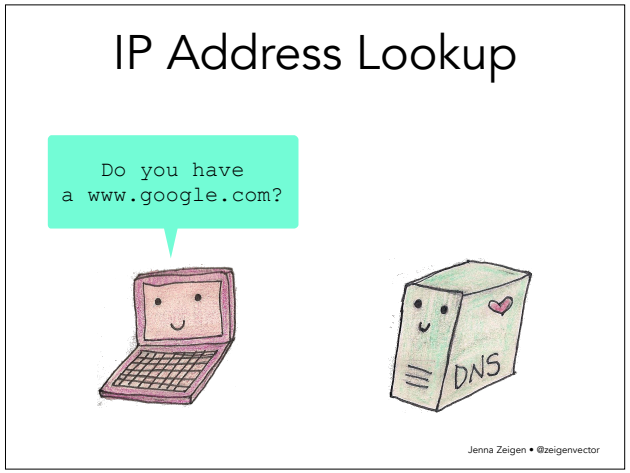
IP Address Lookup



The browser then kicks off a request to get the IP address for www.google.com, which goes through the local router, which also checks its cache.

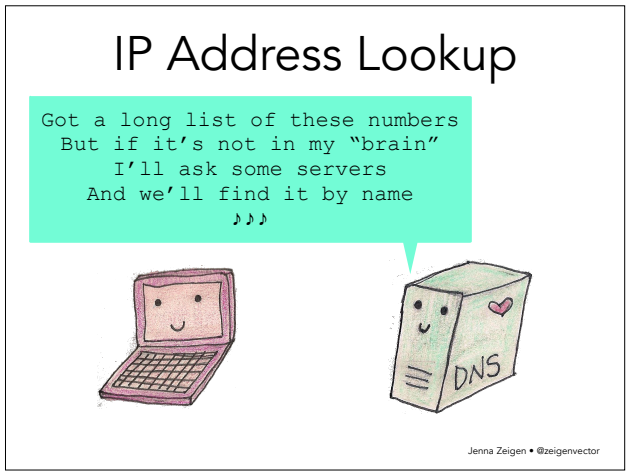


(Big thanks to @jedschmidt for this witty commentary)

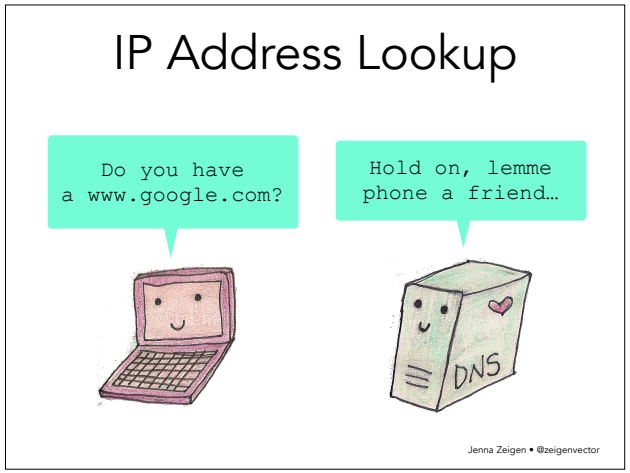


If the local router doesn't have anything cached, the browser ends up hitting the local ISP DNS server. This process uses UDP (User Datagram Protocol), or TCP if the request is too large.

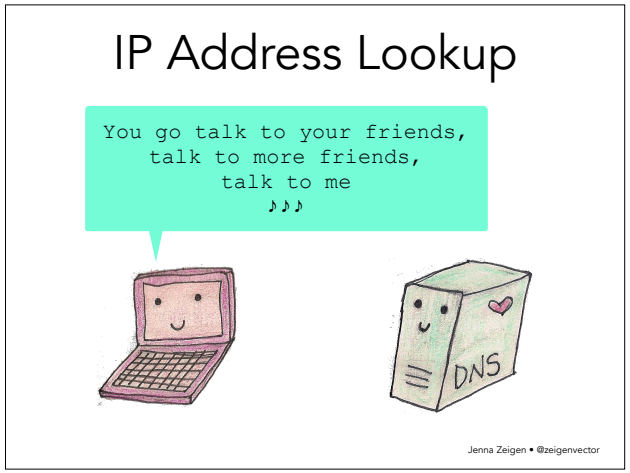
UDP is kind of like the smallest bit of network you can use. It's great for unidirectional transactions, but delivery is not guaranteed in any order, or guaranteed at all. It's kind of like if you were to through a bunch of balls at someone and hope that they catch them.



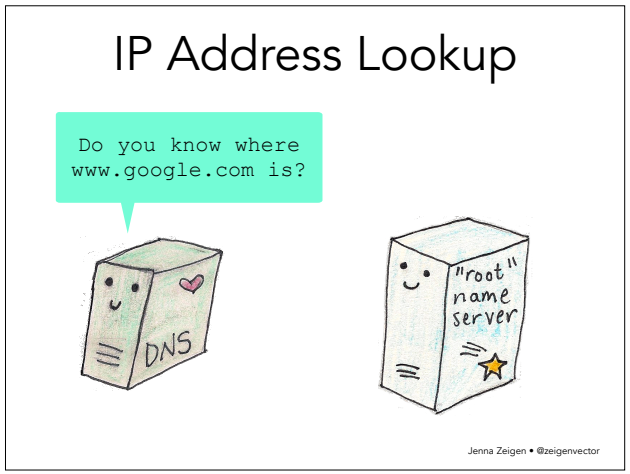
Upon receiving the request, the DNS server first checks its cache.



If it doesn't have the address in its cache, it recursively looks up the address by asking some more servers…



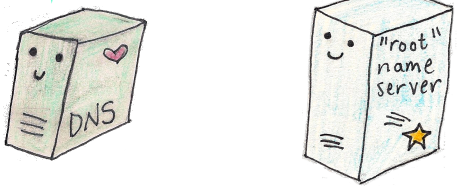
(Meanwhile, the client has to wait a while for the answer…)



IP Address Lookup

Do you know where www.google.com is?

No, but maybe ask ".com"?



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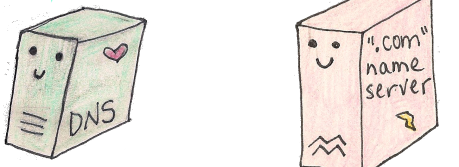
IP Address Lookup

Do you know where www.google.com is?



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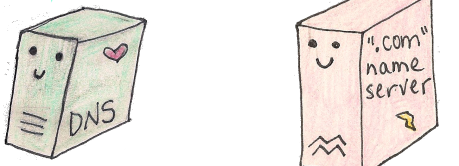
IP Address Lookup

Do you know where www.google.com is?

No, but maybe ask "google.com"?



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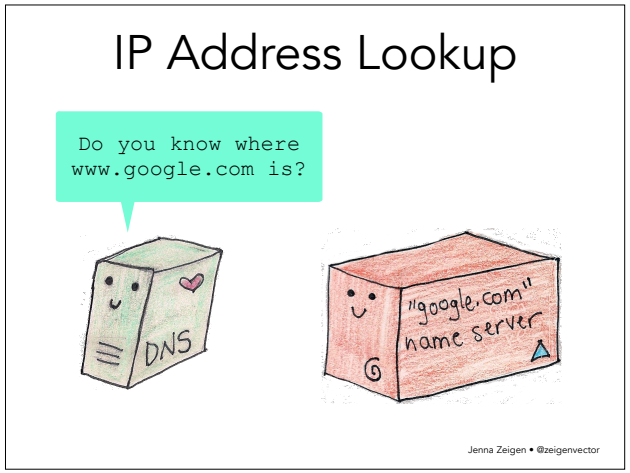
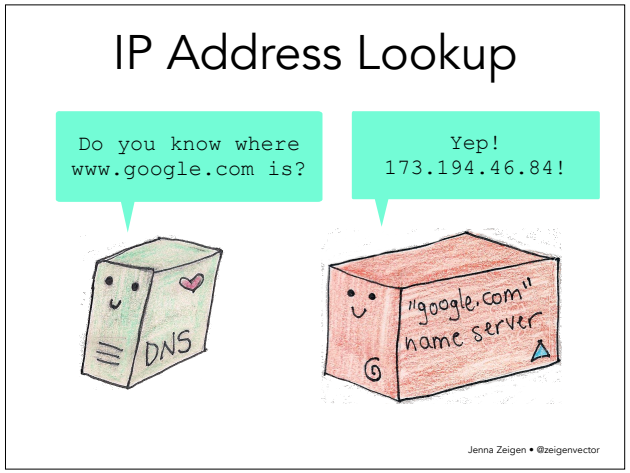
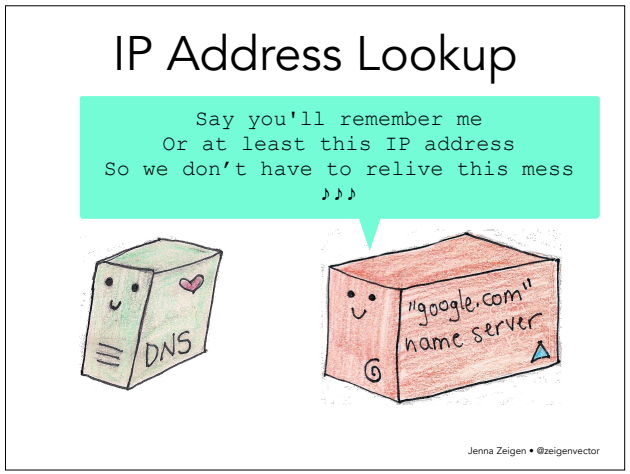
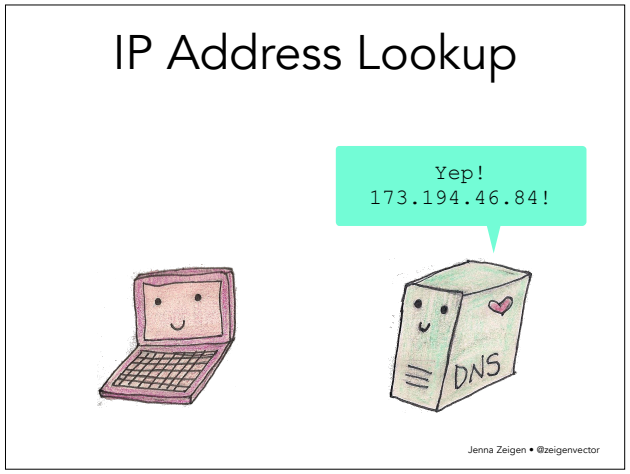


