

# LIFE OF A pixel

*Philip Rogers (pdr@)*

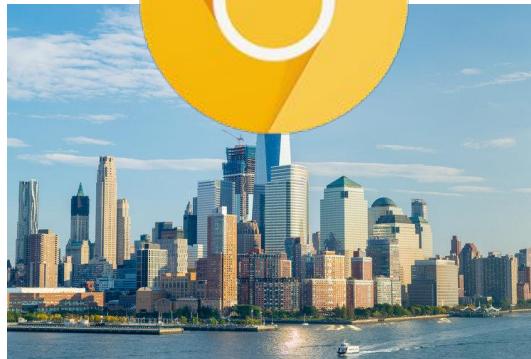
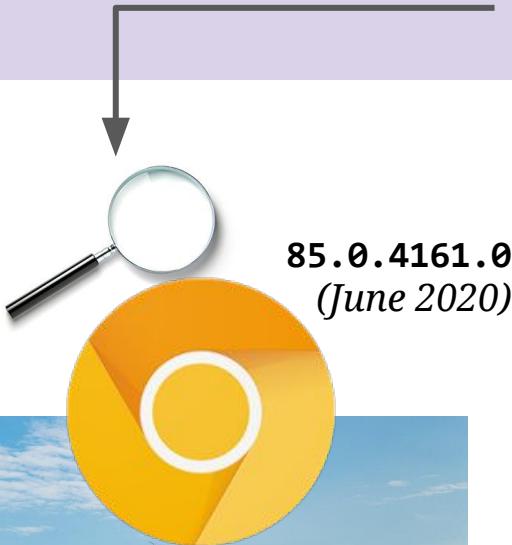
*Based on a 2017 presentation by  
skobes@, with new additions.*

*June, 2020*

*"The unexamined pixel is not worth rendering."  
— Socrates*

*slides: [bit.ly/lifeofapixel](https://bit.ly/lifeofapixel)*

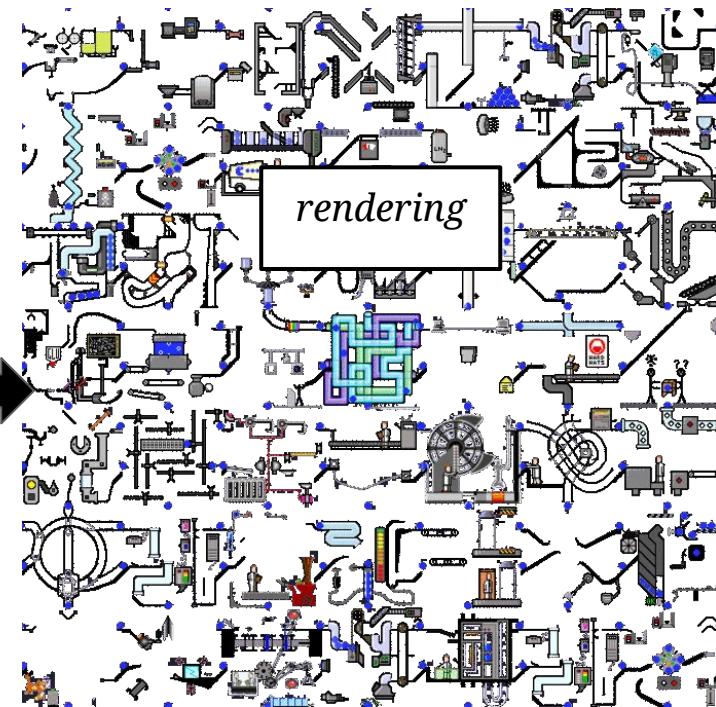
# LIFE OF A pixel



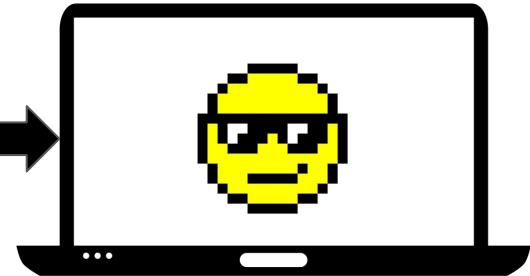
# LIFE OF A pixel

*content*

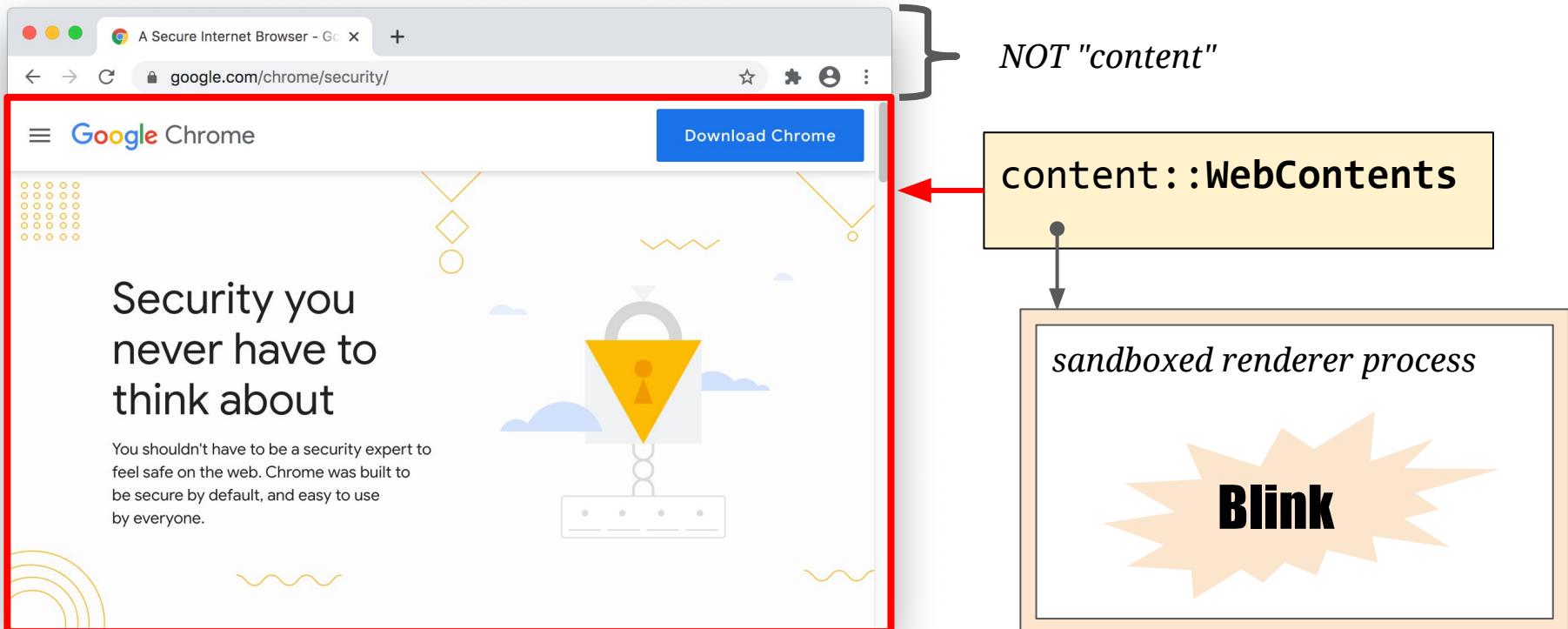
```
<!DOCTYPE html>
<html lang="en">
  <head>
    <meta charset="u
    <title>Page name<
    <meta name="descri
    <link href="assets/
    <link rel="shortcut
  </head>
```



*pixels*



# content



# content

- **HTML**

*(Hyper-Text Markup Language)*

`<p> hello </p>`



- **CSS**

*(Cascading Style Sheets)*

`p { color: red }`

- **JS**

*(JavaScript)*

`p.innerHTML = "goodbye";`

- **images**

``

*(other kinds of rendered content: <video>, <canvas>, WebAssembly, WebGL, WebVR, PDF, ...)*

# content

<https://www.nytimes.com>

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**White House to Tie Hard-Line Conditions Into Dreamers' Deal**  
By MICHAEL D. SHEAR 8:27 PM ET  
In exchange for letting the young undocumented immigrants known as Dreamers stay in the U.S., the White House will push for terms that include a crackdown on children fleeing Central America. The deal will also insist on the construction of a wall across the southern border.  
256 Comments

**Suspected ISIS Members Surrender in Iraq**  
By ROD NORDLAND and JOHN BICKEL, Photos by Ivor Prickett for The New York Times  
Video by CAMILLA SCHUM, ROD NORDLAND and JOHN BICKEL  
A Family Battle With Opioids  
BY JUDITH CHICUREL  
A friend, reflecting on his son's opioid journey, once remarked, "I wish I'd held him closer." Is it ever close enough?

**More Than 1,000 ISIS Fighters Surrender**  
The militants turned themselves in after the latest in a string of humiliating defeats in Iraq and Syria. Many claim not to have been soldiers, but only cooks or clerks.  
256 Comments

**Trump Risks Inciting World War III', G.O.P. Senator Says**  
By JONATHAN MAZER 8:27 AM ET  
In a remarkable rebuke of his party's president, Bob Corker, the influential head of the Senate Foreign Relations

**Listen to 'The New Washington'**  
Senator Marco Rubio spoke with Carl Hulse about President Trump, the recovery efforts in Puerto Rico, U.S.-Cuban relations and more.  
Follow The New Washington: Apple Podcasts Radio Public Stitcher Once Racing to Flee the Senate, Rubio Now Digs In

**Sunday Review**  
A Family Battle With Opioids BY JUDITH CHICUREL A friend, reflecting on his son's opioid journey, once remarked, "I wish I'd held him closer." Is it ever close enough?  
Reviews for America BY JUDITH LIEBER  
I used to give this place five stars! But since the change of management, it's going downhill.  
Fake Assumptions About the Iran Nuclear Deal  
Who Invented 'Zero'?  
Confessions of a Sensible Gun Owner  
N.R.A. and G.O.P. Together  
Editorial: Mr. Trump's Attack on Birth Control  
Bruni: Be Afraid of Bannon  
Douthat: Pigs of Liberalism  
Krisol: Inside North Korea, and Feeling the Drums of War  
Seeing Trump Through a Glass, Darkly  
Op-Docs: The Many Sad Fates of Mr. Toledoano

**TIMES INSIDER »** What's a Science Reporter to Do When Sound Evidence Isn't Sound?  
**THE CROSSWORD »** Play Today's Puzzle

```
</div>
<div class="column">
  <div class="collection crosswords-collection">
    <article class="story">
      <h3 class="kicker">
        <a href="http://wordplay.blogs.nytimes.com">Wordplay
      </h3>
    </article>
  </div><!-- close column -->
</div><!-- close layout -->
</div><!-- close crossword-subscription -->
</div><!-- close collection -->
</div>
</div><!-- close user-subscriptions -->
<div id="HMPmiddle" class="ad hpmiddle-ad nocontent robots-nocontent"></div>
<div class="region c-column-middle-span-region">
  <div class="collection">
    <link rel="stylesheet" type="text/css" href="https://int.nyt.com/app
<style type="text/css">
/*HIDE WATCHING HEADER*/
.portal-container>header { display: none }
</style>
<div id="nytint-hp-watching">
  <div class="portal-container">
    <header class="portal-header">
      <h4>Watching</h4>
    </header>
    <div class="portal-posts-frame expanded"></div>
    <footer class="portal-footer"></footer>
  </div>
</div>
<script type="text/javascript">
require(['foundation/main'], function() {
  require('homepage/main', 'https://int.nyt.com/apps/portals/assets/portal/app
}, function() {
  require(['portal/app'], function(Portal) {
    var opts = {
      env: 'production_published',
      matchHeight: {
        match: ':span-ab-layout.layout > .ab-column',
        container: '.c-column.column',
        maxHeight: 2000
      }
    }
    if (window.location.search.indexOf('portal_variant=watchingNoScroll') !=-
      opts.variation = 'simple';
      opts.poll = false;
      opts.limit = 20;
    }

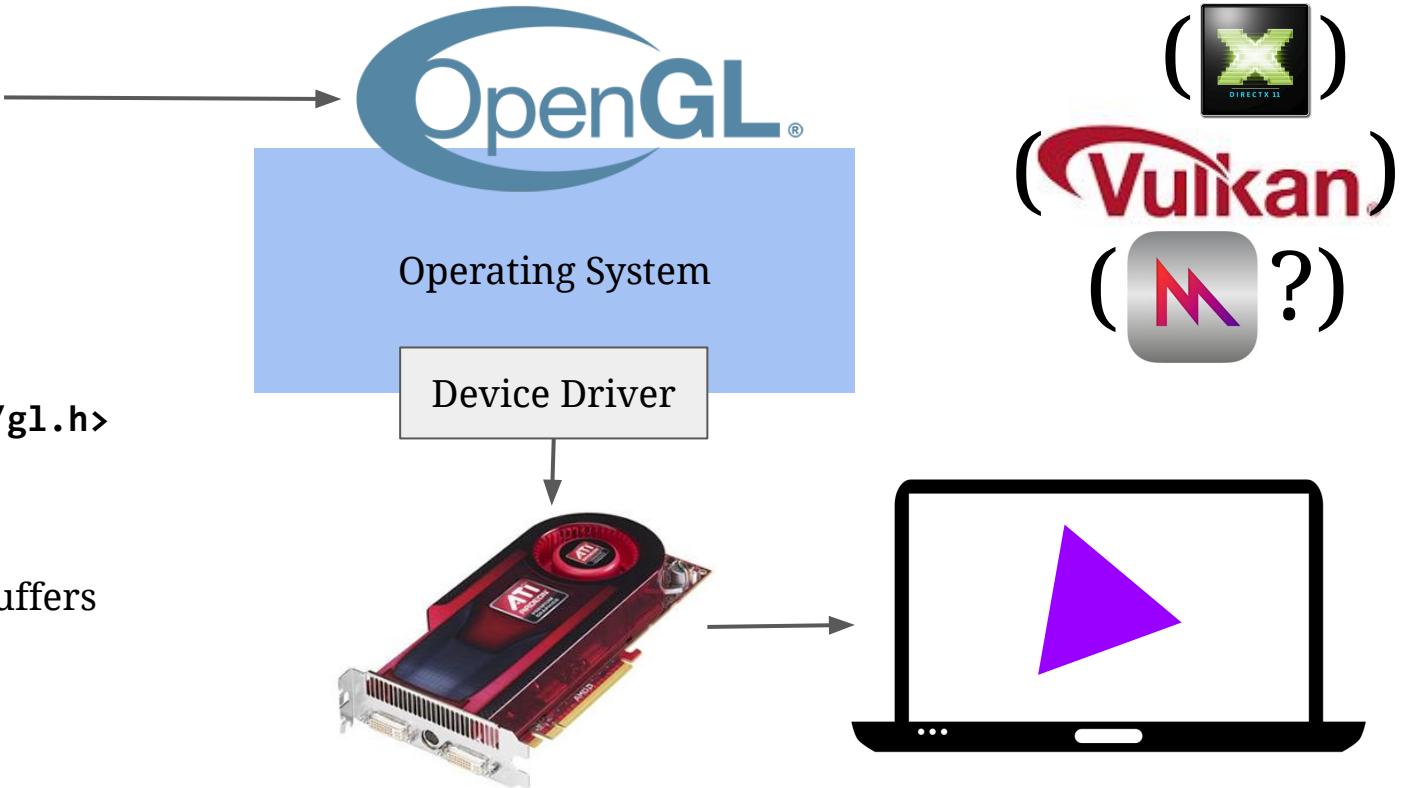
    var watching = Portal.create('#nytint-hp-watching', opts);
  });
});
```

