How modern Web Browsers work[1]

Prof. Dr. Stefan Zander

07. March 2018

[1] Special Topic for the Module "Entwicklung Webbasierter Anwendungen"

Objectives:

- *Learn about the basic building blocks of modern Web browsers*
- *Get acquainted with the processing internals and the DOM building logic*
- *Understand what happens inside the browser when you type in an URL*

Contents

1 Preface

In the years of IE 90% dominance there was nothing much to do but regard the browser as a "black box", but now, with open source browsers having more than half of the usage share, it's a good time to take a peek under the engine's hood and see what's inside a web browser. Well, what's inside are millions of C++ lines...

—Tali Garsiel

This lecture note is a revised summary of the excellent article "How Browsers Work: Behind the scenes of modern web browsers" published by Tali Garsiel and Paul Irish in 2011. The original article is available at: `https://www.html5rocks.com/en/tutorials/internals/howbrowserswork/`.

There is also a video available at vimeo about Tali's talk: `http://vimeo.com/44182484`.

The following information and facts about the internal operation principles of WebKit and Gecko is the result of extensive research done by the Israeli developer **Tali Garsiel**. Over a few years, she reviewed all the published data about browser internals and spent a lot of time reading Web browser source code. Tali published her research on her site[2]. In the following years, her research results have been revised and republished on numerous occasions and provided insights to a larger audience.

[2] See `http://taligarsiel.com/`

Why should you learn about browser internals?

Learning the internals of browser operations helps you make better decisions and know the justifications behind development best practices. It also helps you to identify performance bottlenecks and build lightning fast websites. As we will see, page loading time has an influence on the Google page rank—a page loading time > 2 sec. results in a lower rank in the Google search results and the Google crawler also crawls such pages less frequently, meaning that search index terms are less frequently updated and the time until new or updated page content will be considered by the Google search engine is extended.

TODO: Add refs

2 Introduction

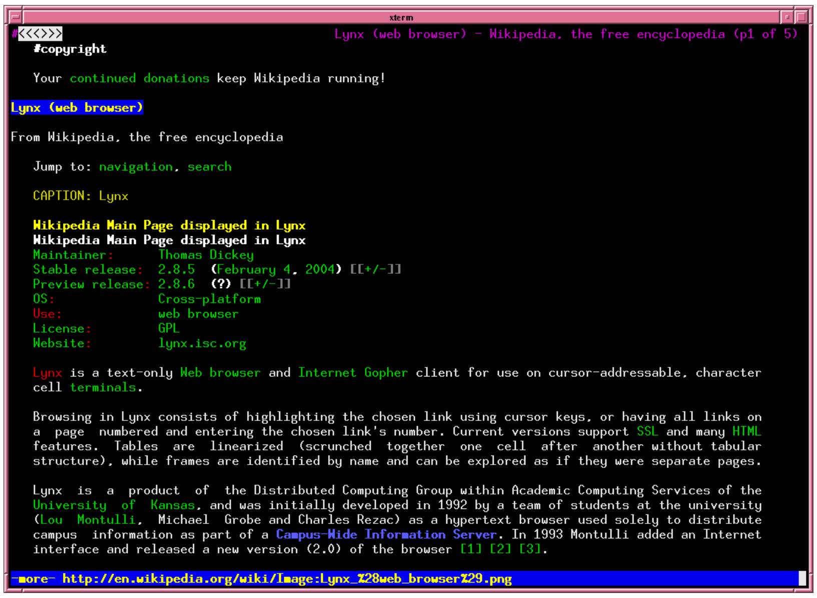
"I just had to take the hypertext idea and connect it to the TCP and DNS ideas and—ta-da!—the World Wide Web."[3]

—Sir Tim Berners-Lee, inventor of the World Wide Web

[3] One of the famous quotes Sir Tim Berners-Lee used to say about the development of the World Wide Web... [his]

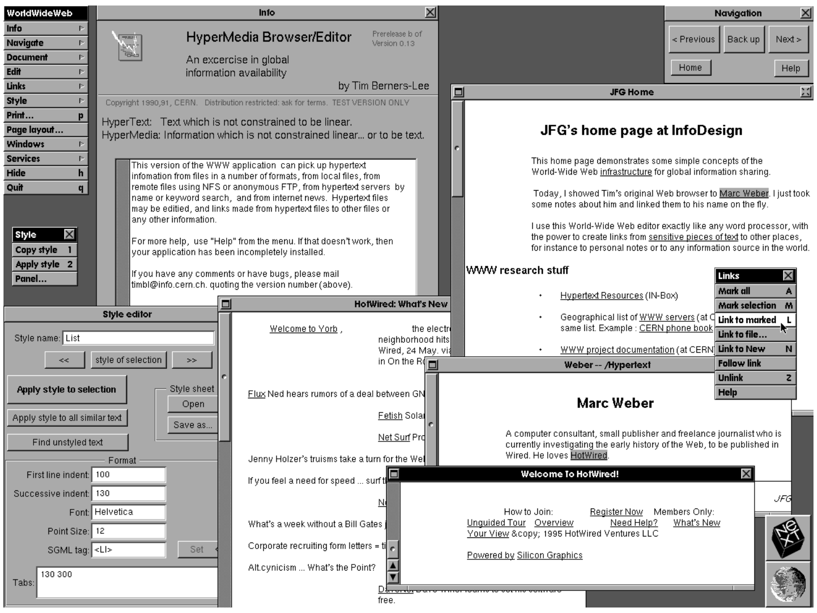
Web browsers are the most widely used software. This lecture explains their fundamental operation principles so that students get an understanding about the things that happen internally when a website is requested, i.e., the time from typing in a website's URL in the browser's address bar until it is rendered by in the browser's viewport.