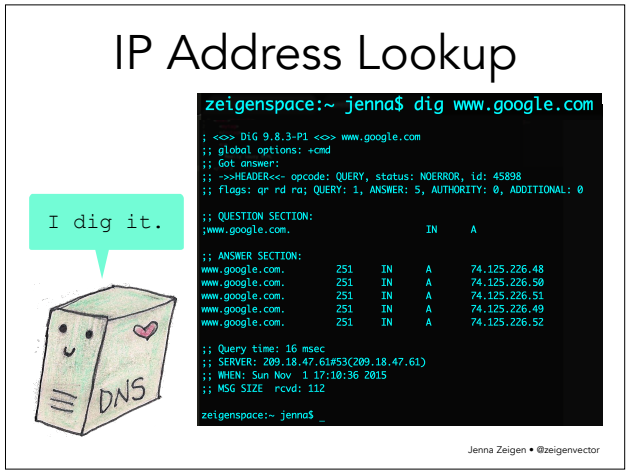




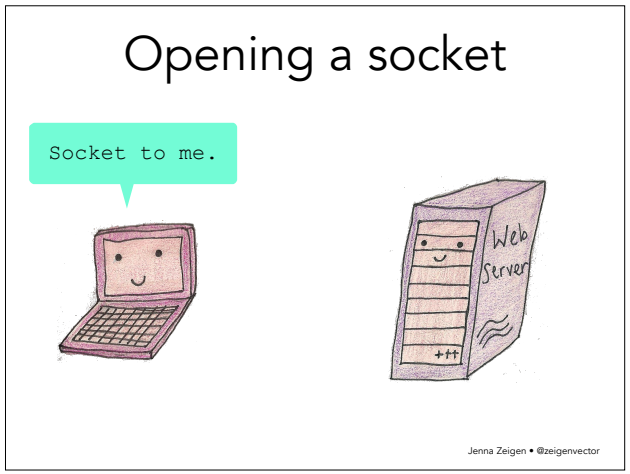
When the name server comes back to the DNS server with the IP address answer, it will also come back with a TTL (time to live), an amount of time that the DNS server should cache the IP address. The longer the TTL, the faster this process, but then it's harder to change things. Historically, this TTL was 24 hours, which is why it could take up to 24 hours for the URL corresponding to an IP to change.



The DNS server then responds to the client with the found IP address.

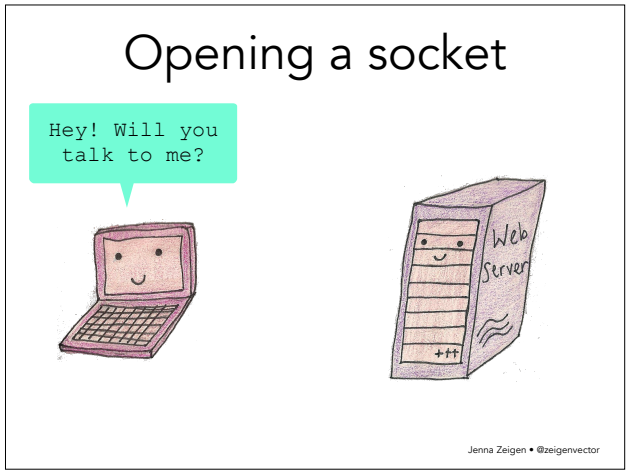


If you want to check out this process hands-on, you can use the `dig` command in your terminal.

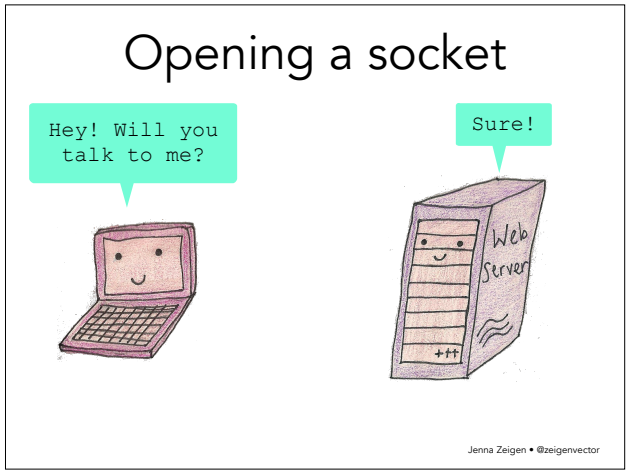


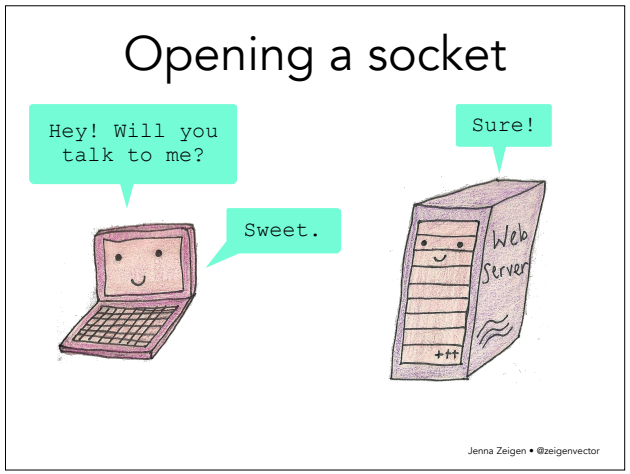
Once the client has the IP address, it takes it and the port number from the URL, and makes a call to the system library function named `socket` and requests a TCP socket stream. We don't usually see port numbers on the end of URLs, but the HTTP protocol defaults to Port 80, and HTTPS to Port 443.

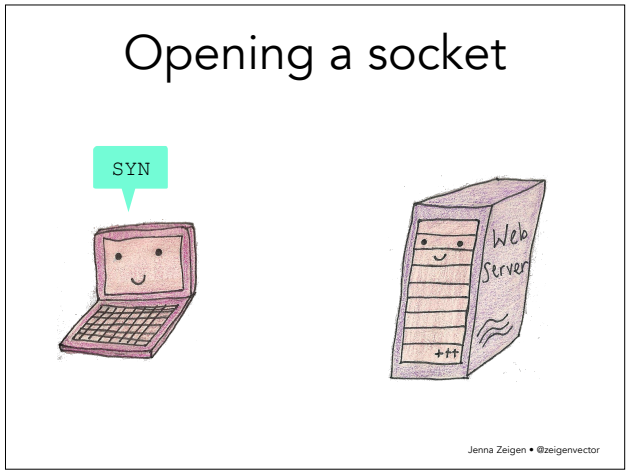
TCP stands for "Transmission Control Protocol." Unlike UDP, its job is to deliver a reliable, ordered, and error checked stream of packets across the network. It's more like a game of catch, to continue the ball metaphor. In fact, it's often called the "TCP handshake". TCP is the protocol that underlies HTTP, TLS, FTP, email, and SSH.



The client then establishes TCP connection(s) with the server. It's kinda like this…

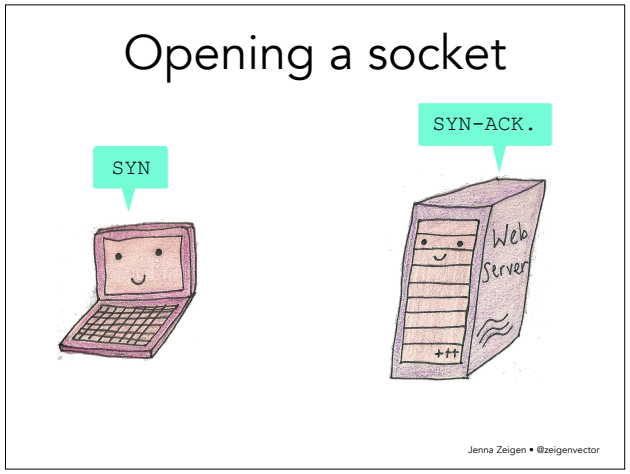




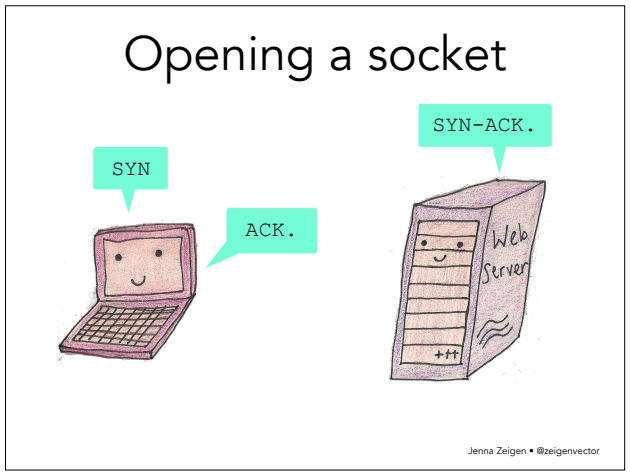


Well, more specifically like this…

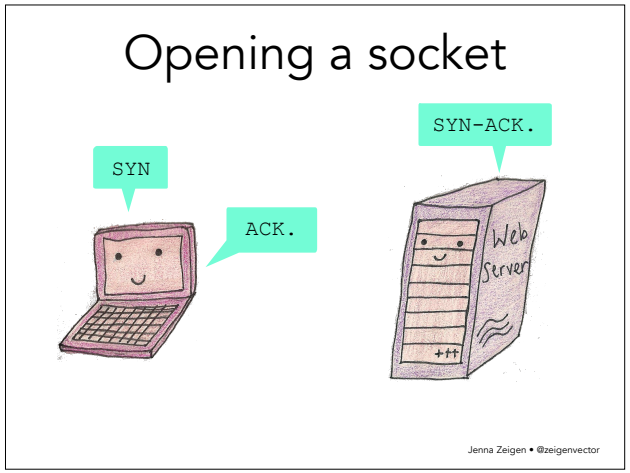
1. The client sends a SYN packet with a randomly-selected sequence number “x”