# pixels



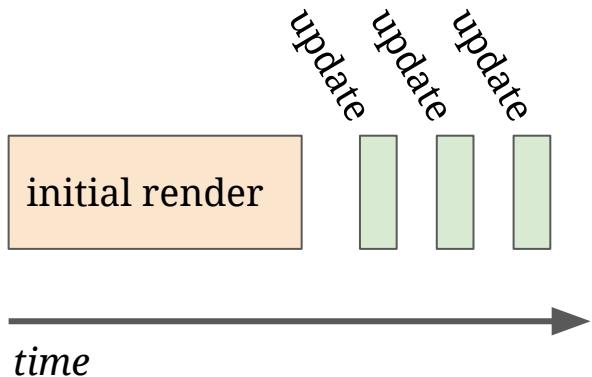
```
#include <GL/gl.h>
```

- textures
- shaders
- vertex buffers
- ...



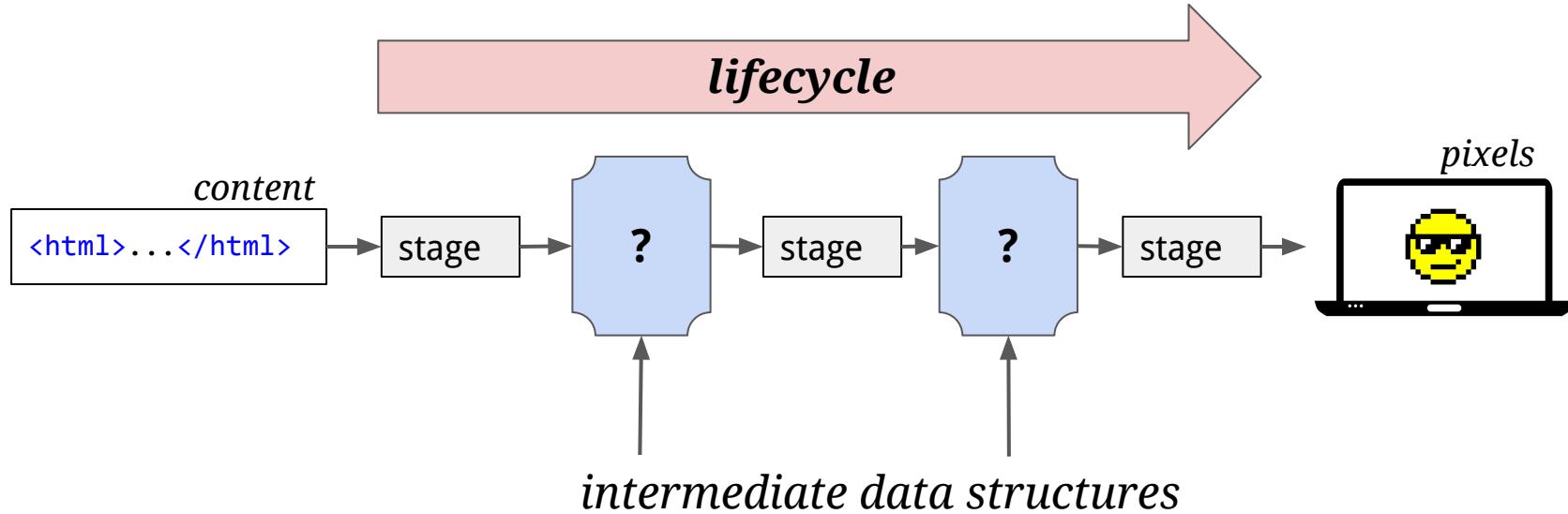
# goals

1. *render content into pixels*
2. *build data structures to enable **updating** the rendering efficiently*

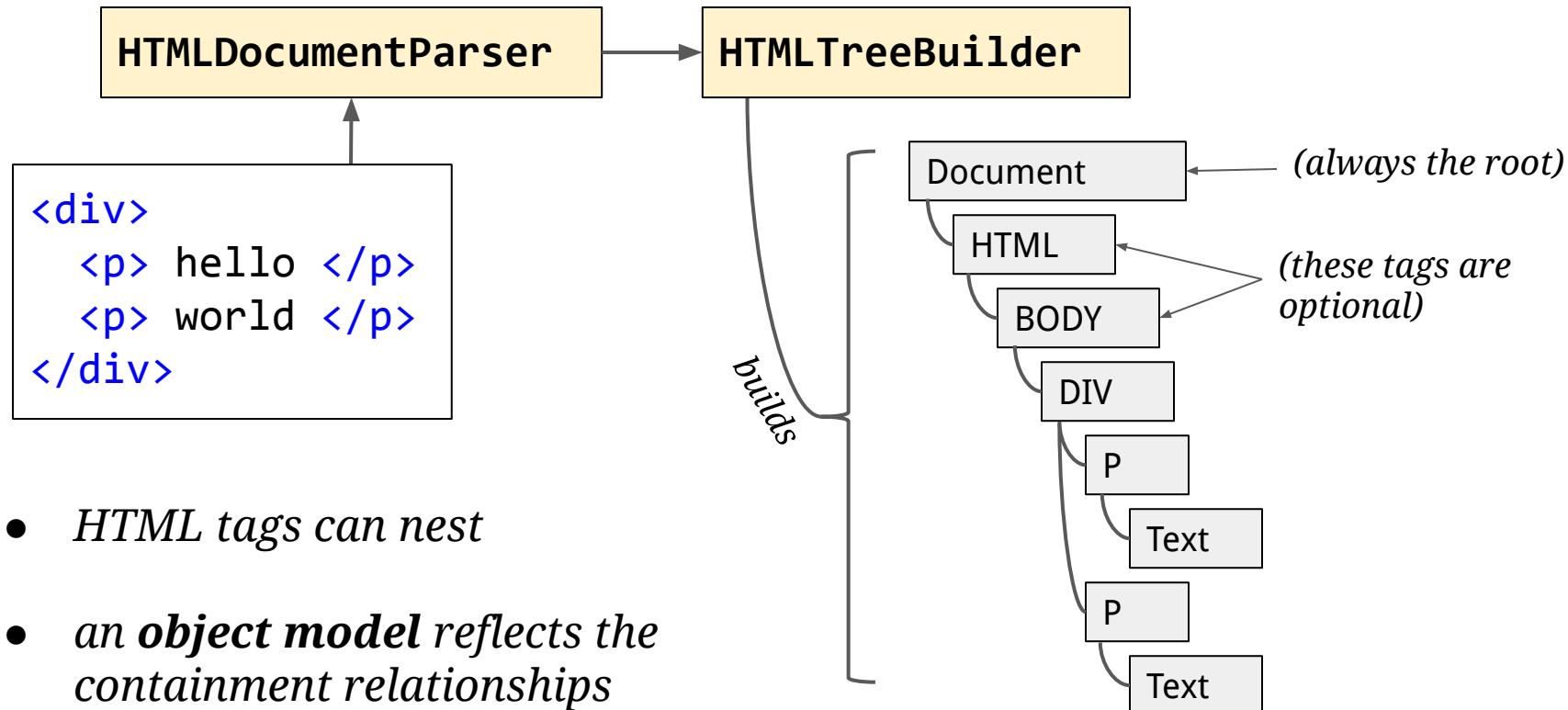


- JavaScript
- user input
- asynchronous loading
- animations
- scrolling
- zooming

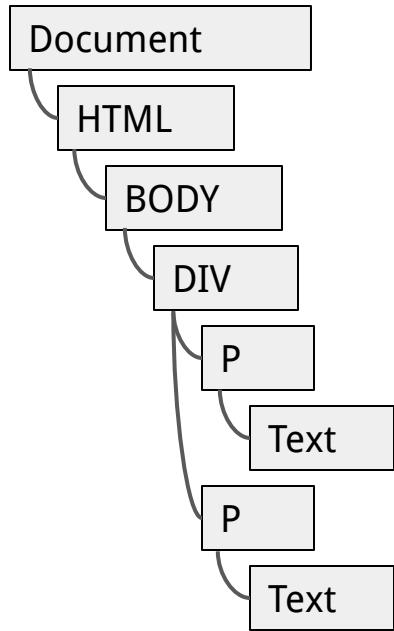
# stages



# parsing



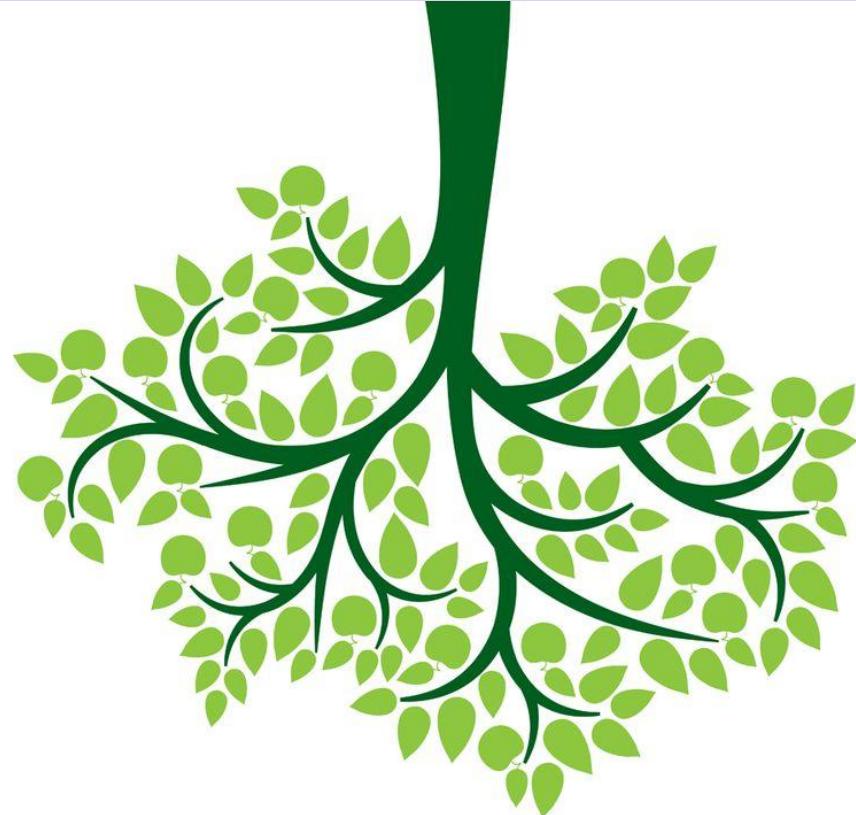
# DOM



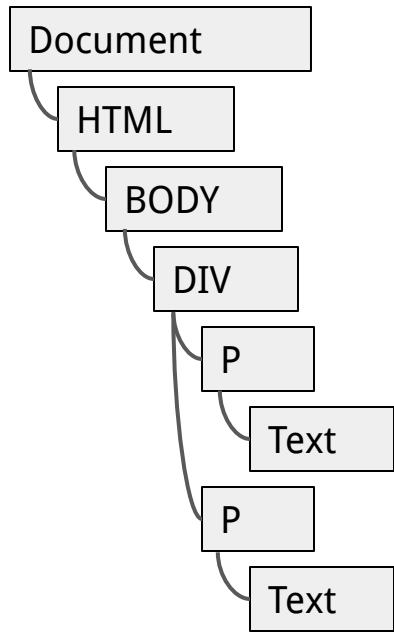
*This is the  
Document  
Object  
Model.*