The complexity of Web browser software has significantly changed over recent years—as the following two screenshots indicate:



```
#<<<>>>                              Lynx (web browser) - Wikipedia, the free encyclopedia (p1 of 5)
   #copyright

   Your continued donations keep Wikipedia running!

Lynx (web browser)

From Wikipedia, the free encyclopedia

   Jump to: navigation, search

   CAPTION: Lynx

   Wikipedia Main Page displayed in Lynx
   Wikipedia Main Page displayed in Lynx
   Maintainer:      Thomas Dickey
   Stable release:  2.8.5  (February 4, 2004) [[+/-]]
   Preview release: 2.8.6  (?) [[+/-]]
   OS:              Cross-platform
   Use:             web browser
   License:         GPL
   Website:         lynx.isc.org

   Lynx is a text-only Web browser and Internet Gopher client for use on cursor-addressable, character
   cell terminals.

   Browsing in Lynx consists of highlighting the chosen link using cursor keys, or having all links on
   a  page  numbered and entering the chosen link's number. Current versions support SSL and many HTML
   features.  Tables  are  linearized  (scrunched  together  one  cell  after  another without tabular
   structure), while frames are identified by name and can be explored as if they were separate pages.

   Lynx  is  a  product  of  the Distributed Computing Group within Academic Computing Services of the
   University  of  Kansas, and was initially developed in 1992 by a team of students at the university
   (Lou  Montulli,  Michael  Grobe and Charles Rezac) as a hypertext browser used solely to distribute
   campus  information as part of a Campus-Wide Information Server. In 1993 Montulli added an Internet
   interface and released a new version (2.0) of the browser [1] [2] [3].

-more- http://en.wikipedia.org/wiki/Image:Lynx_%28web_browser%29.png
```

Figure 1: Screenshot of the Lynx Browser, the first and purely text-based browser for the World Wide Web.



Info

HyperMedia Browser/Editor

Prerelease b of Version 0.13

An excercise in global information availability

by Tim Berners-Lee

Copyright 1990,91, CERN. Distribution restricted: ask for terms. TEST VERSION ONLY

HyperText: Text which is not constrained to be linear.
HyperMedia: Information which is not constrained linear... or to be text.

This version of the WWW application can pick up hypertext infomation from files in a number of formats, from local files, from remote files using NFS or anonymous FTP, from hypertext servers by name or keyword search, and from internet news. Hypertext files may be editied, and links made from hypertext files to other files or any other information.

For more help, use "Help" from the menu. If that doesn't work, then your application has been incompletely installed.

If you have any comments or have bugs, please mail timbl@info.cern.ch. quoting the version number (above).

JFG Home

JFG's home page at InfoDesign

This home page demonstrates some simple concepts of the World-Wide Web infrastructure for global information sharing.

Today, I showed Tim's original Web browser to Marc Weber. I just took some notes about him and linked them to his name on the fly.

I use this World-Wide Web editor exactly like any word processor, with the power to create links from sensitive pieces of text to other places, for instance to personal notes or to any information source in the world.

WWW research stuff

- Hypertext Resources (IN-Box)
- Geographical list of WWW servers (at C same list. Example : CERN phone book
- WWW project documentation (at CERN

Style editor

Style name: List

Format

First line indent: 100
Successive indent: 130
Font: Helvetica
Point Size: 12
SGML tag: <LI>
Tabs: 130 300

HotWired: What's New

Welcome to Yorb , the electr neighborhood hits Wired, 24 May. vi in On the R

Flux Ned hears rumors of a deal between GN

Fetish Sola

Net Surf Pr

Jenny Holzer's truisms take a turn for the We

If you feel a need for speed ... surf t

What's a week without a Bill Gates

Corporate recruiting form letters = t

Alt.cynicism ... What's the Point?

free.

Weber -- /Hypertext

Marc Weber

A computer consultant, small publisher and freelance journalist who is currently investigating the early history of the Web, to be published in Wired. He loves HotWired.

Welcome To HotWired!