2. The server replies with a SYN-ACK packet with an acknowledgement number set to “x+1” and a different randomly-selected sequence number “y”



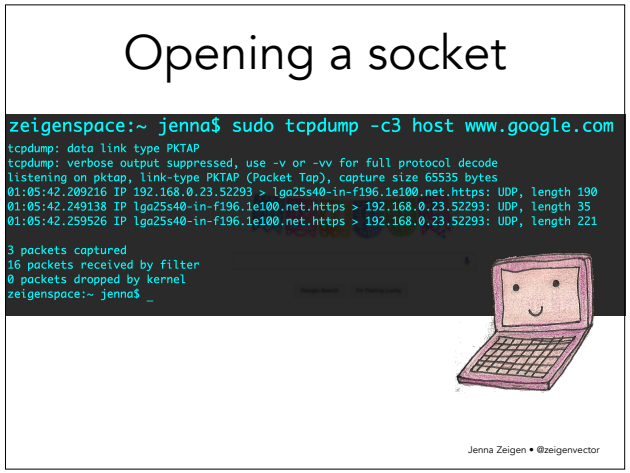
3. The client responds with an ACK packet, with the sequence number set to the received acknowledgement number “x+1”, and a new acknowledgement number set to “y+1”



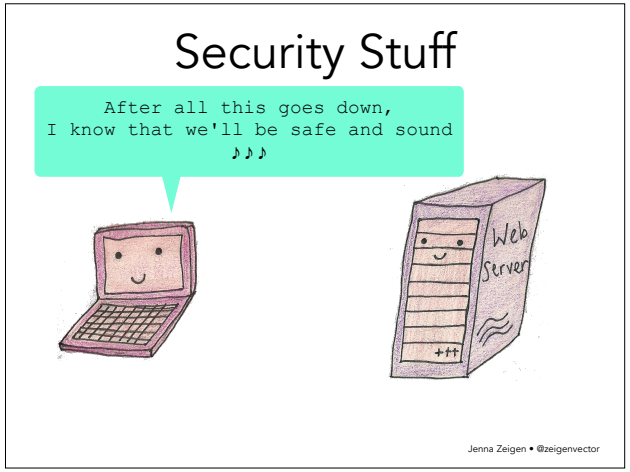
To prepare for the likely event that the client is going to need more things from the server, more than one connection will be opened.

TCP also has congestion control— requests start small and ramp up in size to make sure the network can support the requests. This is more of a relic from the past when networks weren't as reliable or fast.

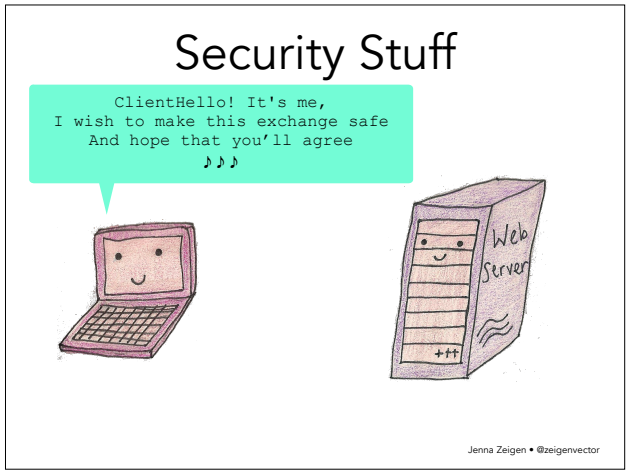
In addition, TCP is where much the latency in this entire process comes from, as it's constrained by the speed of light. This is why it is advantageous to server assets from a server as close to your user as possible.



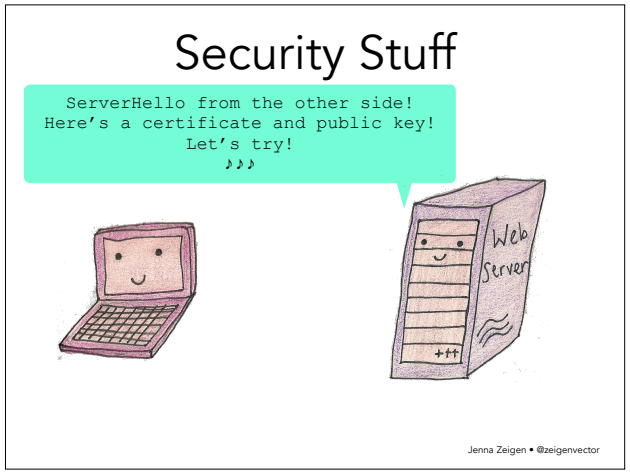
If you want to check out TCP for yourself, you can use `tcpdump` from your terminal. `tcpdump` will show you all the network traffic, which is why you see UDP packets here. If you prefer a GUI option, you can also use Wireshark.



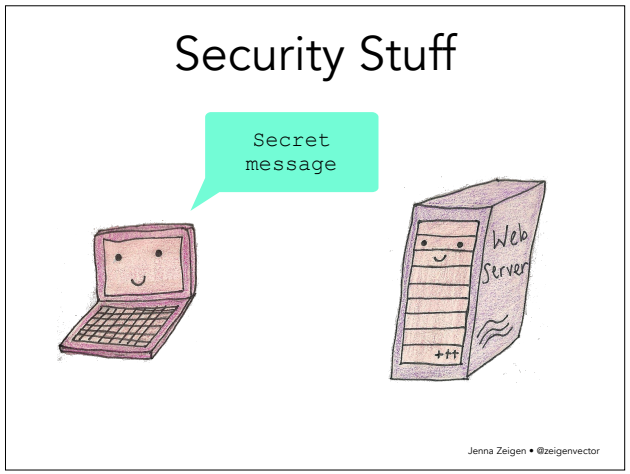
If the request is over HTTPS, we need another step to ensure the security of the transaction. HTTPS uses TLS, or Transport Layer Security. TLS's predecessor was Secure Sockets Layer (SSL).



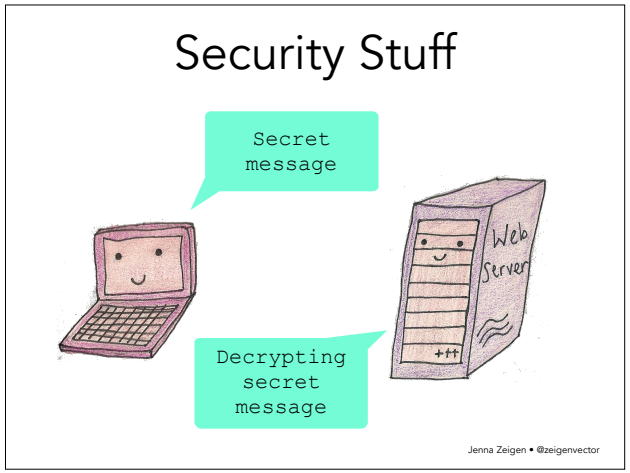
To kick of the process, the client computer sends a ClientHello message to the server with its TLS version, list of cipher algorithms and compression methods available.



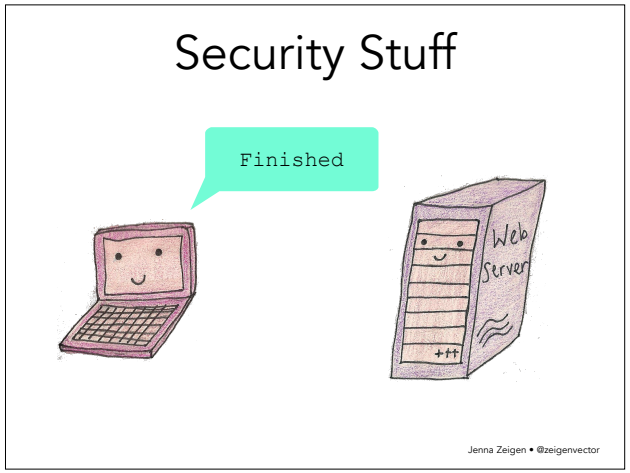
The server replies with a ServerHello message to the client with the TLS version, selected cipher, selected compression methods and the server's public certificate. The certificate contains a public key that will be used by the client to encrypt the rest of the handshake until a symmetric key can be agreed upon.



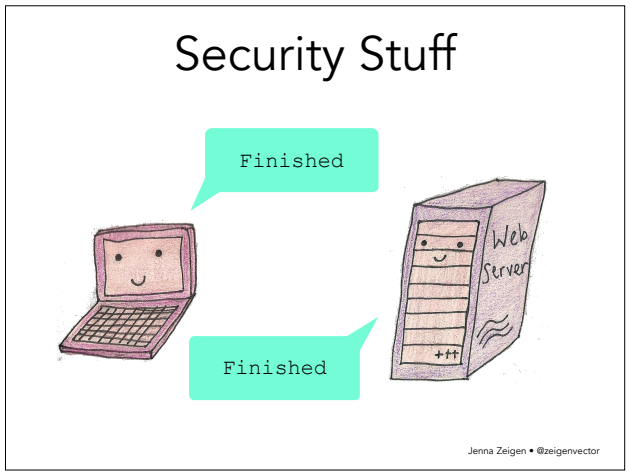
The client verifies the server digital certificate. If trust can be established, the client generates a string of pseudo-random bytes and encrypts this with the server's public key.