*The DOM  
is a tree!*

- *parents*
- *children*
- *siblings*



# DOM

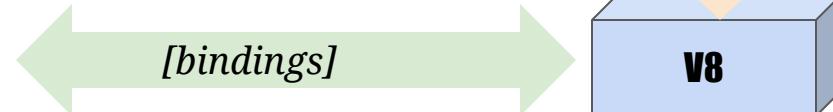


*The DOM is both*

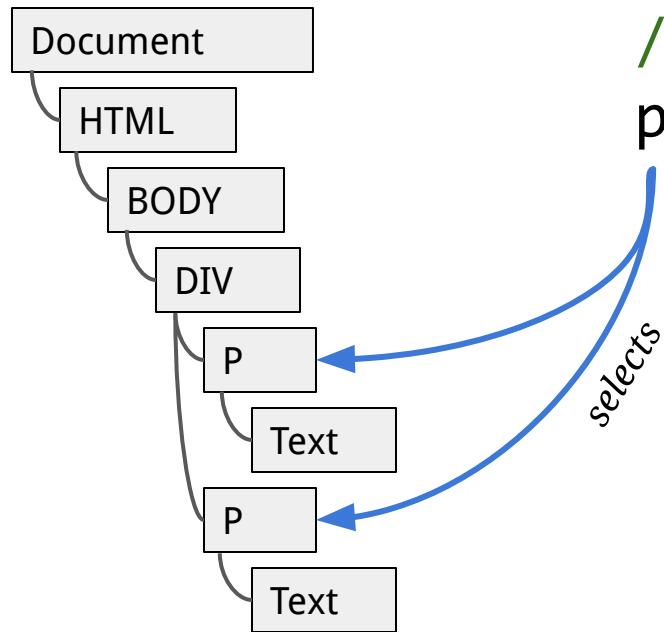
- *Chrome's internal representation*  
AND
- *the API exposed to JavaScript*

```
var div = document.body.firstChild;
var p2 = div.childNodes[1];
p2.appendChild(document.createElement("span"));
p2.foo = {arbitrary: "state"};
```

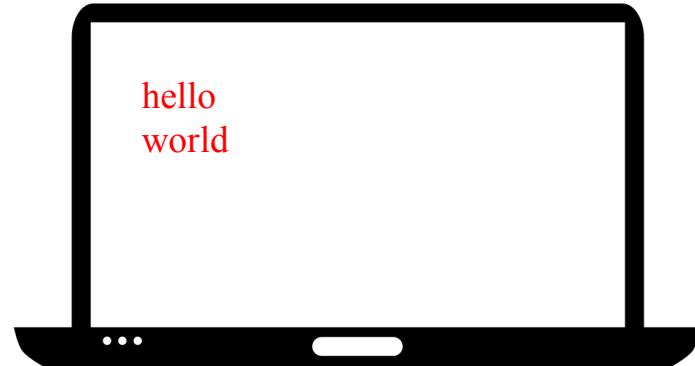
[ JS ]



# style



```
/* every <p> has red text */  
p { color: red }
```



# style

font-weight: bold;

**hello**

margin-left: 2cm;

hello

outline: dashed blue;

hello

transform: rotate(20deg);

*hello*

background: url(kitten.jpg);



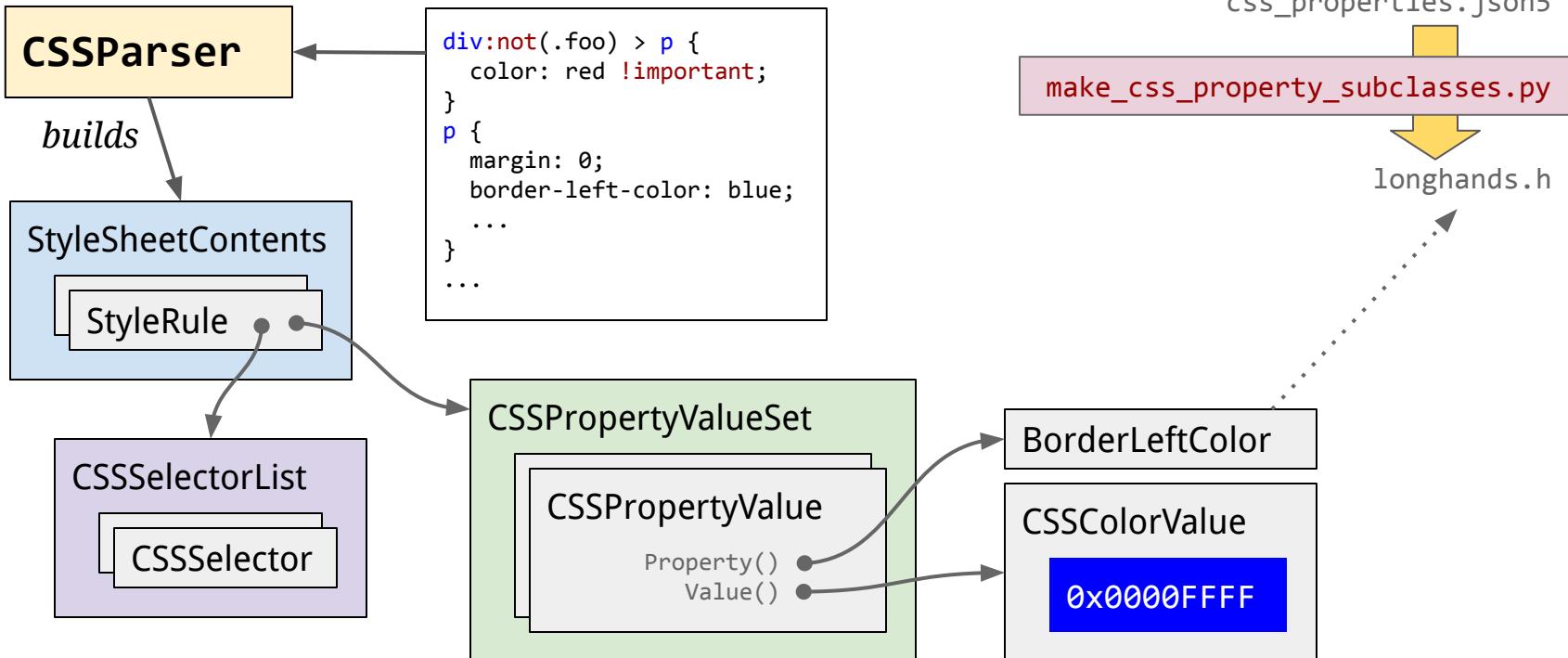
# style

```
/* every other <p> in any <div> without class="foo" */
div:not(.foo) > p:nth-of-type(2n) {
    color: red !important;
}

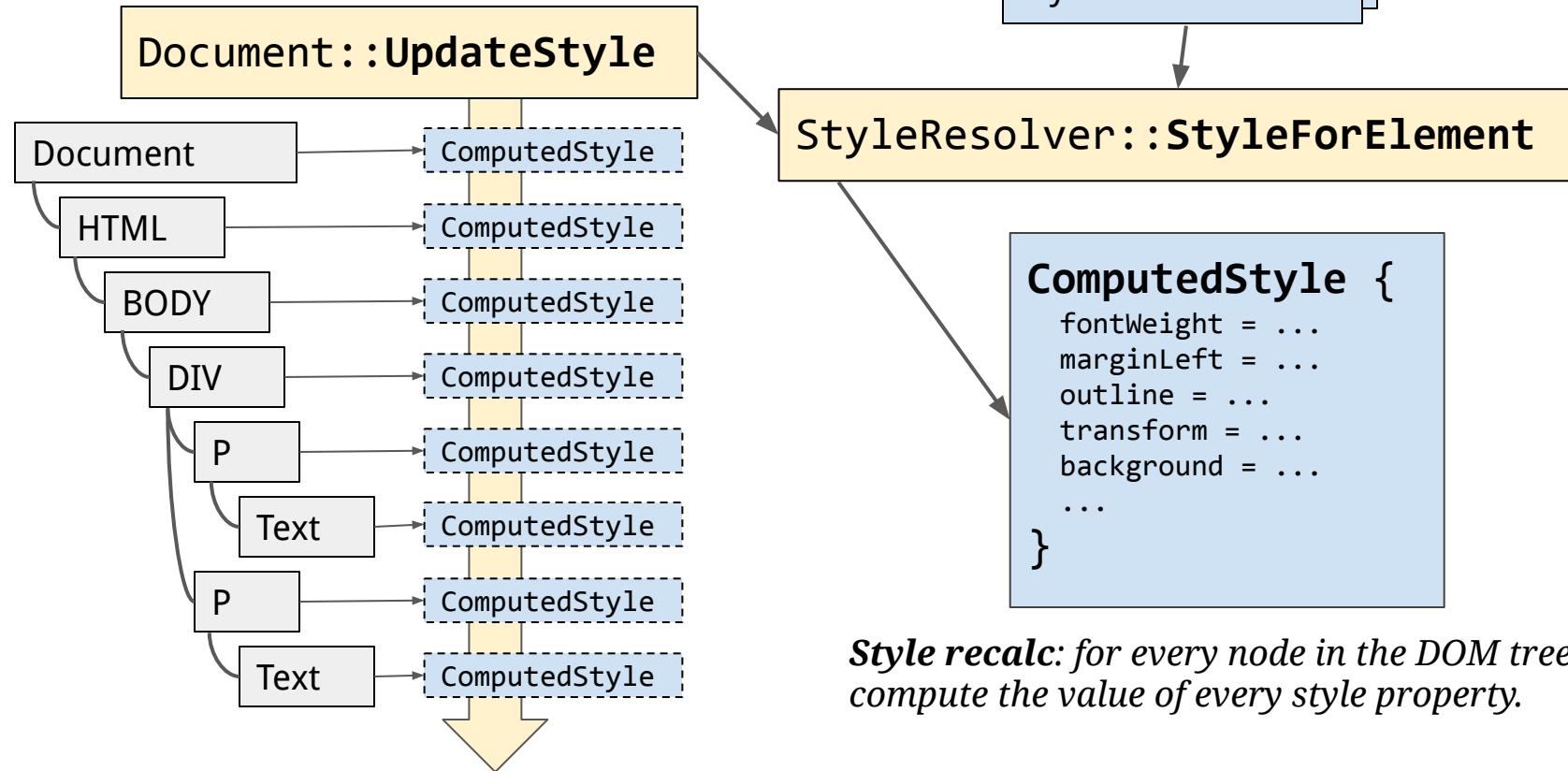
p {
    color: blue;
}
```

- *selectors can be complex!*
- *declarations may conflict!*

# style



# style



# style

The screenshot shows a web browser window with the URL `google.com/chrome/productivity/`. On the left, there's a sidebar with accessibility information for an `h1` element. The main content area features a large blue `h1` heading with the text "Whatever it is, get it done fast". To the right of the heading is a blue button labeled "Download Chrome". On the far right, the Chrome DevTools Elements tab is open, showing the DOM structure and the computed styles for the selected `h1` element. A red box highlights the "color" property in the "Properties" panel, which is set to `rgb(0, 0, 255)`.

```
getComputedStyle(element)["color"]
```

[JS]

(But: `getComputedStyle` returns some layout data also.)

# layout

The screenshot shows the W3C website's homepage. A large red box highlights the main content area, which includes the header, navigation menu, and the main article. A dashed red box highlights the specific news item about the election of the Advisory Board.

**STANDARDS** **PARTICIPATE** **MEMBERSHIP** **ABOUT W3C**

**WEB AND INDUSTRY**

- Automotive
- Entertainment (TV and Broadcasting)
- Publishing
- Web Payments
- Web of Data
- Web and Telecommunications

*Leading the web to its full potential*

**W3C Advisory Committee Elects Advisory Board**

3 June 2020 | Archive

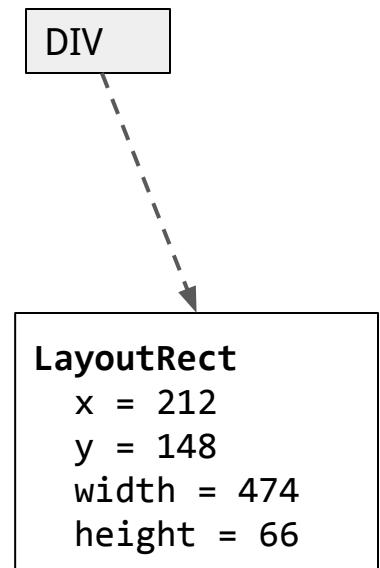
 The W3C Advisory Committee has filled five open seats on the W3C Advisory Board. Beginning 1 July 2020, the following new elected participants, Tantek Çelik (Mozilla), Tatsuya Igarashi (Sony), Florian Rivoal (W3C Invited Expert), Tzviya Siegman (Wiley) and David Singer (Apple), will join continuing participants Elika J Etemad (W3C Invited Expert), Avneesh Singh (DAISY Consortium), Eric Siow (Intel), Léonie Watson (TetraLogical), Chris Wilson (Google) and Hongru (Judy) Zhu (Alibaba). Many thanks to Jay (Junichi) Kishigami (NTT) and Charles Neville (ConsenSys), whose terms end this month

**ABOUT W3C**

The World Wide Web Consortium (W3C) is an international community that develops open standards to ensure the long-term growth of the Web.