How to Join: Register Now Members Only:
Unguided Tour Overview Need Help? What's New
Your View &copy; 1995 HotWired Ventures LLC

Powered by Silicon Graphics

Figure 2: Screenshot of the first WWW browser with a graphical user interface, the NeXT Browser used at CERN.

TODO: Add image of first NEXT browser; compare it with inspector of Google Chrome; add some description (refs are in the keynote file)

2.1 *What is a Web Browser*

See https://seng130.wordpress.com/lectures-2/browser-architecture/

This section outlines some of the central functionalities provided by a modern Web browser. It helps in understanding what a browser exactly is.

1. Is an application that we use when we browse the World Wide Web.
2. It renders text-based HTML documents into visual pages, which are what we see inside a browser.
3. It speaks HTTP protocol and communicates with Web servers.
4. It understands URL and knows how to translates URL into Web resources, e.g., HTML text files, images, videos, etc. (*URL dereferencing*)
5. It is a virtual machine that runs the JavaScript programs embedded inside HTML documents.
6. It understands CSS rules and applies the rules to layout the pages.
7. It interacts with a user in front of a browser and translates user inputs into browser events, e.g., clicking a link, clicking a button, submitting text inside a text box.
8. It provides sophisticated tools for analyzing the structure of Web content and network traffic
9. It contains a JavaScript console to utilize its JavaScript engine

3 *The Browser's Main Functionality*

The main function of a browser is to present the web resource you choose, by requesting it from the server and displaying it in the browser window. The resource is usually an HTML document, but may also be a PDF, image, or some other type of content. The location of the resource is specified by the user using a URI (Uniform Resource Identifier).

The way the browser interprets and displays HTML files is specified in the HTML and CSS specifications. These specifications are maintained by the **World Wide Web Consortium** organization[4], commonly denominated as **W3C**, which is the standards organization for the web. For years browsers conformed to only a part of the specifications and developed their own extensions. That caused serious compatibility issues for web authors. Today most of the browsers more or less conform to the specifications.

[4] `https://www.w3.org/`

Browser user interfaces have a lot in common with each other. Among the common user interface elements are:

- Address bar for inserting a URI
- Back and forward buttons
- Bookmarking options
- Refresh and stop buttons for refreshing or stopping the loading of current documents

- Home button that takes you to your home page

Strangely enough, the browser's user interface is *not specified* in any formal specification, it just comes from good practices shaped over years of experience and by browsers imitating each other. The HTML5 specification does not define UI elements a browser must have, but lists some common elements. Among those are the address bar, status bar and tool bar. There are, of course, features unique to a specific browser like Firefox's downloads manager.

4 *The Browser's High Level Structure*

The following components are considered the main building blocks of modern Web browsers (cf. [Grosskurth and Godfrey, 2006]):

A reference architecture for modern Web browsers

1. **The user interface**: this includes the address bar, back/forward button, bookmarking menu, etc. Every part of the browser display except the window where you see the requested page.
2. **The browser engine**: marshals actions between the UI and the rendering engine.
3. **The rendering engine**: responsible for displaying requested content. For example if the requested content is HTML, the rendering engine parses HTML and CSS, and displays the parsed content on the screen.
4. **Networking**: Responsible for network calls such as HTTP requests, using different implementations for different platform behind a platform-independent interface.
5. **UI backend**: used for drawing basic widgets like combo boxes and windows. This backend exposes a generic interface that is not platform specific. Underneath it uses operating system user interface methods.
6. **JavaScript interpreter**: Used to parse and execute JavaScript code.
7. **Data storage**: This is a persistence layer. The browser may need to save all sorts of data locally, such as cookies. Browsers also support storage mechanisms such as localStorage, IndexedDB, WebSQL and FileSystem.

Figure 3 provides a graphical overview of the reference elements together with a visualization of their relationships among each other. Figure 4 shows an implementation of the reference architecture elements for the Firefox browser.

It is important to note that browsers such as Chrome run multiple instances of the rendering engine: one for each tab. Each tab runs in a separate process.

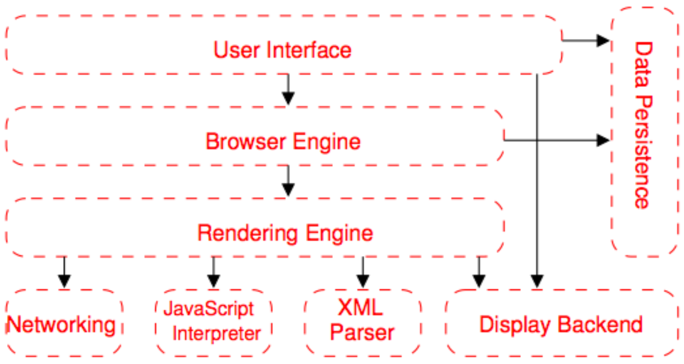


Figure 3: A reference architecture for Web browsers [Grosskurth and Godfrey, 2006]