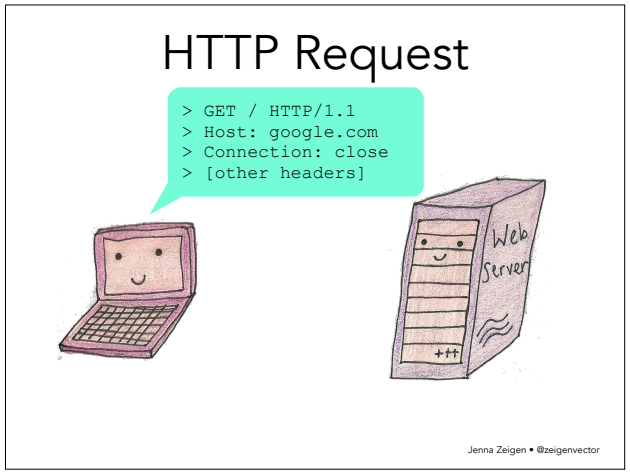
The server then decrypts the message and uses it to create its own version of the symmetric key.



The client sends a Finished message to the server, encrypting a hash of the transmission up to this point with the symmetric key.

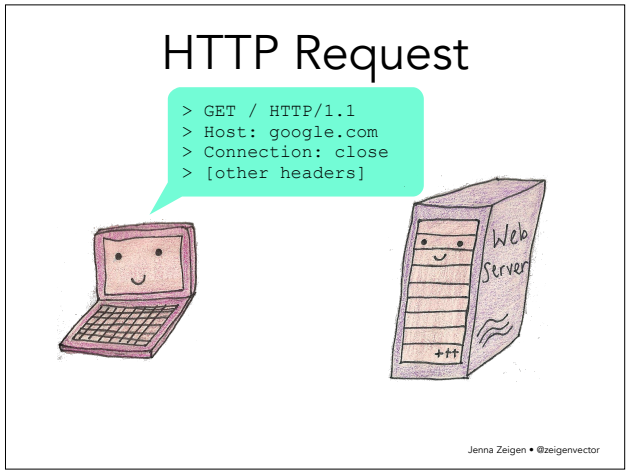


The server generates its own hash, and then decrypts the client-sent hash to verify that it matches. If it does, it sends its own Finished message to the client, also encrypted with the symmetric key.

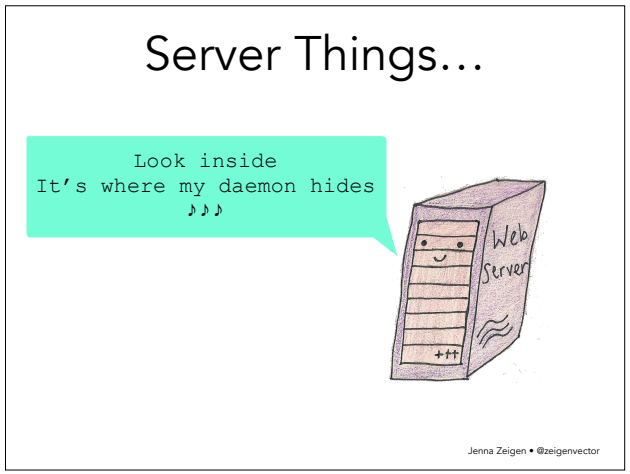


With all this done, the client is ready to send an HTTP request to the server. HTTP stands for "HyperText Transfer Protocol." Unless the client and server negotiate using a more advanced version of HTTP, they're going to use HTTP/1.1.

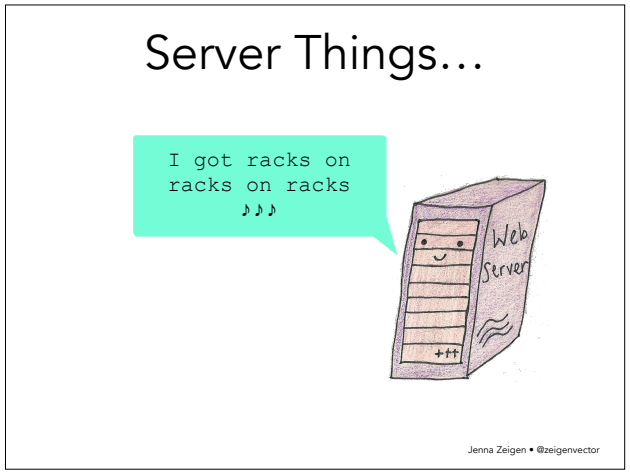
HTTP/1.1 is stateless, uses a request/response model, and is a plain-text protocol.



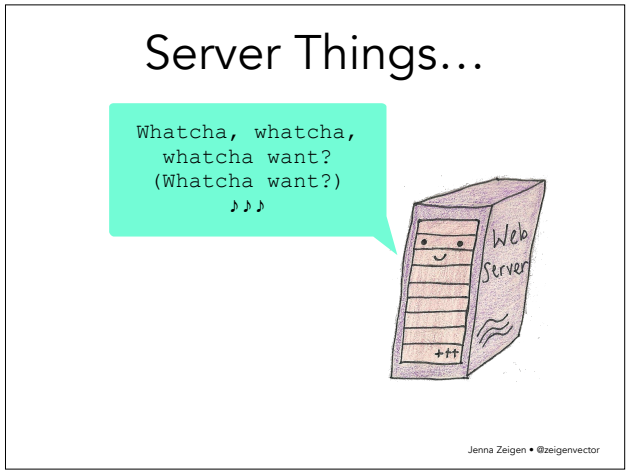
The client will send an request like this, containing the request and headers, followed by a single blank newline to the server indicating that the content of the request is done.



The server then processes the request. The HTTPD (HTTP Daemon) server is the one handling the requests and responses on the server side. Some popular HTTPD servers are Apache and nginx.

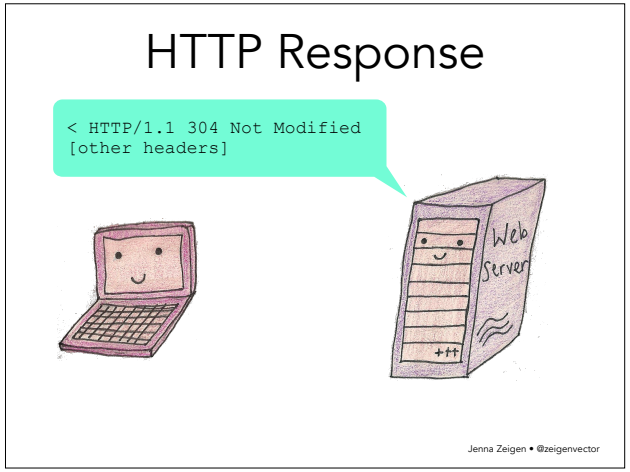


The server is going to do a bunch of "server stuff" including load balancing, routing, and database calls.



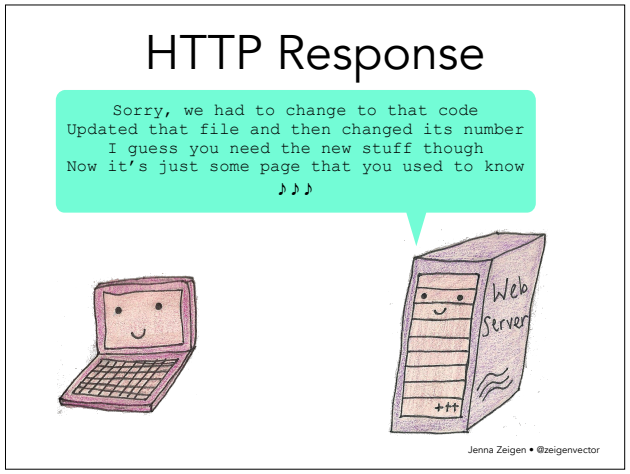
The server breaks down the request to the following parameters:

1. HTTP Request Method (either GET, POST, PUT, etc.). In this case, with a URL entered directly into the address bar, this will be GET.
2. Domain. In this case the domain is "google.com."
3. Requested path/page. In this case, the path is "/" because no specific path or page was requested (/ is the default, root path, just like in the Unix file system).

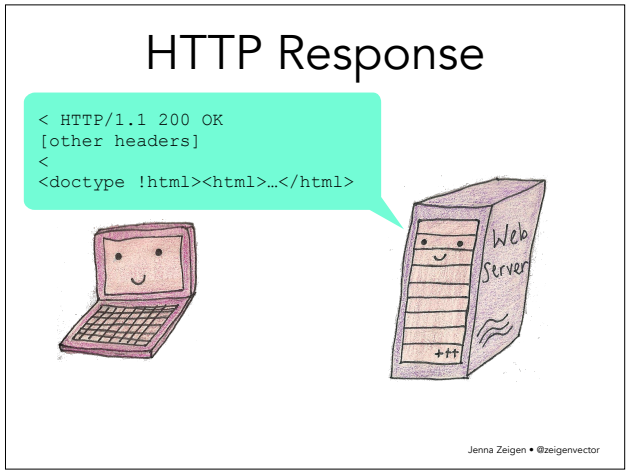


If you've been to this site before, and the HTTP headers sent by the web browser included sufficient information for the server to determine if the version of the file cached by the web browser has been unmodified since the last retrieval, it may instead respond with something like this.

This is so much less work for the client and server at this point, but is the result of author work, making sure that the proper mechanisms are in place for the required data to be transmitted.