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# layout

A screenshot of a web browser window displaying a page from Gutenberg.org. The page contains several paragraphs of text, each enclosed in a separate rectangular box, illustrating a block layout structure. The browser interface includes standard controls like back, forward, and search, along with a URL bar showing the secure connection.

The last burst carried the mail to the summit of the hill. The horses stopped to breathe again, and the guard got down to skid the wheel for the descent, and open the coach-door to let the passengers in.

"Tst! Joe!" cried the coachman in a warning voice, looking down from his box.

"What do you say, Tom?"

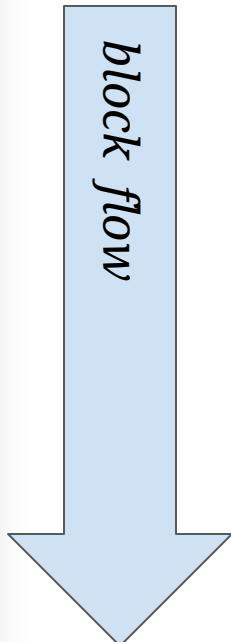
They both listened.

"I say a horse at a canter coming up, Joe."

"I say a horse at a gallop, Tom," returned the guard, leaving his hold of the door, and mounting nimbly to his place. "Gentlemen! In the king's name, all of you!"

With this hurried adjuration, he cocked his blunderbuss, and stood on the offensive.

The passenger booked by this history, was on the coach-step, getting in; the two other passengers were close behind him, and about to follow. He remained on the step, half in the coach and half out of; they remained in the road below him. They all looked from the coachman to the guard, and from the guard to the coachman, and listened. The coachman looked back and the guard looked back, and even the emphatic leader pricked up his ears and looked back, without contradicting.

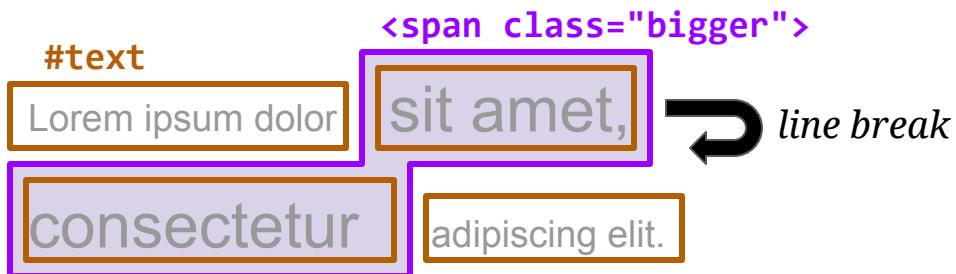


*Simple "block" layout objects are placed one after another, flowing down the page.*

# layout



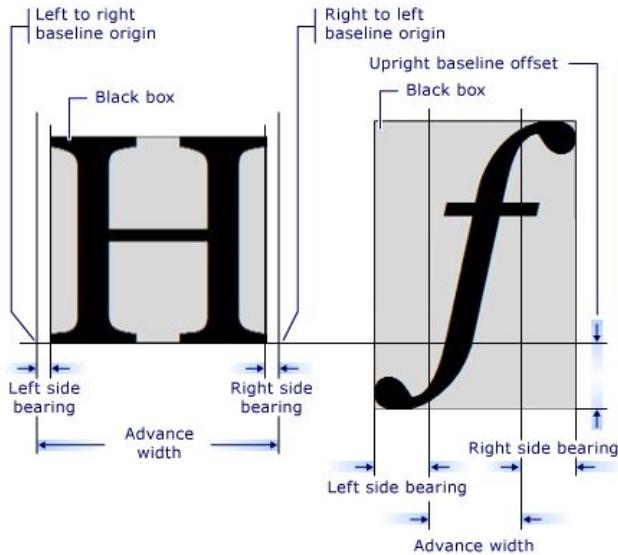
*Text and "inline" elements flow left-to-right, and are broken into lines.*



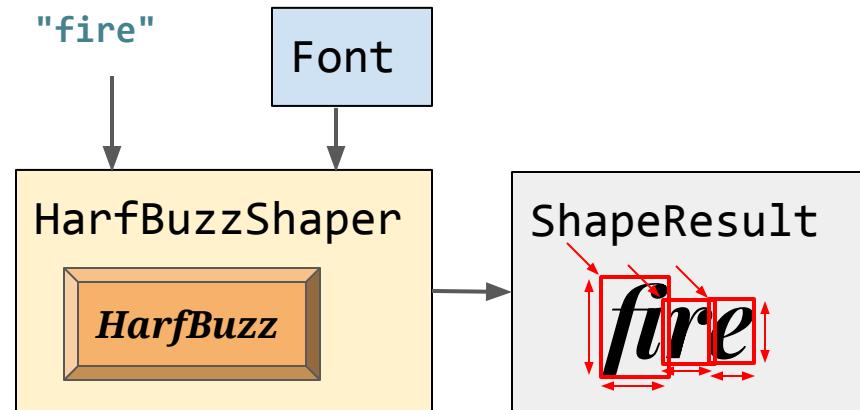
العربية ←  
עברית ←

*(Some languages flow right-to-left.)*

# layout

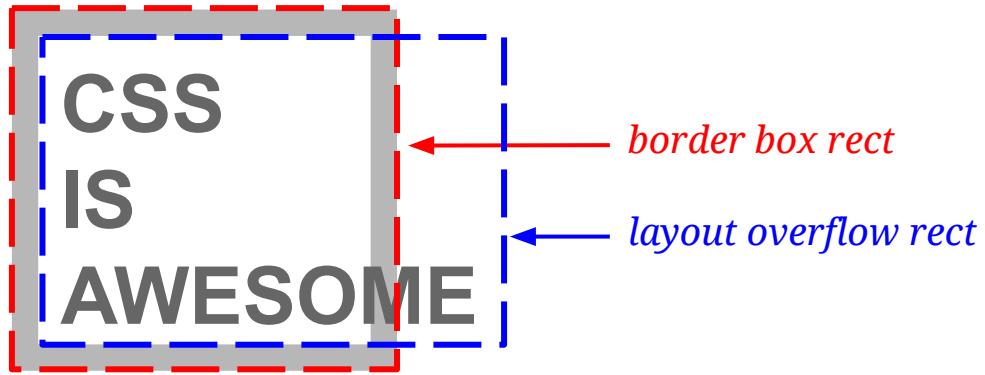


*Layout measures runs of text in fonts.*



*Shaping selects the glyphs and computes their placement.*

# layout



*Overflow can be visible,  
hidden, or scrollable.*

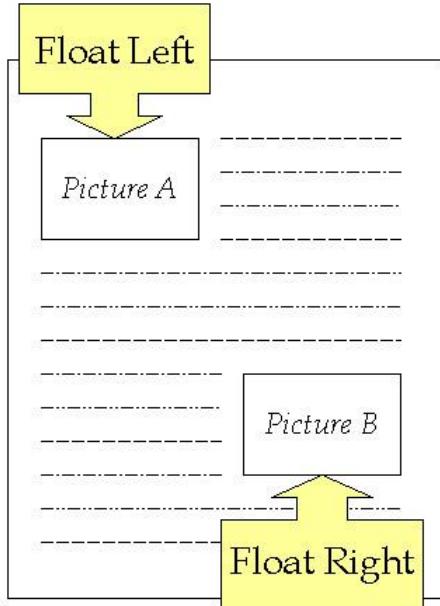
*The contents of a layout object  
can **overflow** its border box.*

A screenshot of a web browser window showing a yellow-highlighted text block. The text is a long Latin placeholder (Lorem ipsum). A horizontal scrollbar is visible at the bottom of the text block, indicating that the content exceeds the available vertical space and is therefore scrollable. The text block has a thin black border.

*...  
purus adipiscing elit.  
n dapibus. Aenean venenatis,  
eros convallis augue,  
et metus. Suspendisse  
osuere. Phasellus tristique,  
 odio ultrices justo, vel  
us ornare euismod tortor, id  
amus sit amet quam ut eros  
Phasellus congue tempus dolor  
vitae finibus est. Aliquam et  
egit facilisis ornare, magna  
purus facilisis risus, in laoreet ante est a quam. Aenean odio  
eros, pulvinar eu tristique id, suscipit et est. Proin interdum  
vel lorem ac pretium. Quisque pulvinar eleifend tellus, vitae  
fringilla leo varius vitae. Nullam a ligula viverra, egestas  
purus id, molestie nulla. Sed pulvinar aliquet orci vitae  
molestie.*

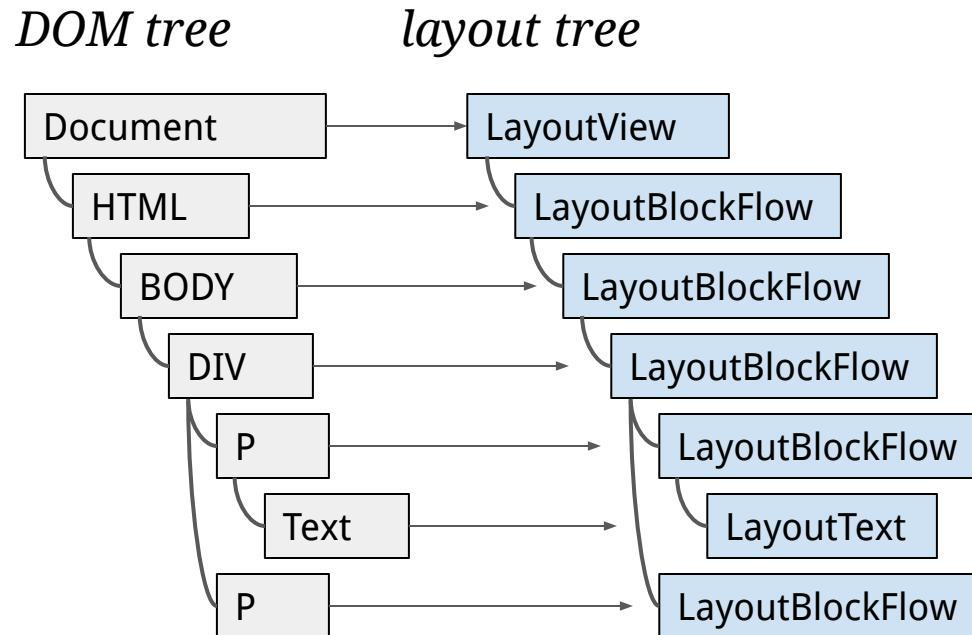
# layout

*Other kinds of layout are even more complex.*



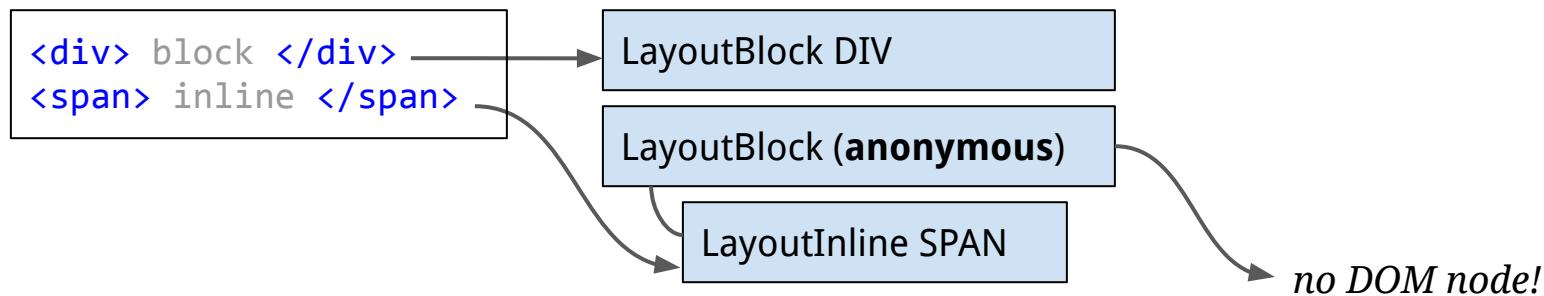
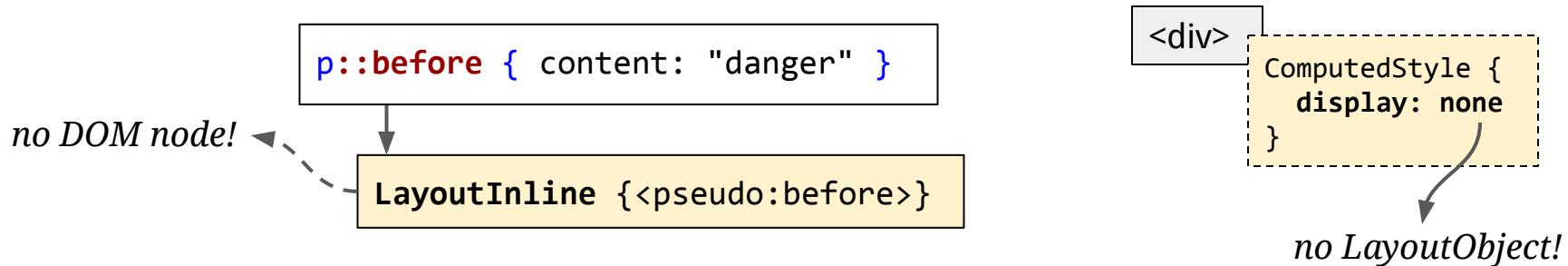
- `<table>`
- `float: left`
- `column-count: 3`
- `display: flex`
- `writing-mode: vertical-lr`
- ...