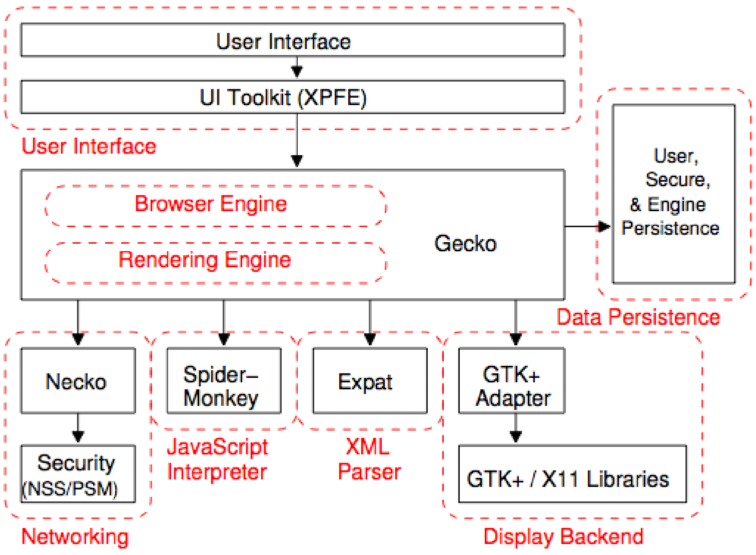


Figure 4: The Firefox browser architecture is based upon the reference architecture components [Grosskurth and Godfrey, 2006]

4.1 *The Rendering Engine*

Different browsers use different rendering engines: Internet Explorer uses Trident, Firefox uses Gecko, Safari uses WebKit. Chrome and Opera (from version 15) use Blink, a fork of WebKit.

WebKit is an open source rendering engine which started as an engine for the Linux platform and was modified by Apple to support Mac and Windows. See `webkit.org` for more details.

By default the rendering engine can display HTML and XML documents and images. It can display other types of data via plug-ins or extension; for example, displaying PDF documents using a PDF viewer plug-in. However, in this chapter we will focus on the main use case: displaying HTML and images that are formatted using CSS.

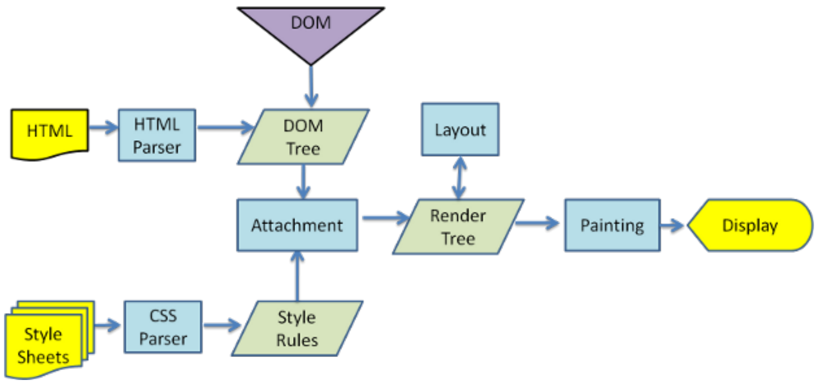


Figure 5: The default workflow of the WebKit render engine

Workflow The rendering engine will start parsing the HTML document and convert elements to DOM nodes in a tree called the **content tree**. The engine will parse the style data, both in external CSS files and in style elements. Styling information together with visual instructions in the HTML will be used to create another tree: the **render tree**.

The render tree contains rectangles with visual attributes like color and dimensions. The rectangles are in the right order to be displayed on the screen.

After the construction of the render tree it goes through a **layout process**. This means giving each node the exact coordinates where it should appear on the screen. The next stage is painting—the render tree will be traversed and each node will be painted using the UI backend layer.

It is important to understand that this is a *gradual process*. For better user experience, the rendering engine will try to display contents on the screen as soon as possible[5]. It will not wait until all HTML is parsed before starting to build and layout the render tree. Parts of the content will be parsed and displayed, while the process continues with the rest of the contents that keeps coming from the network.

[5] This is referred to as the **Compositing Forest** (cf. `https://www.chromium.org/developers/design-documents/gpu-accelerated-compositing-in-chrome`) since four conceptually different tree structures are processed in parallel:

1. DOM tree
2. RenderObject tree
3. RenderLayer tree
4. GraphicsLayer tree

Parsing Since parsing is a very significant process within the rendering engine, we will go into it a little more deeply. Let's begin with a little introduction about parsing.

Parsing a document means translating it to a structure the code can use. The result of parsing is usually a tree of nodes that represent the structure of the document. This is called a parse tree or a syntax tree.

Parsing is based on the syntax rules the document obeys: the language or format it was written in. Every format you can parse must have deterministic grammar consisting of vocabulary and syntax rules. It is called a context free grammar. Human languages are not such languages and therefore cannot be parsed with conventional parsing techniques.

Parsing can be separated into two sub processes: **lexical analysis** and **syntax analysis**.