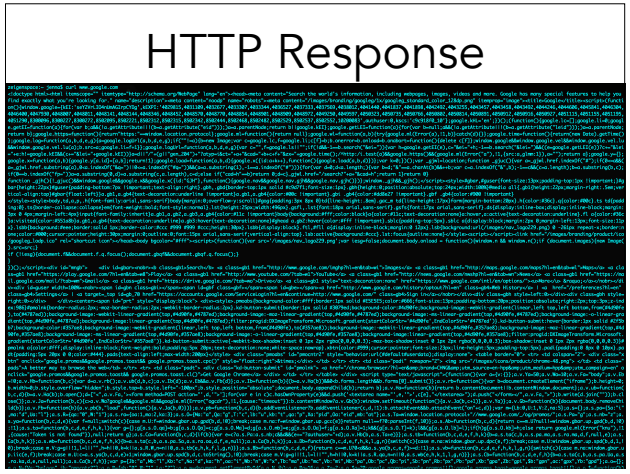


For example, having ETags in the header will allow the server to determine if the cached version of a page is still valid. The first time the server sends the page, it will send an ETag, a unique identifier for the version of the page, in the header of the response. The client will then cache this. The next time the client needs this page, it will get the ETag from it's cached version and send it to the server. If the ETags match, the server will send the `304 Not Modified` status code.

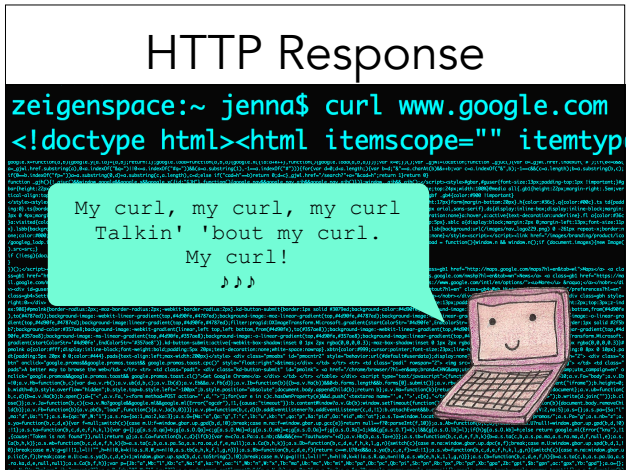


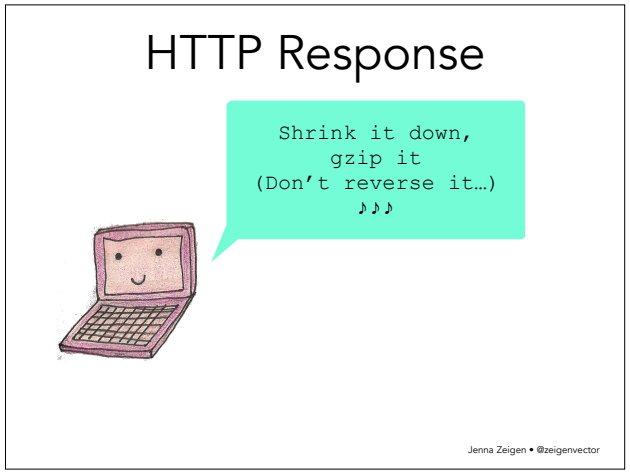
If they don't match, then there's much more to be done. An otherwise successful request and smooth servering process will prompt the server to send a response like this, with a 200 OK status code, other headers, a single blank newline, and then the payload, which in this case is the entire HTML document.

If something went wrong, you could also get less-happy status codes. The 400-series represents a client error like `403 Forbidden` or `404 Not Found`. The 500-series represents server errors, such as the `500 Internal Server Error`.



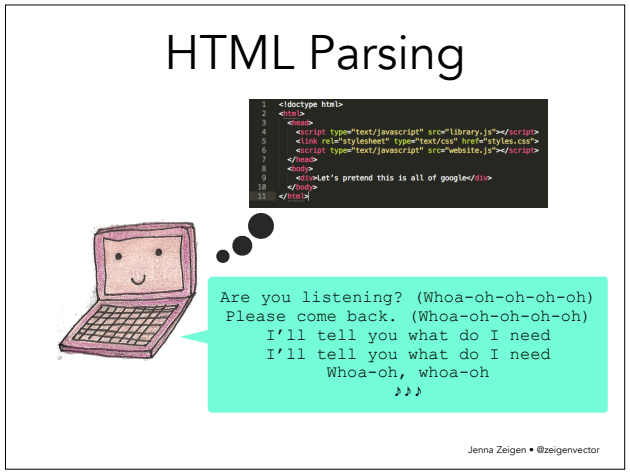
If you want to investigate what's going on in an HTTP request, you can use `curl` from your terminal.



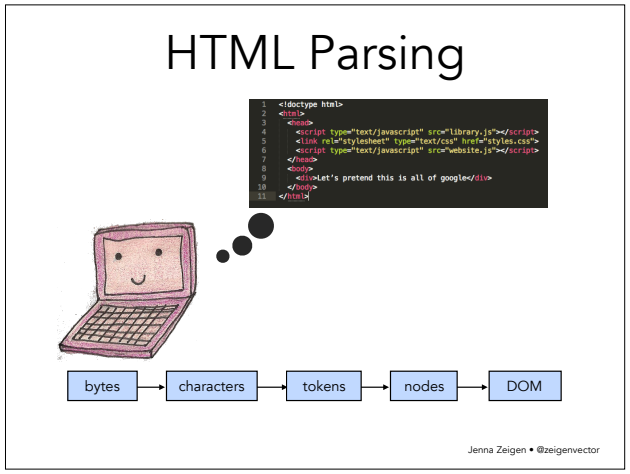


With HTTP, the size of the request directly correlates to the time it takes to finish the request. Because of this, compression helps a lot to get your page to the user as fast as possible. Gzip is most popular compression method for these web things. Gzip works by replacing repeated substrings with references to where the decompressor can find that substring, and this is great for HTML (think of how many times div appears in an HTML document! In fact, gzipping generally reduces the response size by about 70%. And if you're worried your users don't have this fancy compression method enabled in their browsers, about 90% of today's Internet traffic travels through browsers that claim to support gzip.

As soon as the browser starts receiving bytes, it starts parsing it. It usually receives it in 8kB chunks, and feeds those bytes right into the parser.

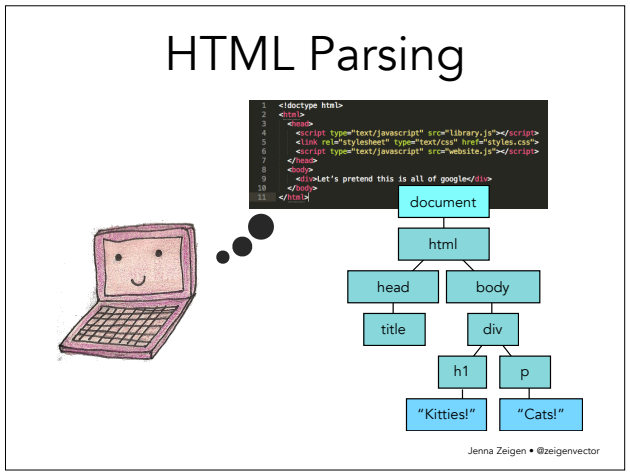


Before the formal parsing for rendering, the bytes get passed through a speculative parser, or look-ahead pre-parser. This parser looks ahead for external resources like JS, CSS, and image files so it can start getting them from the server immediately. If it finds them, it'll use the extra TCP requests, if they're from the same host. Otherwise, the client has to do the whole DNS dance again. This optimization wasn't always in the stack, but when released, improved page load performance by about 20%.

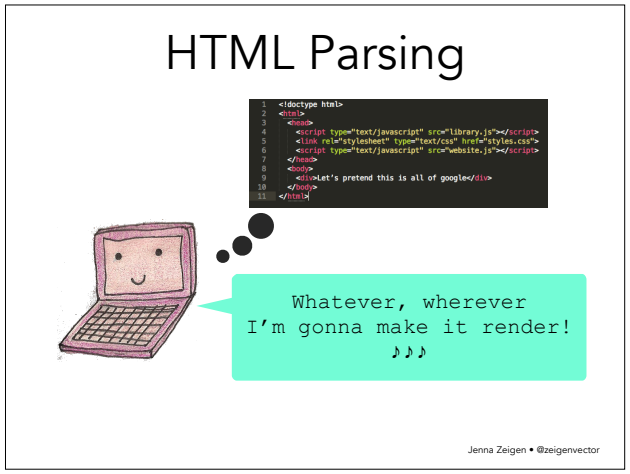


Meanwhile, the bytes are fed into the primary parser. The parsing algorithm is described in detail by the HTML5 specification. It goes something like this:

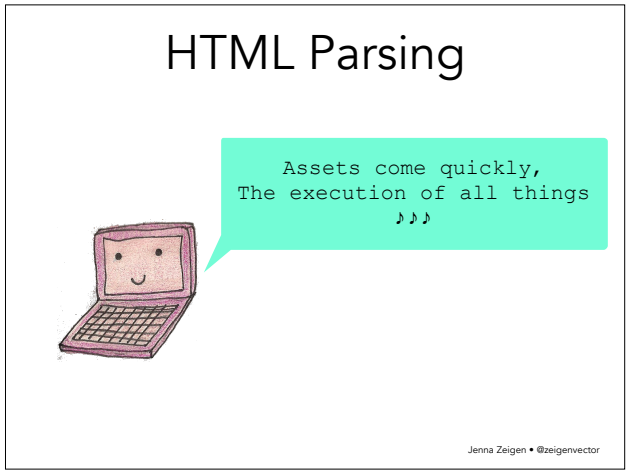
1. The browser reads the raw bytes of the HTML off the disk or network and translates them to individual characters based on specified encoding of the file, e.g. UTF-8.
2. The characters get broken up into tags, e.g. `html`, `head`, and `div`.
3. The tags then then get made into nodes.
4. The nodes are then arranged into the DOM tree.