# layout

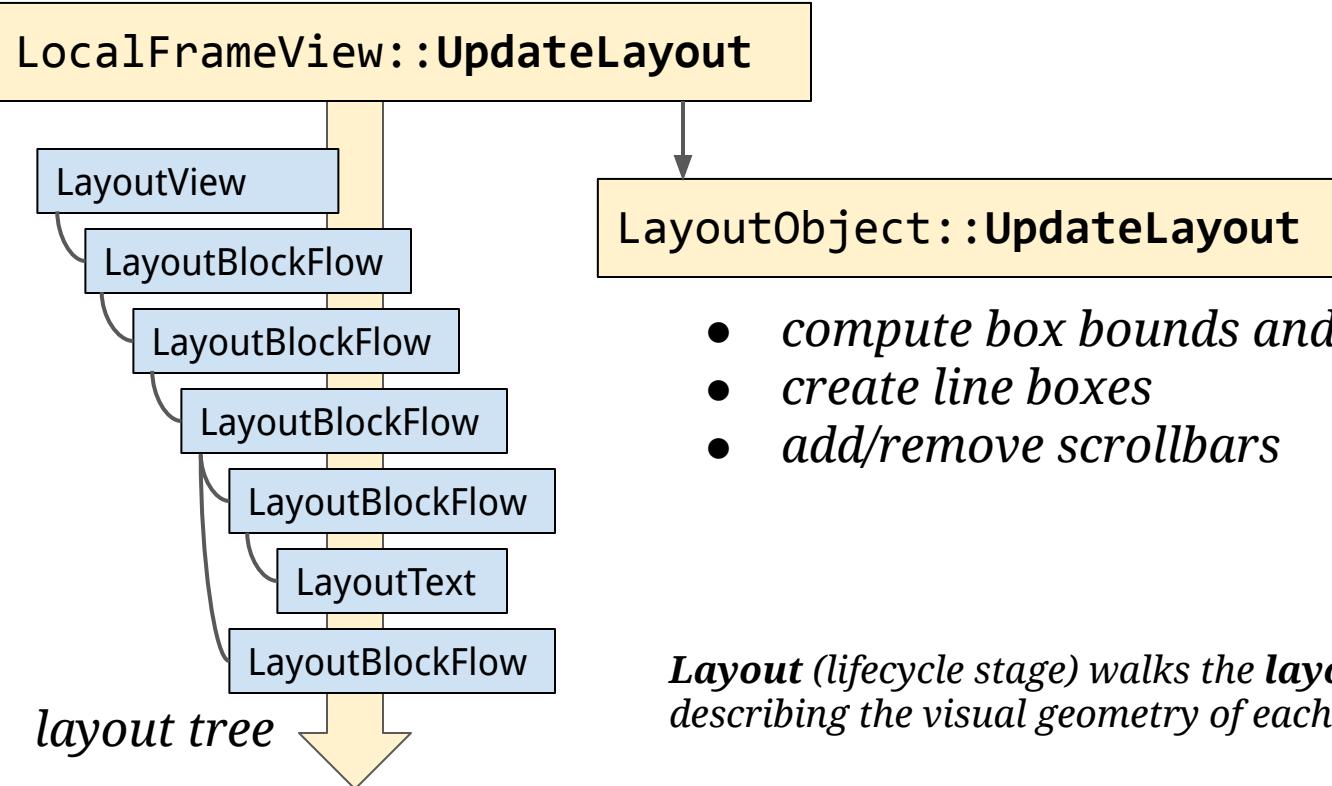


# layout

*DOM nodes are mostly 1:1 with layout objects, with some exceptions.*



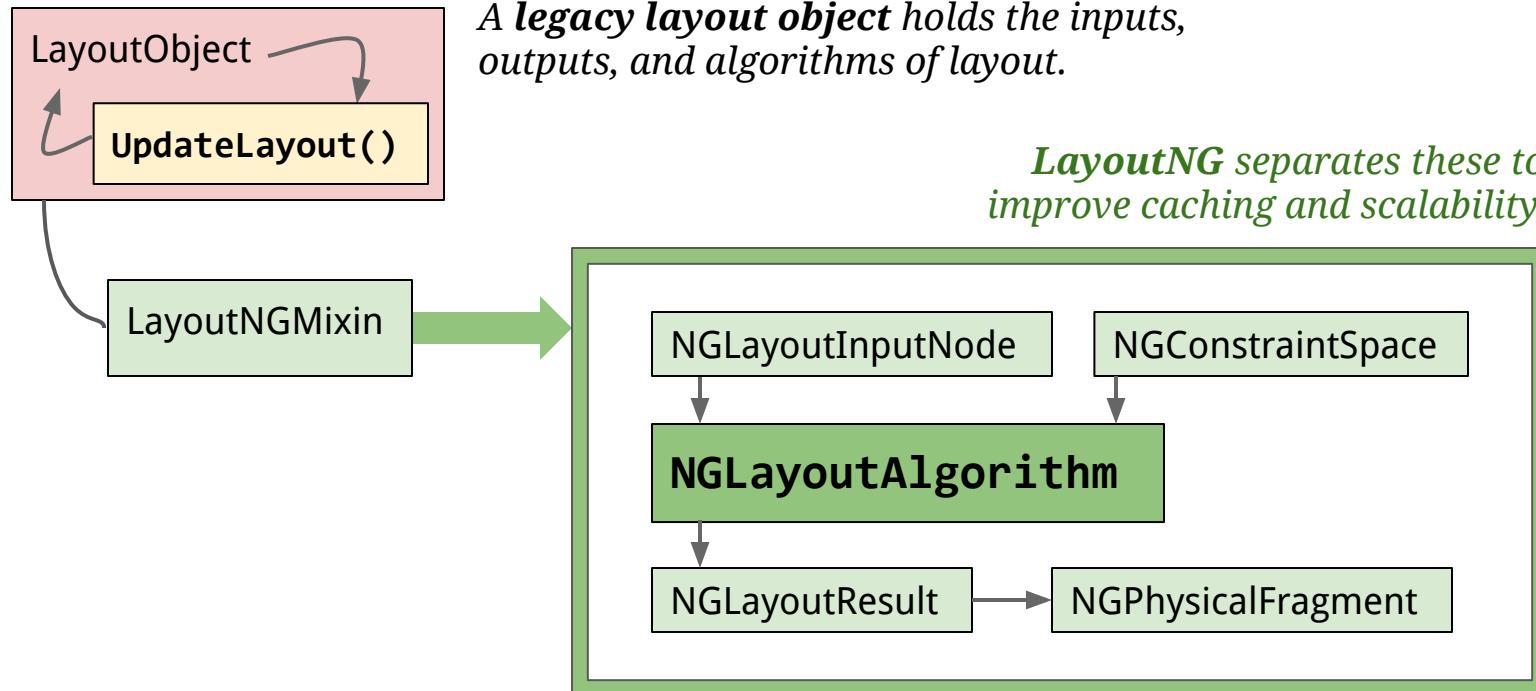
# layout



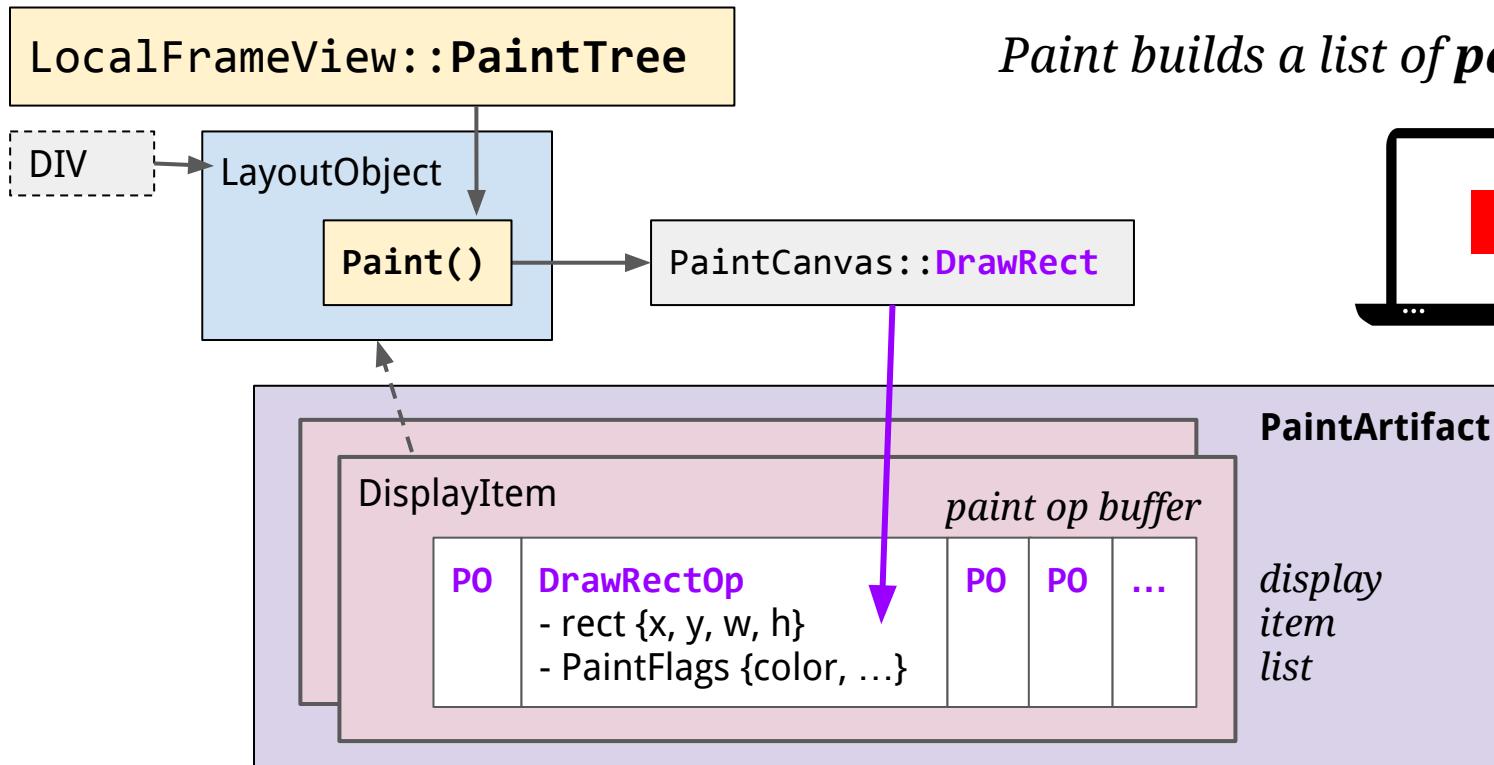
- *compute box bounds and overflow*
- *create line boxes*
- *add/remove scrollbars*

*Layout (lifecycle stage) walks the **layout tree** filling in state describing the visual geometry of each LayoutObject.*

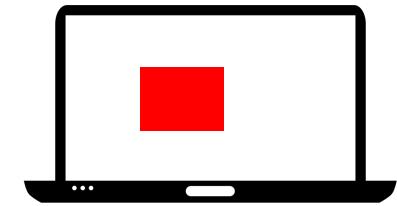
# layout



# paint



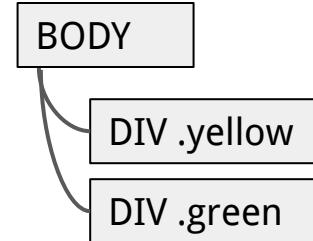
*Paint builds a list of **paint ops**.*



# paint

*Paint uses **stacking order**,  
not DOM order.*

```
<div class="yellow"></div>
<div class="green"></div>
<style>
  .yellow { z-index: 2; ... }
  .green  { z-index: 1; ... }
</style>
```