Lexical analysis is the process of breaking the input into tokens. Tokens are the language vocabulary: the collection of valid building blocks. In human language it will consist of all the words that appear in the dictionary for that language.

Syntax analysis is the applying of the language syntax rules.

The parsing process is **iterative**. The parser will usually ask the lexer[6] for a new token and try to match the token with one of the syntax rules. If a rule is matched, a node corresponding to the token will be added to the parse tree and the parser will ask for another token.

[6] The lexer (sometimes called *tokenizer*) that is responsible for breaking the input into valid tokens.

If no rule matches, the parser will store the token internally, and keep asking for tokens until a rule matching all the internally stored tokens is found. If no rule is found then the parser will raise an exception. This means the document was not valid and contained syntax errors.

4.2 HTML Content Parsing

The main task of the HTML parser is to parse the HTML markup into a **parse tree**.

There are programs that can create parsers for languages that are defined on the bases of a context free grammar[7,8] by analyzing a grammar's vocabulary and syntax rules. Such grammars can usually described using the Backus Naur Form (BNF). However, human language and HTML (as we will see) are not context free grammars. HTML cannot easily be defined by a context free grammar that parsers need. Therefore, a standard parser for parsing HTML does not exist[9].

[7] A language can be parsed by regular parsers if its grammar is a context free grammar.

[8] An intuitive definition of a context free grammar is a grammar that can be entirely expressed in BNF. For a formal definition see your theoretical informatics' lecture notes.

[9] There is a formal format for defining HTML–DTD (Document Type Definition), but it is not a context free grammar.

TODO: Add consequences

This appears strange at first sight; HTML is rather close to XML. There are lots of available XML parsers. There is an XML variation of HTML–XHTML–so what's the big difference?

The difference is that the HTML approach is more *forgiving*: it lets you omit certain tags (which are then added implicitly), or sometimes omit start or end tags, and so on. On the whole it's a *soft syntax*, as opposed to XML's stiff and demanding syntax.

This seemingly small detail makes a world of a difference. On one hand this is the main reason why HTML is so popular: it forgives your mistakes and makes life easy for the Web author. On the other hand, it makes it difficult to write a formal grammar. So to summarize, HTML cannot be parsed easily by conventional parsers, since its grammar is not context free. HTML cannot be parsed by XML parsers.

This has some consequence for Web development:

4.3 *The Parse Tree*

The output tree (i.e., the **parse tree**) is a tree of DOM element and attribute nodes. DOM is short for **Document Object Model**. It is the object presentation of the HTML document and the interface of HTML elements to the outside world like JavaScript. The root of the tree is the `Document` object.

The DOM has an almost one-to-one relation to the markup.

For example, the HTML code in Listing 4.3 will be translated by a Web browser in the internal DOM tree structure as illustrated in Figure 6.

```
<html>
  <body>
    <p>
      Hello World
    </p>
    <div> <img src="example.png"/></div>
  </body>
</html>
```

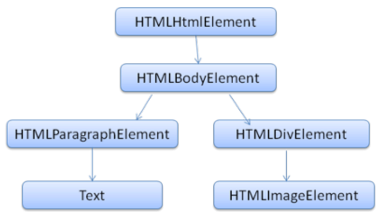


Figure 6: The corresponding internal DOM tree created out of the HTML code example

Like HTML, DOM is specified by the W3C organization[10]. It is a generic specification for manipulating documents. A specific module describes HTML specific elements[11].

[10] Seen `www.w3.org/DOM/DOMTR`

[11] The HTML definitions can be found here: `www.w3.org/TR/2003/REC-DOM-Level-2-HTML-20030109/idl-definitions.html`.

By saying the tree contains DOM nodes, the more precise meaning is that the tree is constructed of elements that implement one of the DOM interfaces. Browsers use concrete implementations that have other attributes used by the browser internally.

4.4 *The Parsing Algorithm*

HTML cannot be parsed using the regular top down or bottom up parsers.

The reasons are:

- The **forgiving nature** of the language.

- The fact that browsers have traditional **error tolerance** to support well known cases of invalid HTML.
- The parsing process is **reentrant**. For other languages, the source doesn't change during parsing, but in HTML, dynamic code (such as script elements containing `document.write()` calls) can add extra tokens, so the parsing process actually modifies the input.

Unable to use the regular parsing techniques, browsers create **custom parsers** for parsing HTML.

The **parsing algorithm** is described in detail by the HTML5 specification[12]. The algorithm consists of two stages:

[12] See `http://www.whatwg.org/specs/web-apps/current-work/multipage/parsing.html`

1. **Tokenization**

   The Tokenization Algorithm

   Tokenization is the *lexical analysis*, i.e., parsing the input into tokens. Among HTML tokens are start tags, end tags, attribute names and attribute values.

   The tokenizer recognizes the token, gives it to the tree constructor, and consumes the next character for recognizing the next token, and so on until the end of the input.