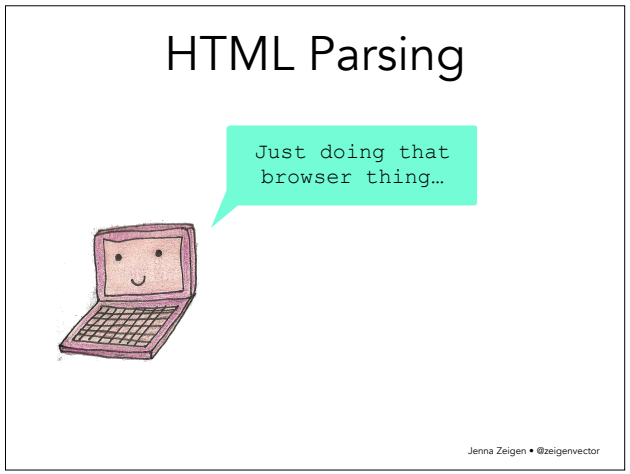
After this process, you end up with a DOM (Document Object Model) tree made from the HTML document. It has an almost one-to-one relationship with the markup.



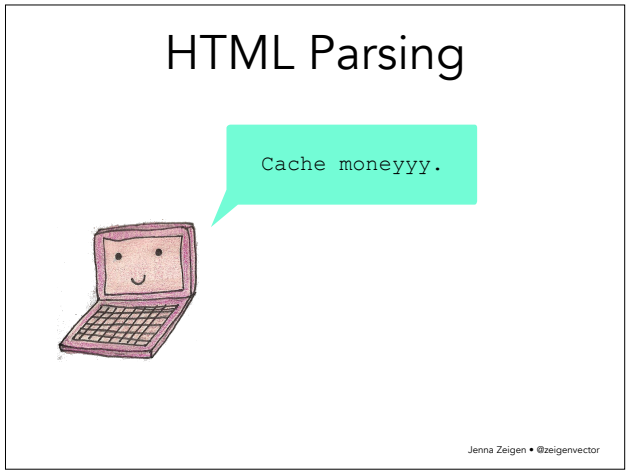
HTML cannot be parsed using the regular top-down or bottom-up parsers because of the forgiving nature of the language. The parser isn't context free because the HTML spec requires the parser to be 100% fault-tolerant. Thus, a lot of the parser's code is for fixing the HTML author mistakes, like invalid tags, unclosed tags, incorrect nesting. This means the parser will never error, but it also means browsers create custom parsers and are like a million lines of C++, and a big chunk is related to this parser.



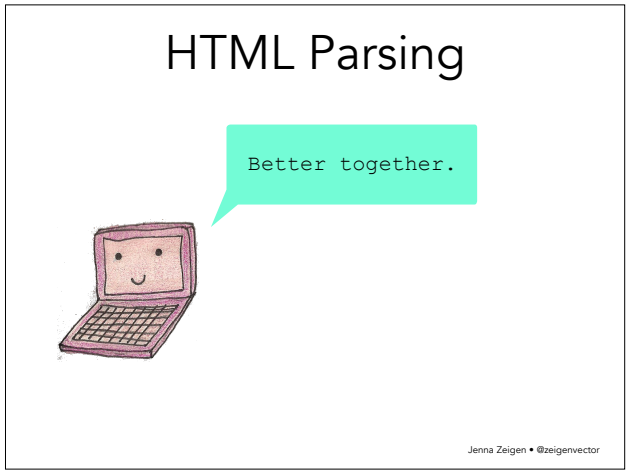
As the parser is parsing, it runs into inlined assets like images, scripts, and stylesheets. The client must request, parse, and execute them all as they are encountered. Hopefully the speculative parser has already started the fetching process!



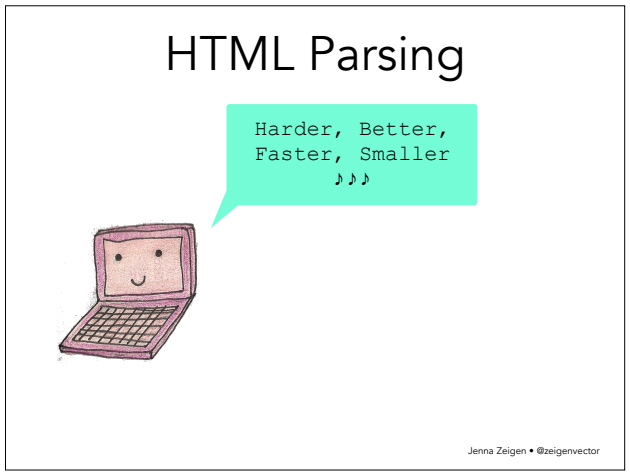
The big hiccup here is that browsers have imposed limits on how many parallel downloads you can have from the same domain. It used to be 2, but now that limit is anywhere from 6 to 13 in modern browsers, depending on the browser. This is a huge bottleneck, but many of the optimizations we hear about stem from trying to get around this. One thing you can do here is to serve your images from multiple hostnames, you can get around the same hostname parallel download limit. Concatenating files together also helps alleviate some pain here.



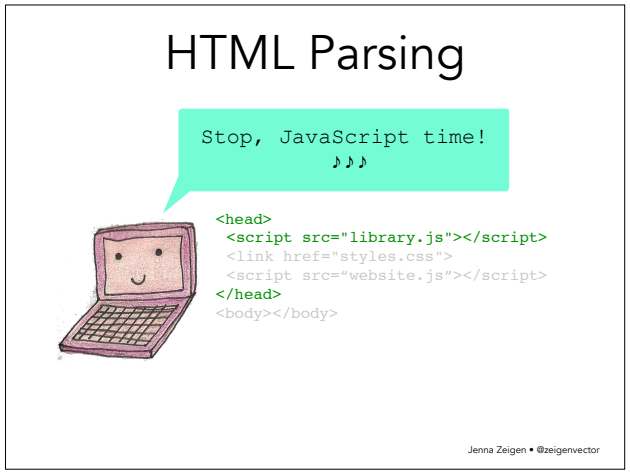
Caching also comes into play here, because TTL in this case is determined by the headers sent with the asset, such as a far-future Expires header. This helps because the file does not need to be downloaded again, therefore not contributing to the download limit.



Another popular optimization is to combine your files together. This includes concatenating JavaScript, making CSS sprites, and inlining your images as data:URIs. However, this might come back to bite you with caching because overtime you change just one file in your bundle, the cache gets invalidated. Because of this, some developers have two bundles— one for application code that is likely to change often and one for vendor code that is less likely to change.

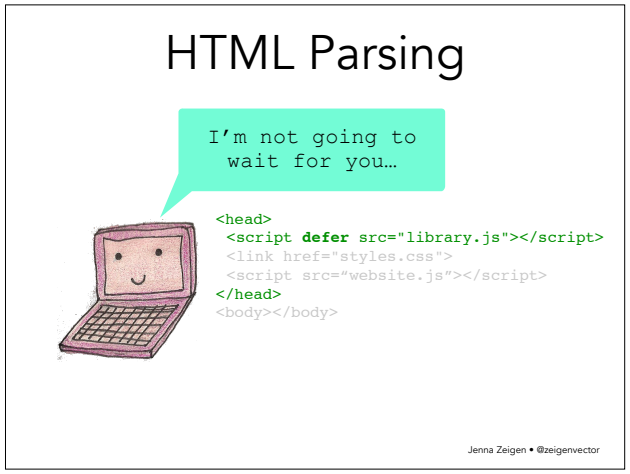


Still with referenced assets the size of the request affect the time it takes to download, so developers often gzip and minify all their CSS and JavaScript, as well as optimize their images. SVGs especially have extra information that can be removed if run through an optimizer such as svgo.

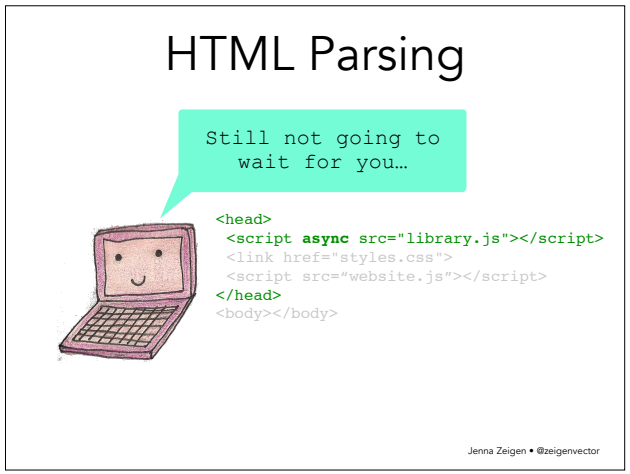


As the parser is doing its parsing and it runs into a JavaScript include, further parsing stops. This is because JavaScript has the ability to manipulate the DOM, using `document.write`, and any HTML that gets added must be fed back into the main parser. The parsing of the document halts until the script has been downloaded, if necessary, and executed. While a script is downloading, the browser won't start any other downloads, even on different hostnames.

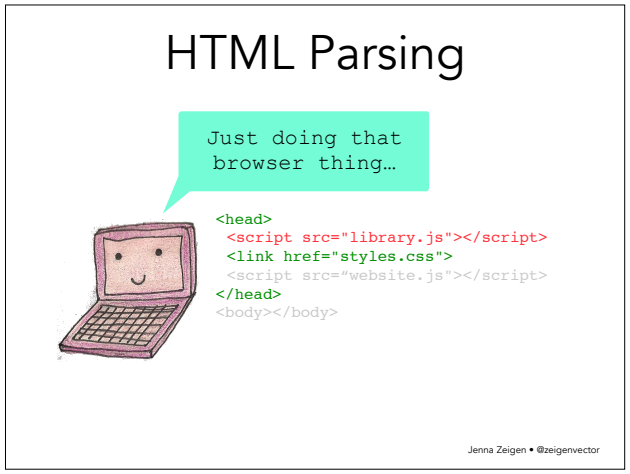
This explains the common optimization of putting scripts at the bottom of the page, right before `</body>`. Thus, when this blocking inevitably occurs, all the good things have already happened and you're well on your way to a render!