*DOM tree*

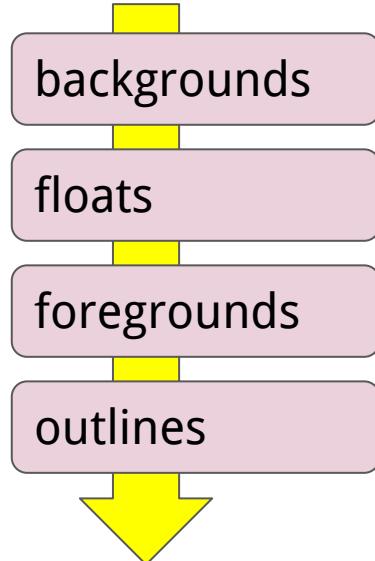


*yellow paints last*

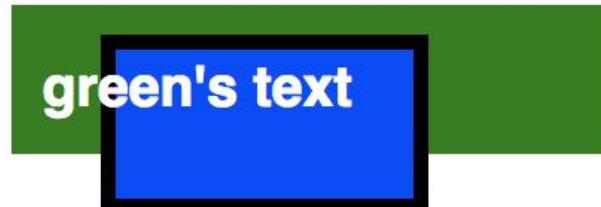
# paint

*Each **paint phase** is a separate traversal of a stacking context.*

*paint phases  
(simplified)*



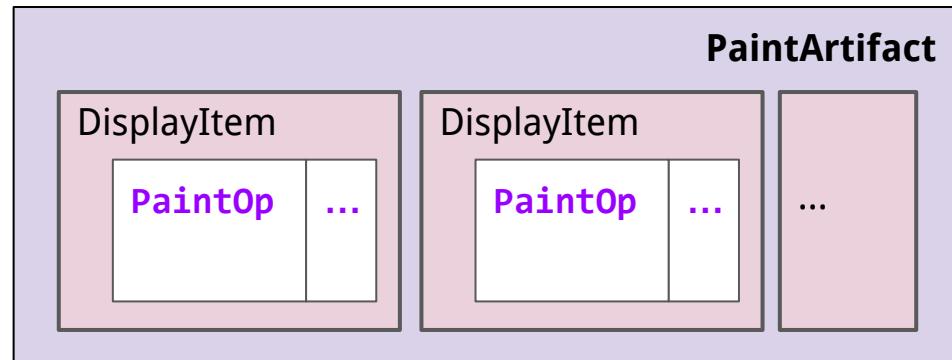
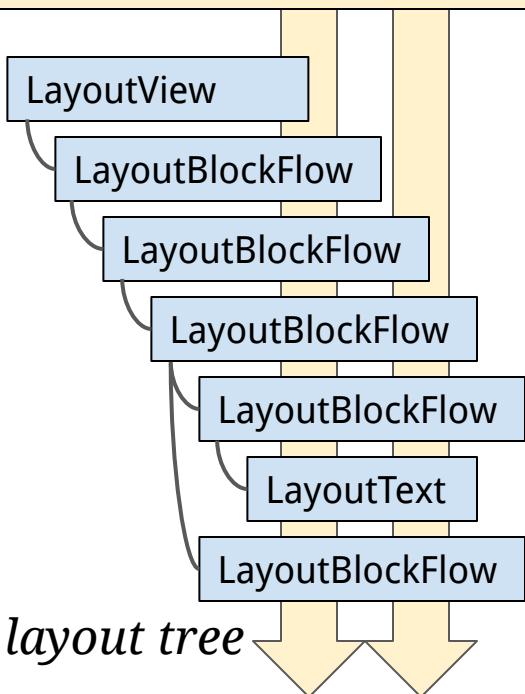
```
<div id="green">  
  green's text  
</div>  
<div id="blue"></div>
```



*blue after green, but  
foregrounds after backgrounds*

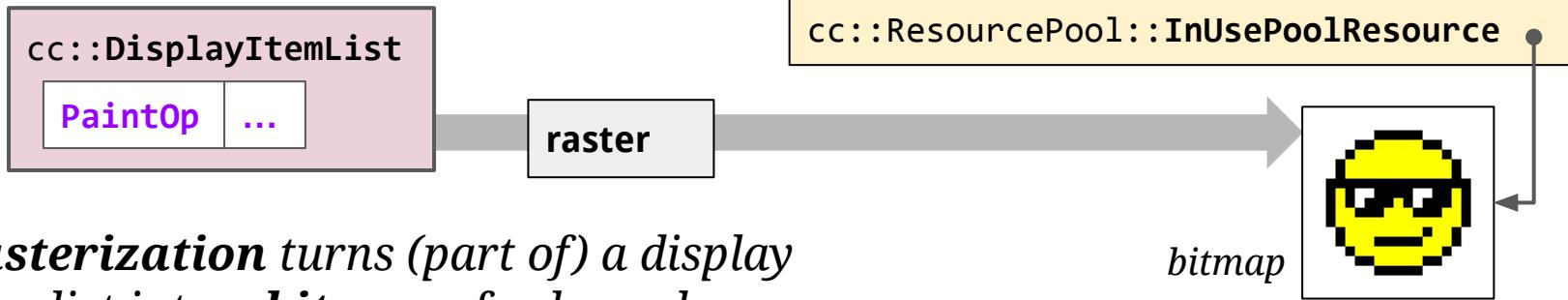
# paint

## LocalFrameView::PaintTree



*Paint (lifecycle stage) makes several passes over the layout tree producing a linear list of display items with paint ops.*

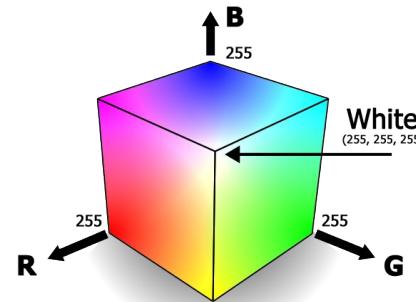
# raster



**Rasterization** turns (part of) a display item list into a **bitmap** of color values.

FFFF	FFFF	0000
FFFF	FFFF	00FF
FFFF	0000	FFFF
FFFF	00FF	00FF
0000	FFFF	FFFF
00FF	00FF	00FF

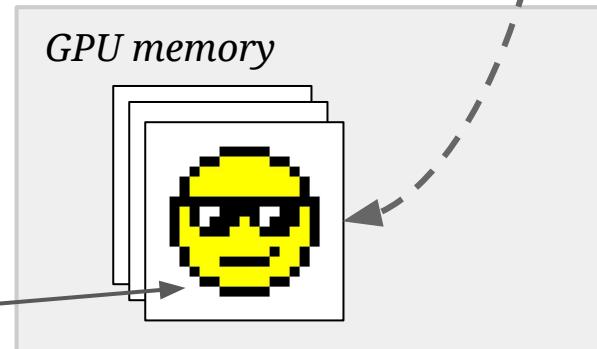
(red, green,  
blue, alpha)