   The algorithm's output is an HTML token. The algorithm is expressed as a *state machine*. Each state consumes one or more characters of the input stream and updates the next state according to those characters. The decision is influenced by the current tokenization state and by the tree construction state. This means the same consumed character will yield different results for the correct next state, depending on the current state. The algorithm is very complex to describe fully; an example to understand the principle can be found in xxx.

2. **Tree Construction**

   Tree Construction Algorithm

   During the tree construction stage the DOM tree with the Document in its root will be modified and elements will be added to it. Each node emitted by the tokenizer will be processed by the tree constructor. For each token the specification defines which DOM element is relevant to it and will be created for this token. The element is added to the DOM tree, and also the stack of open elements. This stack is used to correct nesting mismatches and unclosed tags. The algorithm is also described as a state machine. The states are called *insertion modes*.

When the HTML document parsing is finished, the browser will mark the document as `interactive` and start parsing **scripts** that are in **deferred mode**: those that should be executed *after* the document is parsed. The document state will be then set to `complete` and a `load` event will be fired.

4.5 *Error Tolerance*

You never get an `Invalid Syntax` error on an HTML page. Browsers fix any invalid content and go on. Take this HTML for example:

```html
<html>
  <mytag>
  </mytag>
  <div>
  <p>
  </div>
    Really lousy HTML
  </p>
</html>
```

Listing 1: A HTML document containing an intentionally large number of errors; however, it will still be processed as if it were error-free by modern Web browsers.

The code in Listing 1 figuratively violates about a million rules ("mytag" is not a standard tag, wrong nesting of the `p` and `div` elements and more) but the browser still shows it correctly and doesn't complain. So a lot of the parser code is fixing the HTML author mistakes.

Error handling is quite consistent in browsers, but amazingly enough it hasn't been part of HTML specifications. Like bookmarking and back/forward buttons, it's just something that developed in browsers over the years. There are known invalid HTML constructs repeated on many sites, and the browsers try to fix them in a way conformant with other browsers.

4.6 *CSS Parsing*

Unlike HTML, CSS is a context free grammar and can be parsed using standard parsers as described in the HTML Parsing section. The CSS lexical and syntax grammar as defined by the CSS specification is available at `http://www.w3.org/TR/CSS2/grammar.html`.

WebKit uses Flex[13] and Bison[14] parser generators to create parsers automatically from the CSS grammar files. As you recall from the parser introduction, Bison creates a bottom up shift-reduce parser. Firefox uses a top down parser written manually. In both cases each CSS file is parsed into a StyleSheet object. Each object contains CSS rules. The CSS rule objects contain selector and declaration objects and other objects corresponding to CSS grammar.

[13] See `http://en.wikipedia.org/wiki/Flex_lexical_analyser`

[14] See `http://www.gnu.org/software/bison/`

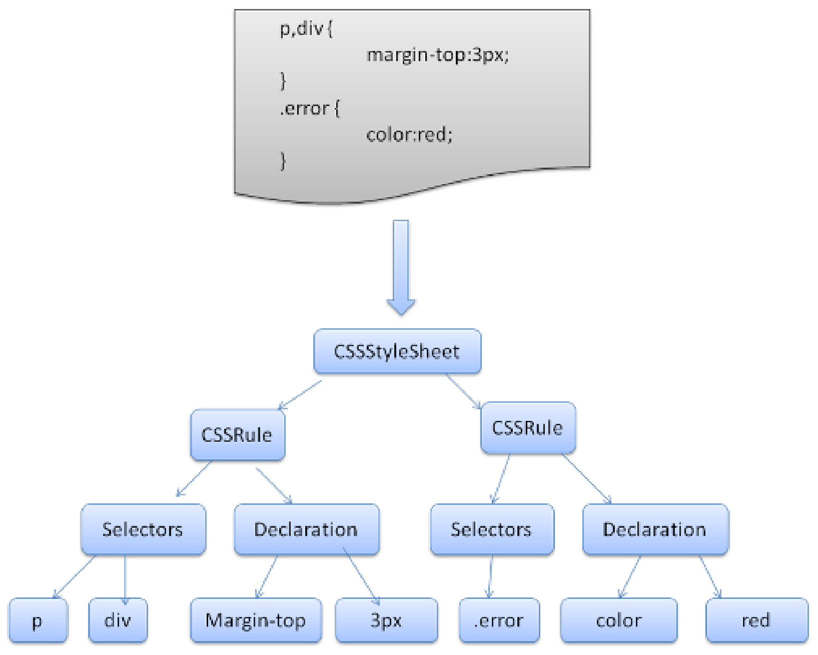


Figure 7: Example of a CSS StyleSheet Object tree created by a CSS Parser

5 *Processing Order*

5.1 *Scripts*

The model of the web is synchronous. Authors expect scripts to be parsed and executed immediately when the parser reaches a `<script>` tag. The parsing of the document halts until the script has been executed. If the script is external then the resource must first be fetched from the network–this is also done synchronously, and parsing halts until the resource is fetched. This was the model for many years and is also specified in HTML4 and 5 specifications. Authors can add the `defer` attribute to a script, in which case it will not halt document parsing and will execute after the document is parsed. HTML5 adds an option to mark the script as asynchronous so it will be parsed and executed by a different thread.