There are also spec-approved ways to get around this blocking too. Authors can add a "defer" attribute to a script tag, in which case it will not halt document parsing and will execute only after the document is parsed.

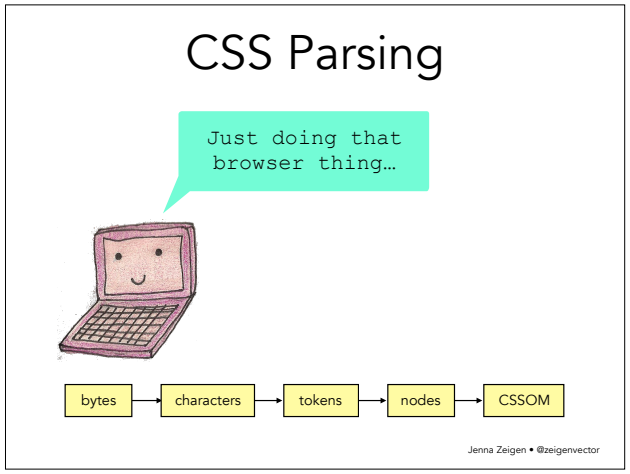


HTML5 adds an another option, to mark the script as asynchronous with the `async` attribute so it will be parsed and executed by a different thread, in parallel. With this, you're kinda promising you won't call `document.write`, or you're okay with it getting thrown out the window. (that was an attempt at a DOM pun…)

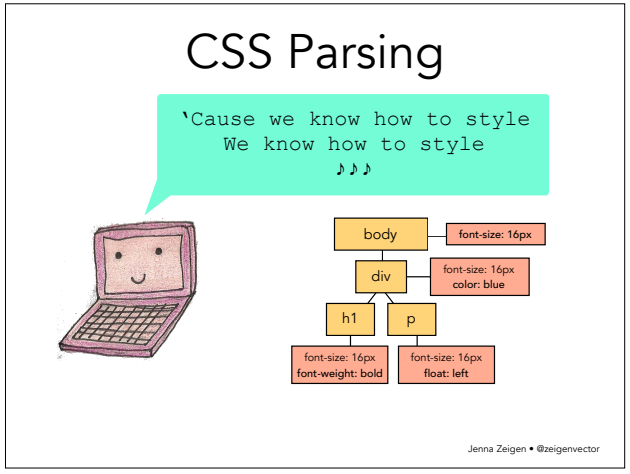


CSS also does its own kind of blocking. It might seem that since CSS doesn't change the DOM tree, there's no reason to wait for it and stop the document parsing. There is an issue, though, of scripts asking for style information during the document parsing stage. If the styles aren't loaded and parsed yet, the scripts will get wrong answers and apparently this has caused lots of problems. It seems to be an edge case but is quite common.

Different browsers have different ways of dealing with this blocking though. Firefox blocks all scripts when there is a stylesheet that is still being loaded and parsed. WebKit blocks scripts only when they try to access certain style properties that may be affected by unloaded stylesheets.



Just like with HTML, the browser needs to convert the CSS file into something it can work with. Instead of making a DOM tree though, it makes a CSSOM tree! The CSS parser, unlike the HTML parser, is context-free, though the steps in the process are largely the same.



The tree data structure makes for CSS because of the recursive nature of style application, the "cascade." It should be noted that the CSSOM tree only includes overrides to the browser's default stylesheet, so things that are included in the application's stylesheet and inlined in the HTML.

HTML Parsing

Just doing that browser thing…

```
<head>
 <script src="library.js"></script>
 <link href="styles.css"> ✓
 <script src="website.js"></script>
</head>
<body></body>
```

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So, once the CSS is done, the JavaScript can definitely continue to load.

HTML Parsing

Just doing that browser thing…

```
<head>
 <script src="library.js"></script> ✓
 <link href="styles.css"> ✓
 <script src="website.js"></script>
</head>
<body></body>
```

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Successive assets then can be downloaded and parsed.

HTML Parsing

Closing tag… ♪♪♪

```
<head>
 <script src="library.js"></script> ✓
 <link href="styles.css"> ✓
 <script src="website.js"></script> ✓
</head>
<body></body>
```

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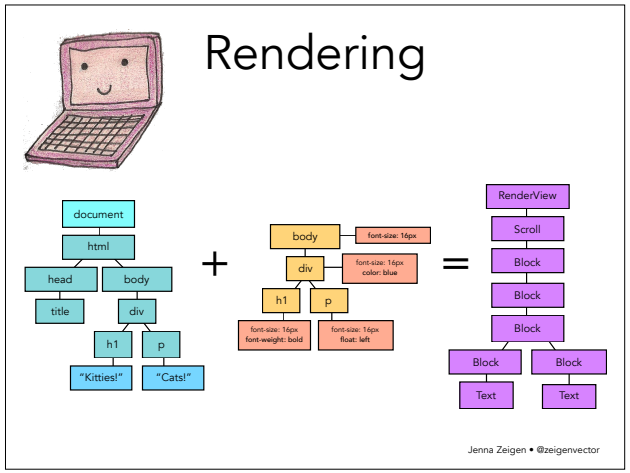
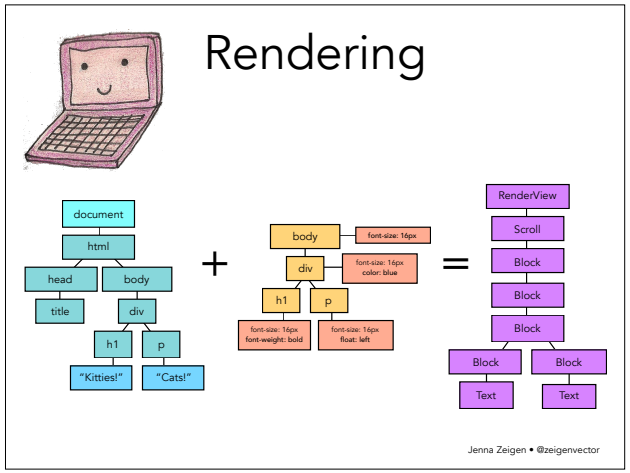
Eventually, the whole document will be fed into the parser and made into DOM tree.

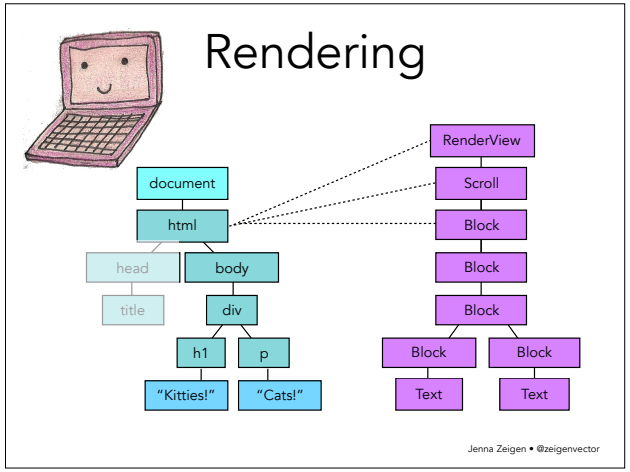


While it's important to download all the assets in the right order, rendering is just as integral a job for the browser. To kick off rendering the page, CSSOM and DOM trees are combined into a render tree, which is then used to compute the layout of each visible element and serves as an input to the paint process which renders the pixels to screen.

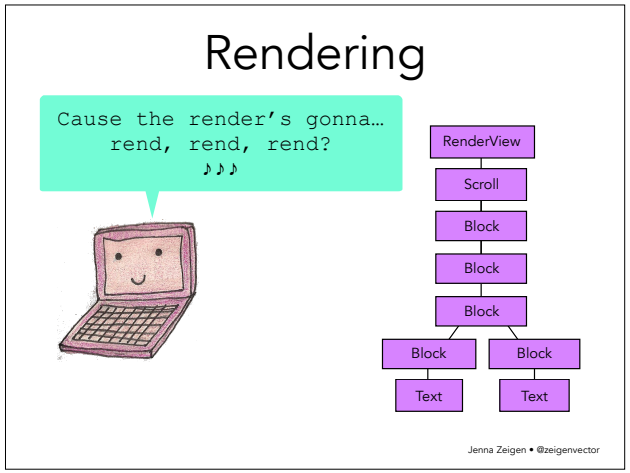


Because of this, HTML and CSS are both render-blocking resources, which means that the browser will hold rendering of any processed content until the DOM and CSSOM trees are constructed.

This is one reason why stylesheets are supposed to go at the top of your HTML document, in `<head>`. Putting stylesheets near the bottom of the document prohibits progressive rendering in many browsers. These browsers block rendering to avoid having to redraw elements of the page if their styles change. From a UX perspective, this to avoid the flash of unsettled content. If that's not enough of a reason, the HTML specification clearly states that stylesheets are to be included in `<head>`, so…

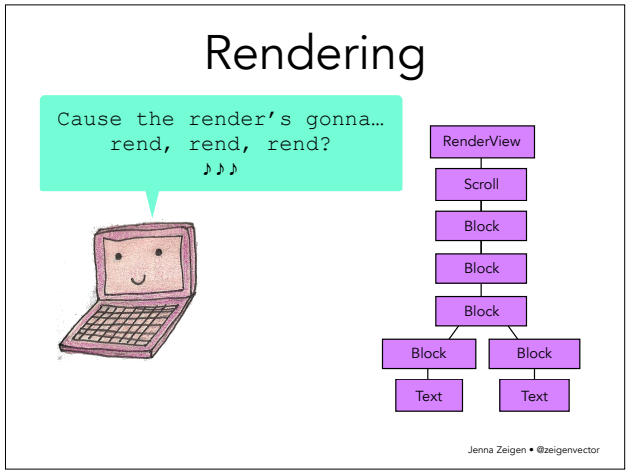


Elements in the render tree correspond to elements in the DOM tree, but it's not 1:1. The render tree only includes things to be rendered, so no non-visual DOM elements like `<script>` or elements with the style `display: none`. Elements with the style `visibility: hidden` will be in the render tree, because it leaves the space for it.