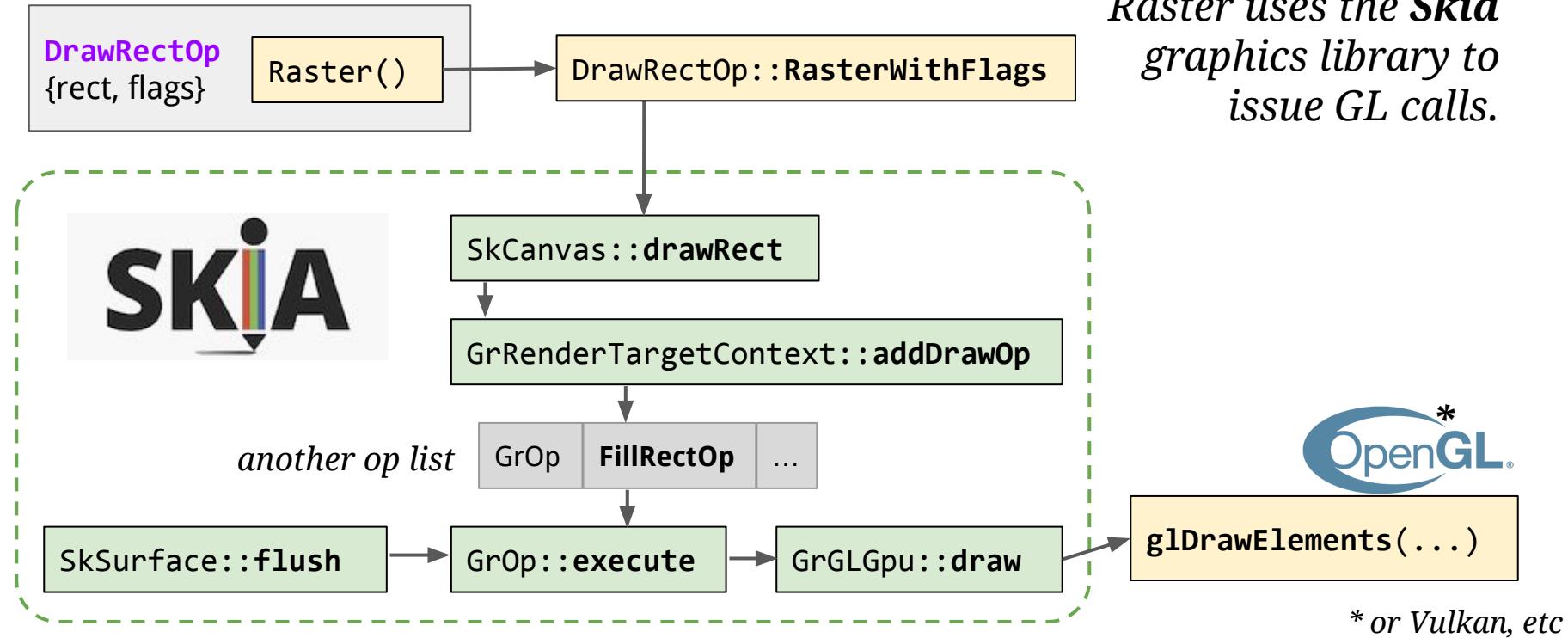
# raster



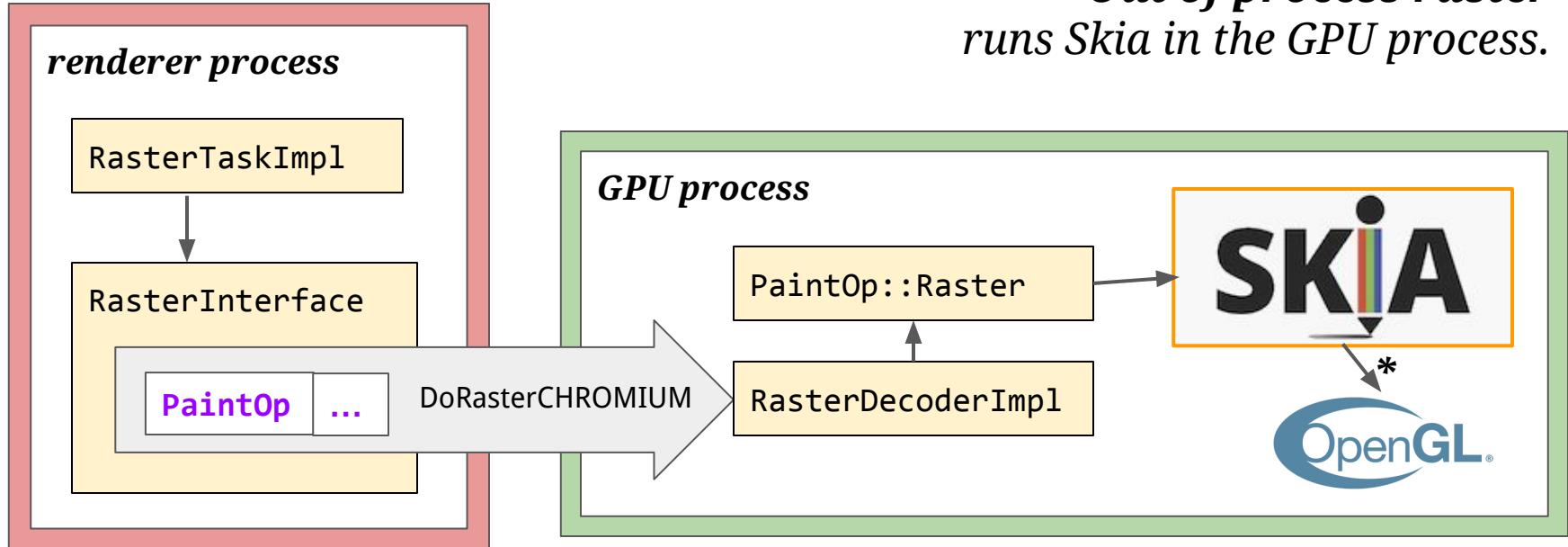
*Raster can be accelerated by the GPU.*



# raster



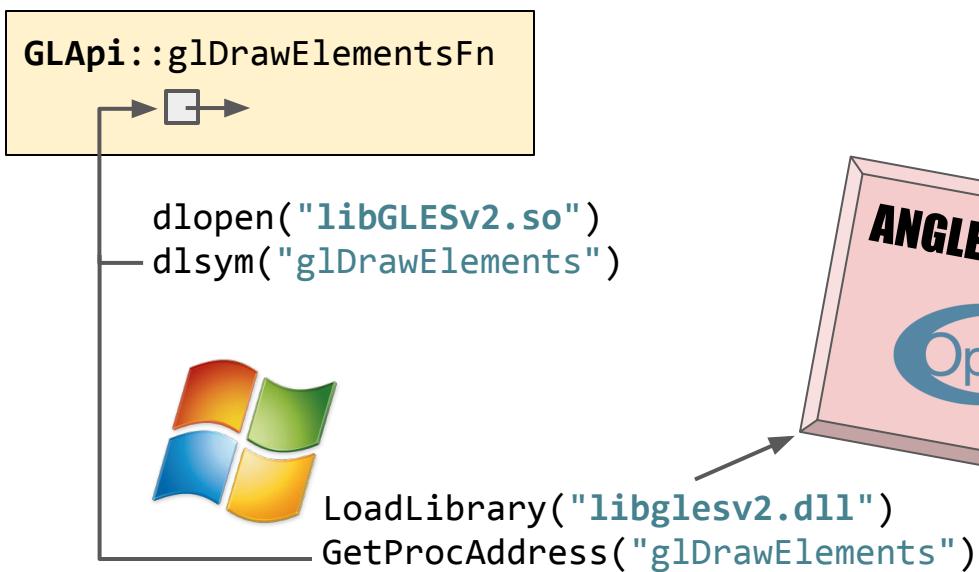
# gpu



\* or Vulkan, etc

# gpu

## GPU process



*In the GPU process, the GL functions link dynamically to native OpenGL.*

*On Windows, we translate to DirectX.*

# change



*We now have a complete **pipeline**.*

*But what if state can **change**?*

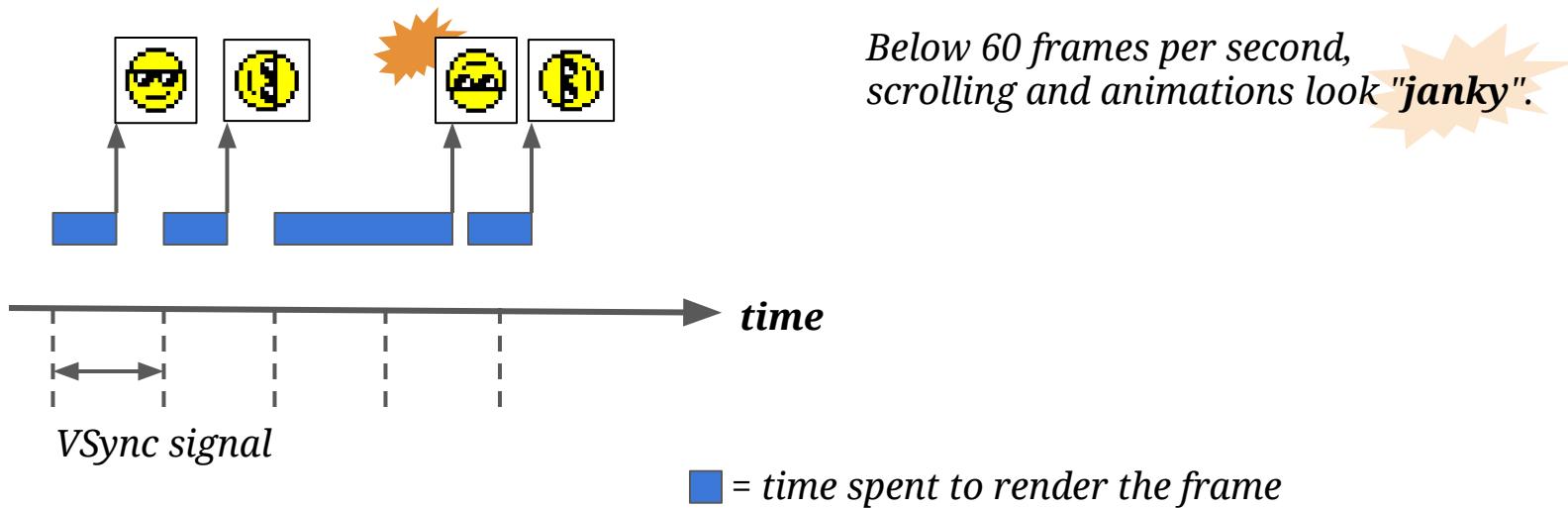
- scrolling
- zooming
- animations
- incremental loading
- JavaScript
- ...



"Change is good."  
"Yeah, but it's not easy."

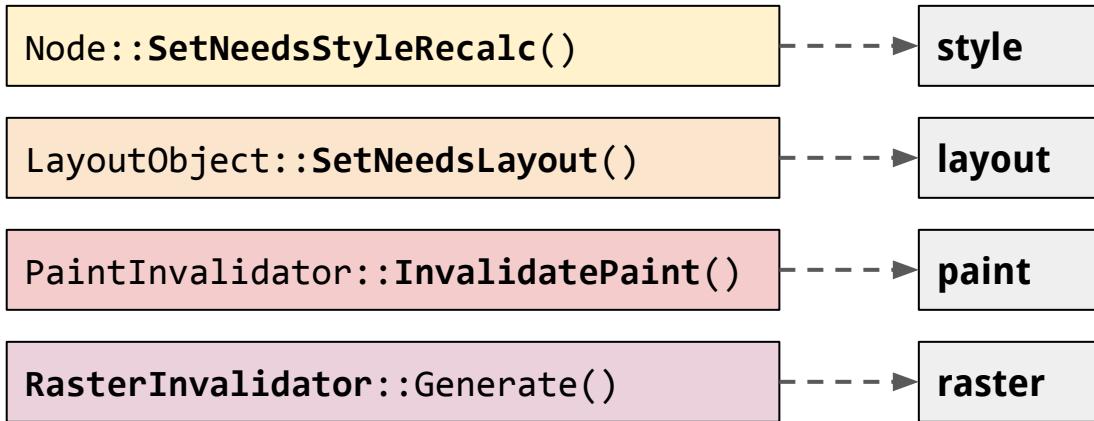
# frames

*The renderer produces **animation frames**.*



# invalidation

*Each pipeline stage tracks granular asynchronous **invalidations**.*



*Outputs are reused from previous frames when possible.*

# repaint

*Paint + raster remain expensive if a large region is transformed...*

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam commodo est orci, quis sodales diam tristique et. Fusce fringilla ac libero eget facilisis. Fusce a vulputate ligula. In tortor

scroll

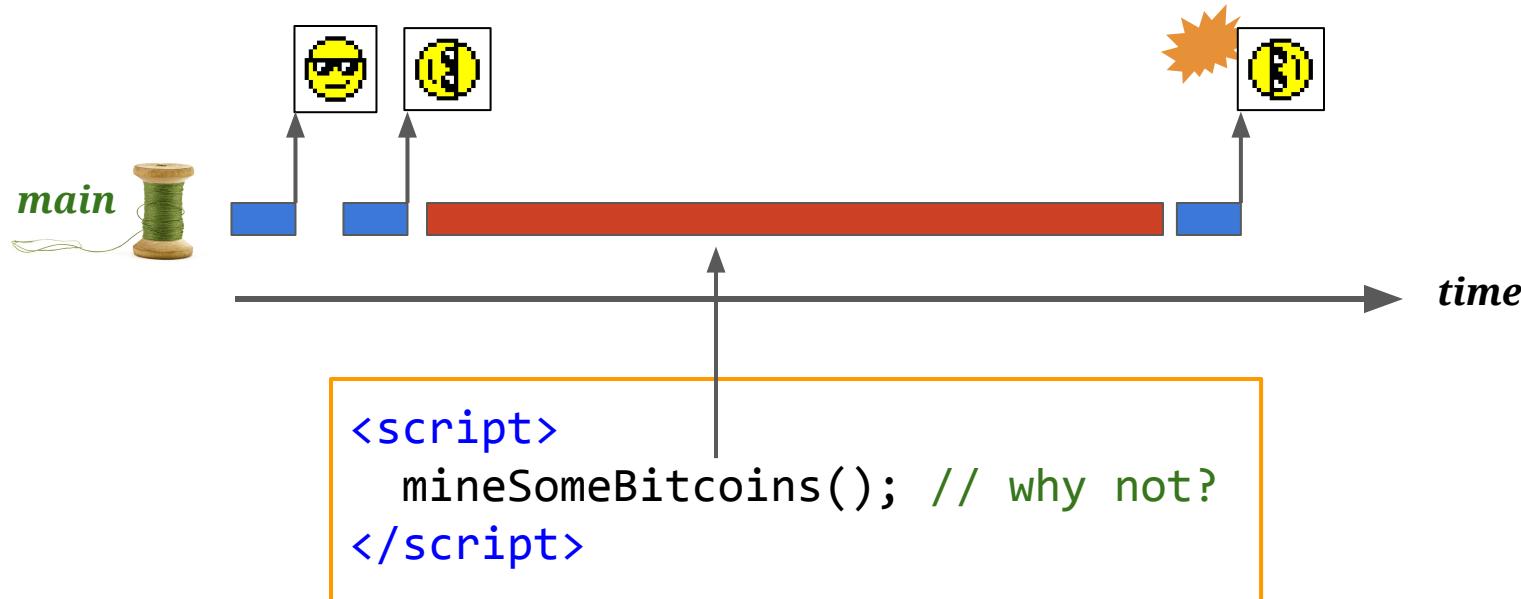


adipiscing elit. Aliquam commodo est orci, quis sodales diam tristique et. Fusce fringilla ac libero eget facilisis. Fusce a vulputate ligula. In tortor ex, porta faucibus fringilla quis, congue a

*all the pixels changed!*

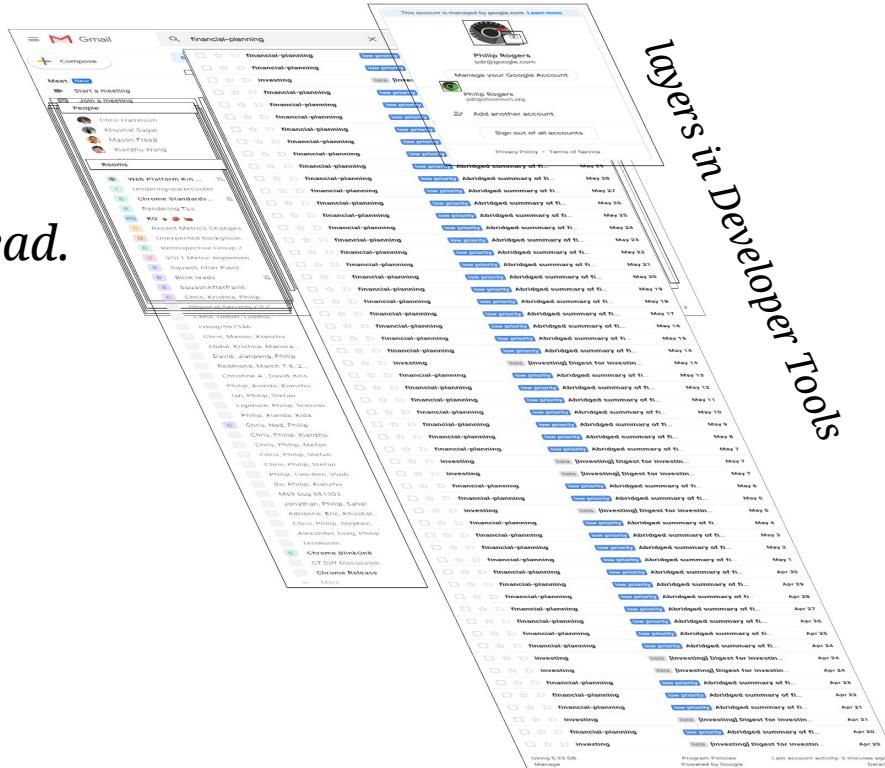
# jank

*... and anything on the **main thread** competes with JavaScript.*



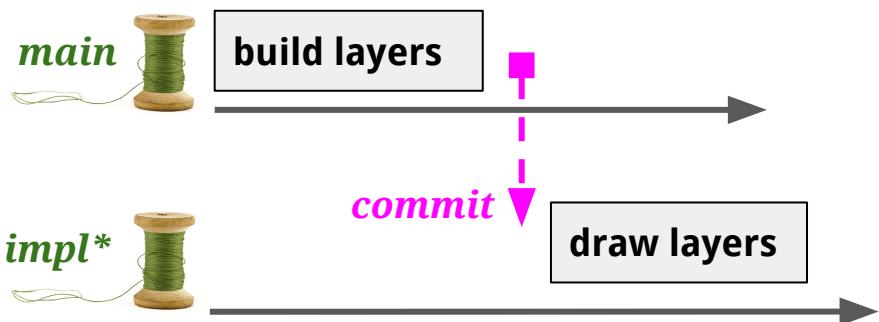
# enter: threaded compositing

- *Decompose the page into layers which raster independently.*
- *Combine the layers on another thread.*

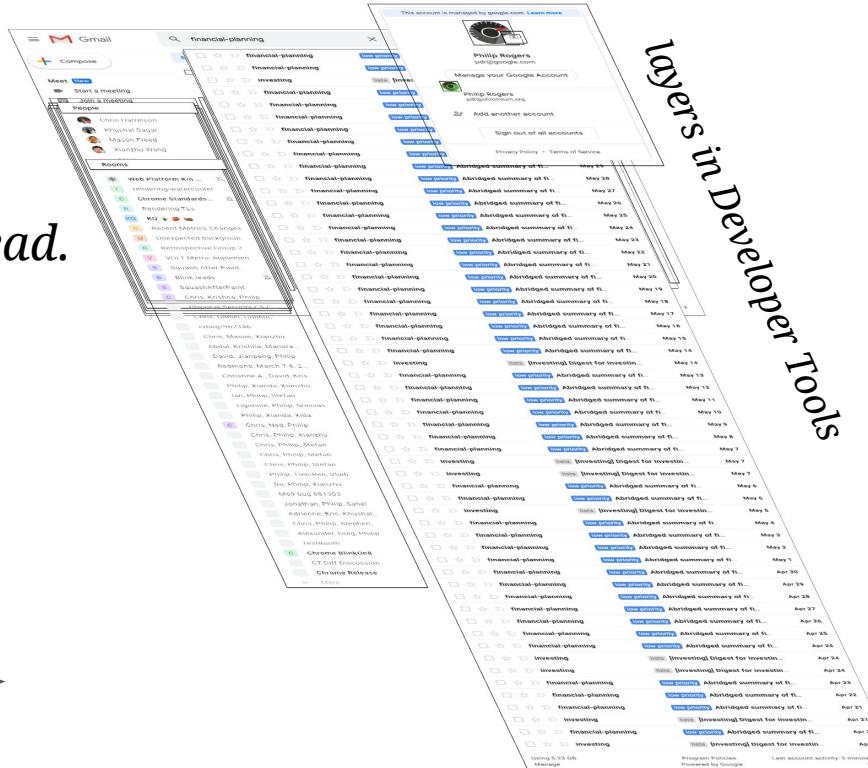


# enter: threaded compositing

- *Decompose the page into layers which raster independently.*
- *Combine the layers on another thread.*