5.2 *Speculative Parsing*

Both WebKit and Firefox implement the speculative parsing optimization. While executing scripts, another thread parses the rest of the document and finds out what other resources need to be loaded from the network and loads them. In this way, resources can be loaded on parallel connections and overall speed is improved. Note: the speculative parser only parses references to external resources like external scripts, style sheets and images—it doesn't modify the DOM tree, that is left to the main parser.

Webkit and Geko employ speculative parsing

Speculative parsers do not modify the DOM tree

5.3 Style Sheets

Style sheets on the other hand have a different model. Conceptually it seems that since style sheets don't change the DOM tree, there is no reason to wait for them and stop the document parsing. There is an issue, though, of scripts asking for style information during the document parsing stage. If the style is not loaded and parsed yet, the script will get wrong answers and apparently this caused lots of problems. It seems to be an edge case but is quite common. Firefox blocks all scripts when there is a style sheet 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 style sheets.

Scripts might request style information from styles the parsing of which has not finished yet.

Script execution is blocked when style information is requested from unfinished CSS parsing tasks.

6 Render Tree Construction

While the DOM tree is being constructed, the browser constructs another tree, the **render tree**. This tree is of visual elements in the order in which they will be displayed. It is the **visual representation of the document**. The purpose of this tree is to enable painting the contents in their correct order. Firefox calls the elements in the render tree *frames*. WebKit uses the term *renderer* or *render object*. A renderer knows how to lay out and paint itself and its children.

Each renderer represents a rectangular area usually corresponding to a node's CSS box, as described by the CSS specification. It includes geometric information like width, height and position.

6.1 Render and DOM Tree

The renderers correspond to DOM elements, but the relation is *not* one-to-one. Non-visual DOM elements will not be inserted in the render tree. An example is the `<head>` element. Also elements whose display value was assigned to `none` will not appear in the tree (whereas elements with `hidden` visibility will appear in the tree).

There are DOM elements which correspond to *several visual objects*. These are usually elements with complex structure that cannot be described by a single rectangle. For example, the `<select>` element has three renderers: one for the display area, one for the drop down list box and one for the button. Also when text is broken into multiple lines because the width is not sufficient for one line, the new lines will be added as extra renderers. Another example of multiple renderers is broken HTML. According to the CSS spec, an inline element must contain either only block elements or only inline elements. In the case of mixed content, anonymous block renderers will be created to wrap the inline elements.

Some render objects correspond to a DOM node but not in the same place in the tree. Floats and absolutely positioned elements are out of flow, placed in a different part of the tree, and mapped to the real frame. A placeholder frame is where they should have been.

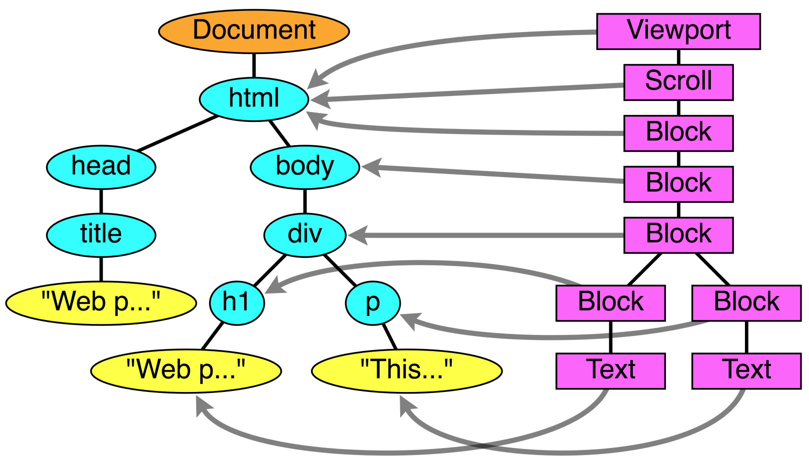


Figure 8: An example of render tree (*purple nodes*) and the corresponding DOM tree. The `Viewport` is the initial containing block.

7 *Style Computation*

Building the render tree requires calculating the visual properties of each render object. This is done by calculating the style properties of each element.

The style includes style sheets of various origins, inline style elements and visual properties in the HTML (like the `bgcolor` property). The later is translated to matching CSS style properties.

Style computation brings up a few difficulties:

1. **Memory Issues**
   Style data is a very large construct, holding the numerous style properties, this can cause memory problems.

2. **Performance Issues**
   Finding the matching rules for each element can cause performance issues if it's not optimized. Traversing the entire rule list for each element to find matches is a heavy task. Selectors can have complex structure that can cause the matching process to start on a seemingly promising path that is proven to be futile and another path has to be tried.