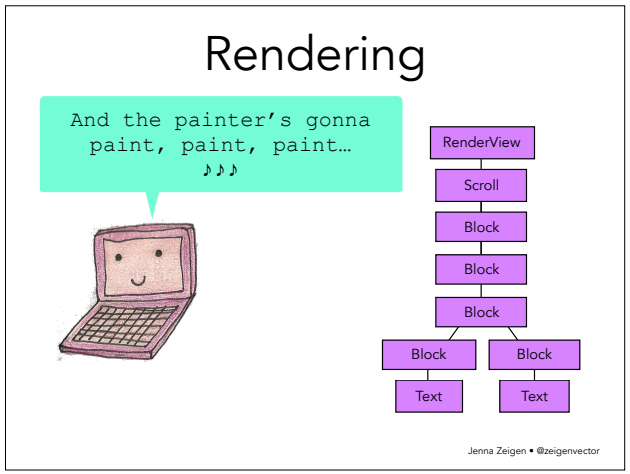
While the render tree contains information about what nodes are visible and computed styles, we haven't yet figured out where all these elements are supposed to go or how big they're supposed to be. This is all part of the "layout" process, also called "reflow."

Layout is a recursive process, starting at the root renderer, which corresponds to the `<html>` element of the HTML document, continuing to compute geometric information for each renderer that requires it. All renderers have a "layout" or "reflow" method which lays out itself and invokes the layout method of its children that need layout.



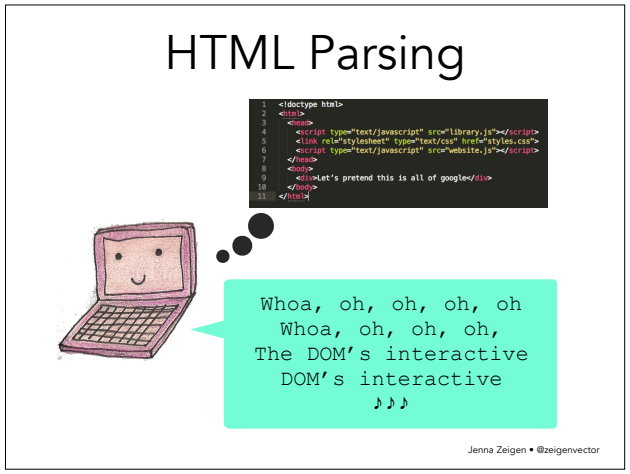
In order not to do a full layout for every small change, browsers use a "dirty bit" system. A renderer that is changed or added marks itself and its children as "dirty", which just means that it needs laying out. There are actually two flags: "dirty" and "children are dirty." The latter means that while the actual renderer may be "clean," it has at least one child that needs a layout.

Layouts can be either global or incremental. Incremental layouts are done in async batches based on a timer in the browser.

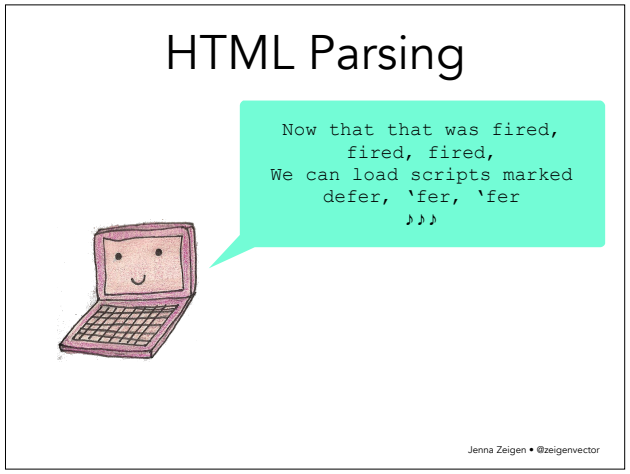


Once we know the location and dimensions of all the elements in the render tree, we can then start representing everything as pixels on the page — painting! In the painting stage, the render tree is traversed recursively and the renderer's "paint" method is called to display the content.

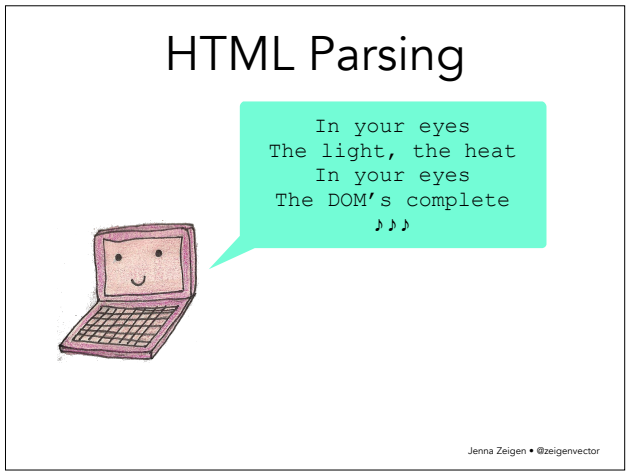
Like layout, painting can also be global or incremental, where only dirty regions are repainted. This is where "region-specific repainting" comes from!



When the HTML document is fully downloaded and parsed, the page is marked as "`interactive`" and the `DOMContentLoaded` event is fired, without waiting for all the assets to finish loading. At this point, you can click around the page— it's interactive!

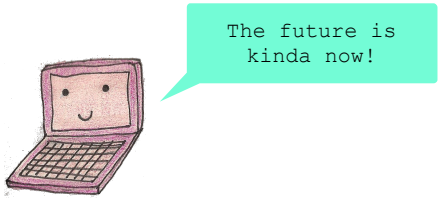


At this point, scripts marked with the `defer` attribute are executed.



Finally, once every resource has been downloaded and parsed, the document is marked as complete, and the `load` event is fired.

HTTP/2



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HTTP/2 is a new HTTP specification that grew out of Google's work on SPDY ("speedy"). It serves to fix a bunch of the aspects of HTTP/1.1 that we need to optimize around all the time. So, once HTTP/2 is implemented across the board, most the of the optimizations I discussed today will be obsolete. Features include:

- HTTP header compression (no repeated headers being passed back and forth)
- Server push technologies (sends assets with the HTML, because it knows you're gonna need it)
- Loading page elements in parallel over a single TCP connection

Overview

1. IP Address Lookup
2. Opening a socket
3. Security Stuff
4. HTTP Request
5. Server Things
6. HTTP Response
7. Parsing
8. Rendering

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Resources

General
- What Happens When (Github)

Transport
- DNS (Wikipedia)
- UDP (Wikipedia)
- TCP (Wikipedia)
- TLS (Wikipedia)

Parsing, Rendering, and Painting
- How Browsers Work (HTML5 Rocks)
- Critical Rendering Path (Google Developers)

Performance
- Best Practices for Speeding Up Your Web Site (Yahoo Developer Network)
- Raul Fraile: How GZIP compression works (JSConfEU 2014)

HTTP/2
- Andy Davies: The Case for HTTP/2 (TXJS 2015)

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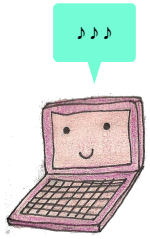
Complete Tracklist

The Beatles - You Know My Name (Look Up The Number)
Carly Rae Jepsen - Call Me Maybe
Radiohead - Creep
Taylor Swift - Blank Space
Taylor Swift - We Are Never Ever Getting Back Together
Taylor Swift - Wildest Dreams
Capital Cities - Safe and Sound
Imagine Dragons - Demons
Young Chris – Racks
Beastie Boys - So What'cha Want
Gotye - Somebody That I Used To Know
The Temptations - My Girl
Missy Elliot - Work It
Calvin Harris ft. Elie Goulding - Outside
Jimmy Eat World - Sweetness
Rilo Kiley - The Execution of All Things
Shakira - Whenever, Wherever
Daft Punk – Harder, Better, Faster, Stronger
MC Hammer - U Can't Touch This
Taylor Swift - Style
Semisonic - Closing Time
Taylor Swift - Shake It Off
Imagine Dragons - Radioactive
Ellie Goulding - Burn
Peter Gabriel - In Your Eyes



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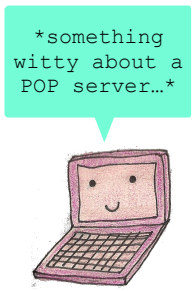

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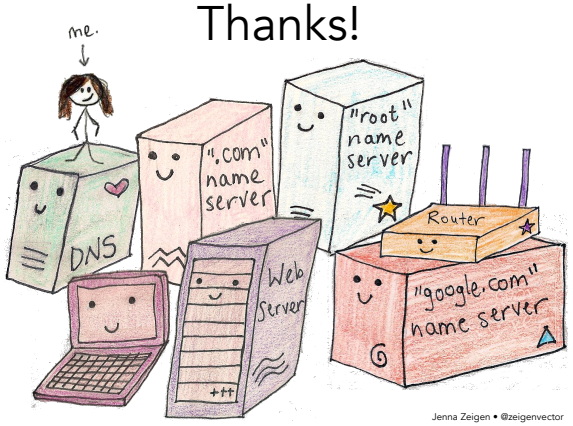
Thanks!



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