3. **Complexity Issues**
   Applying the rules involves quite complex cascade rules that define the hierarchy of the rules.

One strategy conduced by browser engines to address such issues and mitigate their effect is by **sharing style data** when certain conditions hold (e.g., elements must be in the same mouse state, have no id, identical set of attributes etc)[15].

[15] See [Garsiel and Irish, 2011] for a complete list of conditions.

Another strategy is **rule manipulation**, which works as follows[16]: After parsing the style sheet, the rules are added to one of several **hash maps**, according to the *selector*. There are maps by *id*, by *class name*, by *tag name* and a *general map* for anything that doesn't fit into those categories. If the selector is an id, the rule will be added to the id map, if it's a class, it will be added to the class map etc. This manipulation makes it much easier to match rules. There is no need to look in every declaration: we can extract the relevant rules for an element from the maps. This optimization eliminates 95+% of the rules, so that they need not even be considered during the matching process.

[16] See [Garsiel and Irish, 2011] for a working example and additional explanations.

The next step is to determine the **order of style rules** that apply to a given DOM element. This process is denominated by the **cascade** term in CSS. A declaration for a style property can appear in several style sheets, and several times inside a style sheet. This means the order of applying the rules is very important. This is called the **cascade order**. According to CSS specification, the cascade order is (from low to high):

```
Browser declarations
User normal declarations
Author normal declarations
Author important declarations
User important declarations
```

The browser declarations are least important and the user overrides the author only if the declaration was marked as important. Declarations with the same order will be sorted by **specificity** and then the order they are specified. The HTML visual attributes are translated to matching CSS declarations . They are treated as author rules with low priority.

We will discuss the specificity aspect in detail in the CSS chapter.

8 *Layout and Painting*

When the renderer is created and added to the tree, it does not have a position and size. Calculating these values is called **layout** or **reflow**.

HTML uses a flow based layout model, meaning that most of the time it is possible to compute the geometry in a single pass. Elements later "in the flow" typically do not affect the geometry of elements that are earlier "in the flow", so layout can proceed left-to-right, top-to-bottom through the document. There are exceptions: for example, HTML tables may require more than one pass.

The coordinate system is relative to the root frame. Top and left coordinates are used.

Layout is a recursive process. It begins at the root renderer, which corresponds to the `<html>` element of the HTML document. Layout continues recursively through some or all of the frame hierarchy, computing geometric information for each renderer that requires it.

The position of the root renderer is `0,0` and its dimensions are the viewport–the visible part of the browser window. All renderers have a **layout** or **reflow method**, each renderer invokes the layout method of its children that need layout.

8.1 Dirty bit system

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»: needing layout.

There are two flags: «dirty», and «children are dirty» which means that although the renderer itself may be OK, it has at least one child that needs a layout.

8.2 Global and incremental layout

Layout can be triggered on the entire render tree—this is **global layout**. This can happen as a result of:

- A global style change that affects all renderers, like a font size change.
- As a result of a screen being resized

Layout can be incremental, only the dirty renderers will be laid out (this can cause some damage which will require extra layouts). Incremental layout is triggered *asynchronously* when renderers are dirty. For example when new renderers are appended to the render tree after extra content came from the network and was added to the DOM tree.

8.3 Painting

In the painting stage, the render tree is traversed and the renderer's `paint()` method is called to display content on the screen. Painting uses the UI infrastructure component.

Firefox goes over the render tree and builds a display list for the painted rectangular. It contains the renderers relevant for the rectangular, in the right painting order (backgrounds of the renderers, then borders etc). That way the tree needs to be traversed only once for a repaint instead of several times–painting all backgrounds, then all images, then all borders etc. Firefox optimizes the process by not adding elements that will be hidden, like elements completely beneath other opaque elements.

Before repainting, WebKit saves the old rectangle as a bitmap. It then paints only the delta between the new and old rectangles.

The browsers try to do the minimal possible actions in response to a change. So changes to an element's color will cause only repaint of the element. Changes to the element position will cause layout and repaint of the element, its children and possibly siblings. Adding a DOM node will cause layout and repaint of the node. Major changes, like increasing font size of the `html` element, will cause invalidation of caches, relayout and repaint of the entire tree.

8.4 The Rendering Engine's Threads

The rendering engine is single threaded. Almost everything, except network operations, happens in a single thread. In Firefox and Safari this is the main thread of the browser. In Chrome it's the tab process main thread. Network operations can be performed by several parallel threads. The number of parallel connections is limited (usually 2–6 connections).

References

The world wide web of tim berners-lee. URL `http://history-computer.com/Internet/Maturing/Lee.html`.

Tali Garsiel and Paul Irish. How browsers work: Behind the scenes of modern web browsers, August 2011. URL `https://www.html5rocks.com/en/tutorials/internals/howbrowserswork/`.

Alan Grosskurth and Michael W. Godfrey. A Reference Architecture For Web Browsers, 2006. URL `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.60.1151`.