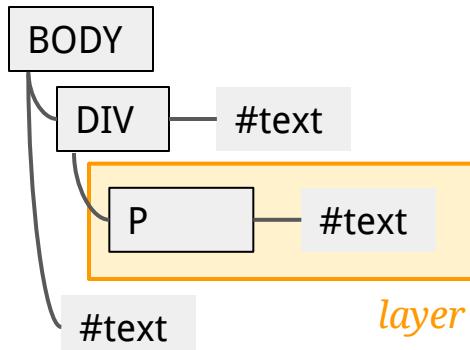


\* ("impl" = compositor thread) ↴(၂) ↴



# layers

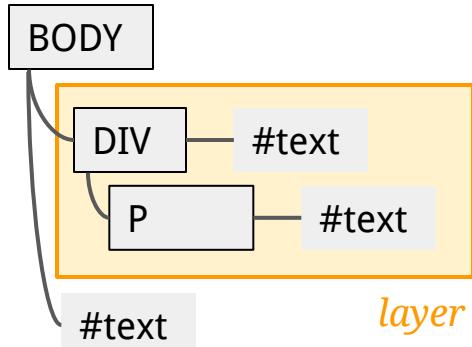
```
<div>  
  AAA  
  <p class="wobble"> BBB </p>  
</div>  
CCC
```



*A simple layer captures a subtree of content.*

# layers

```
<div class="wobble">  
  AAA  
  <p> BBB </p>  
</div>  
CCC
```



*A simple layer captures a subtree of content.*

# threaded compositing



***Animation:***  
*a layer moves*

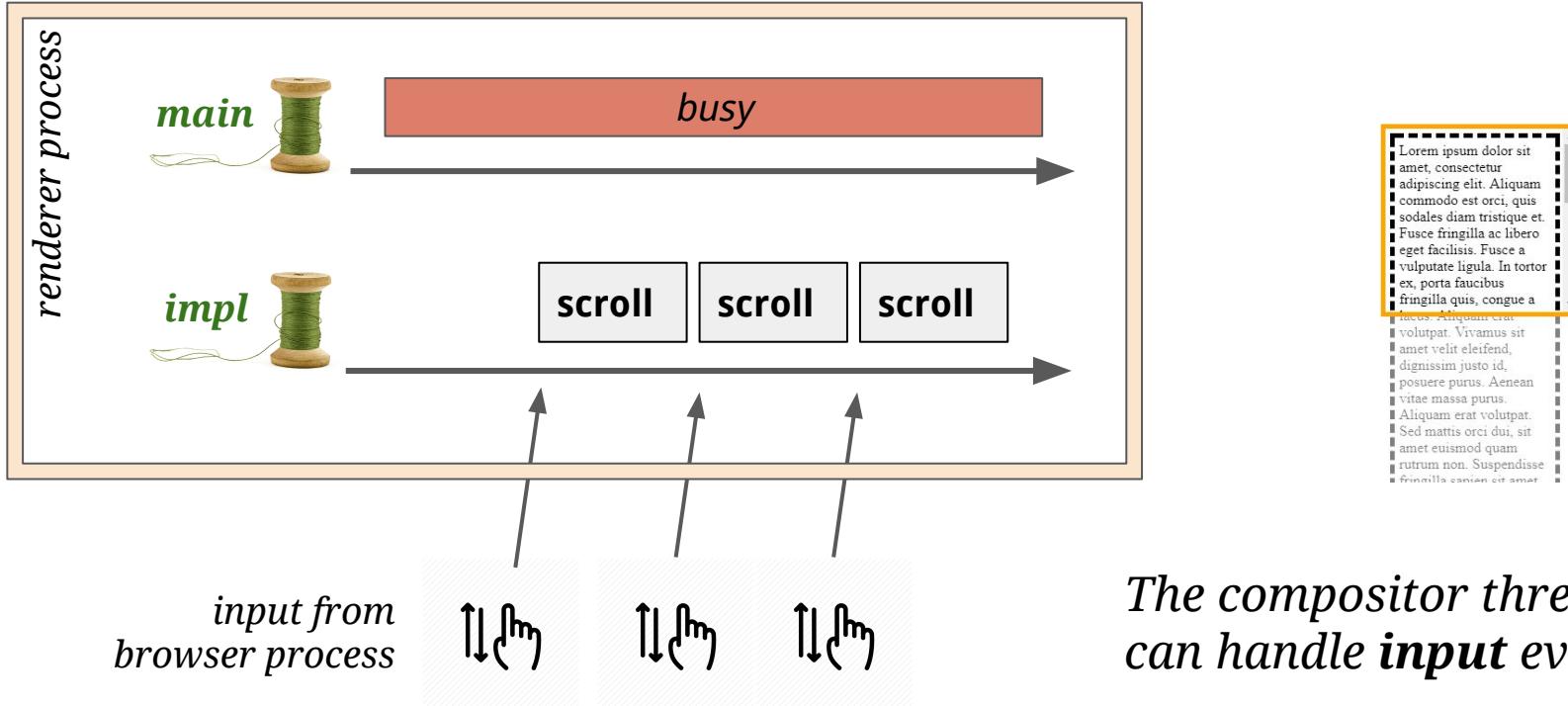
***Scrolling:***  
*a layer moves;*  
*another clips*

>Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam commodo est orci, quis sodales diam tristique et. Fusce fringilla ac libero eget facilisis. Fusce a vulputate ligula. In tortor ex, porta faucibus fringilla quis, congue a  
fucus. Aliquam erat volutpat. Vivamus sit amet velit eleifend, dignissim justo id, posuere purus. Aenean vitae massa purus. Aliquam erat volutpat. Sed mattis orci dui, sit amet euismod quam rutrum non. Suspendisse fringilla canien sit amet

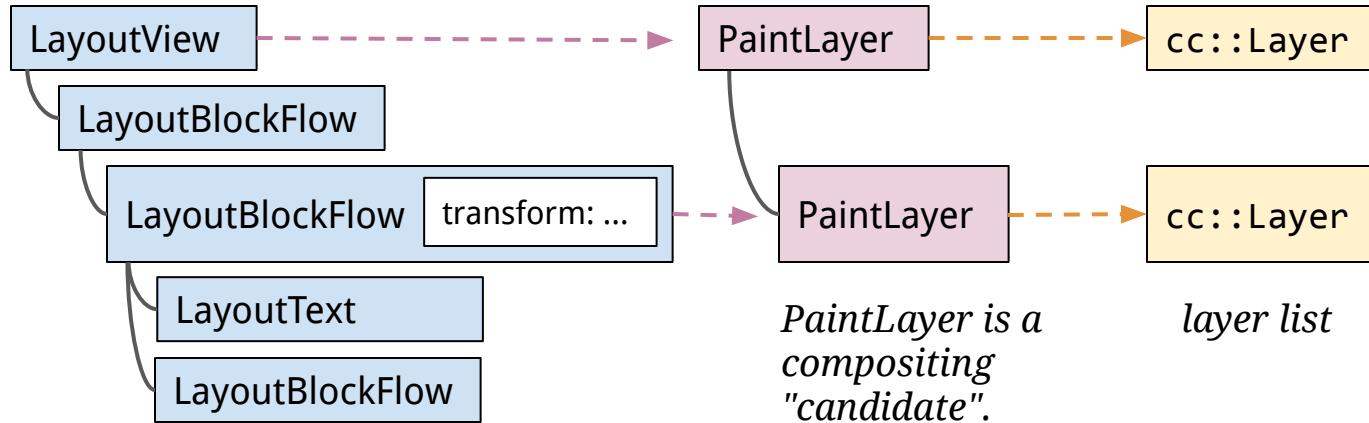
***Pinch Zoom:***  
*a layer scales*



# threaded input



# layer list

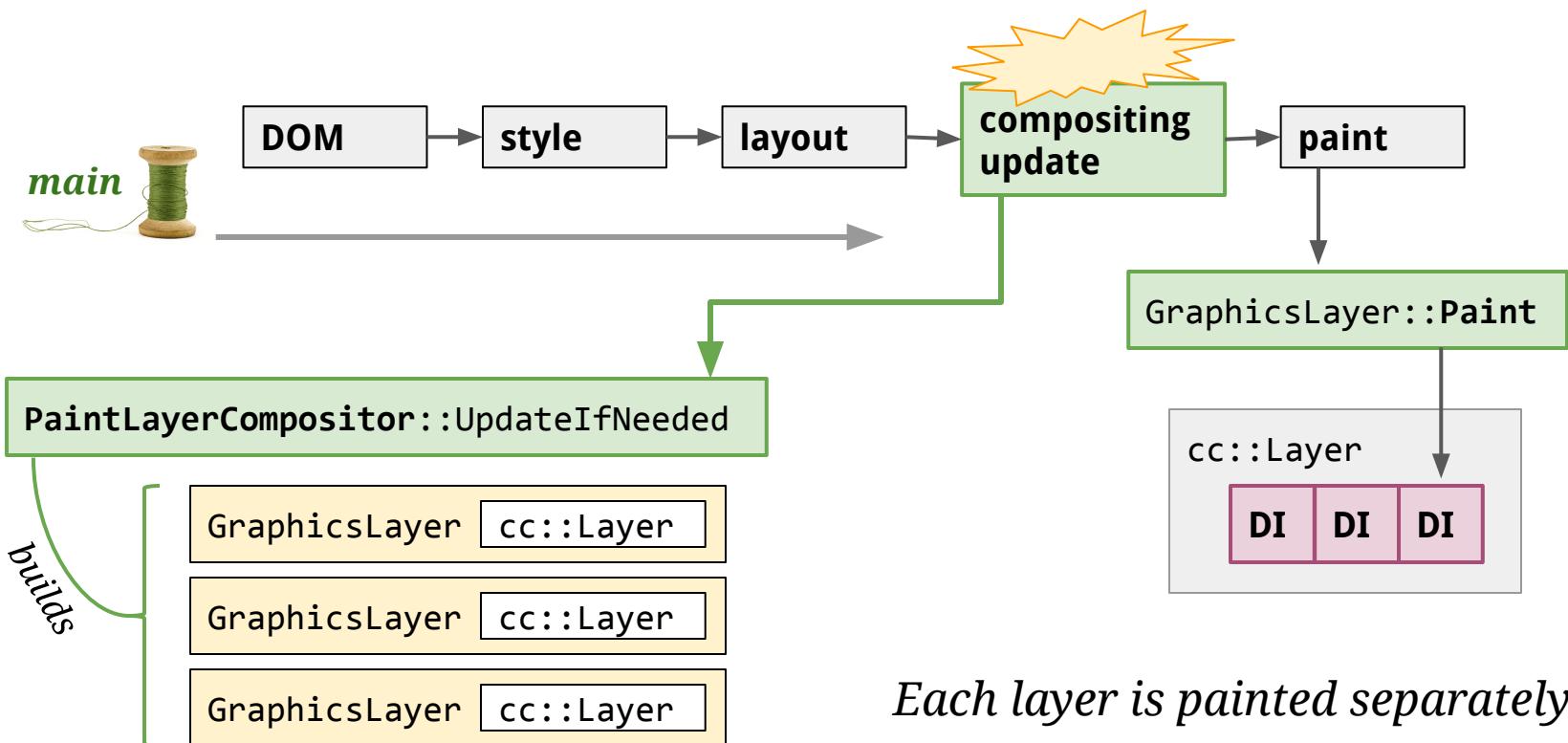


*layout tree*

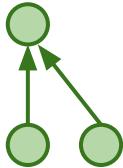
*PaintLayer is a  
compositing  
"candidate".*

*The layer list is based on the layout tree. It  
has no hierarchy.*

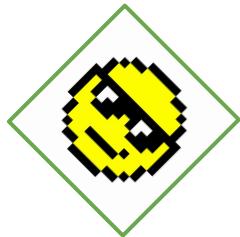
# compositing update



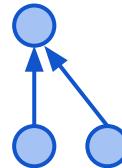
# property trees



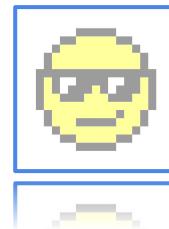
*transform  
tree*



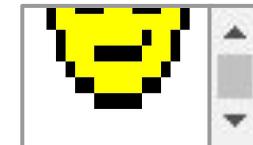
*clip  
tree*



*effect  
tree*

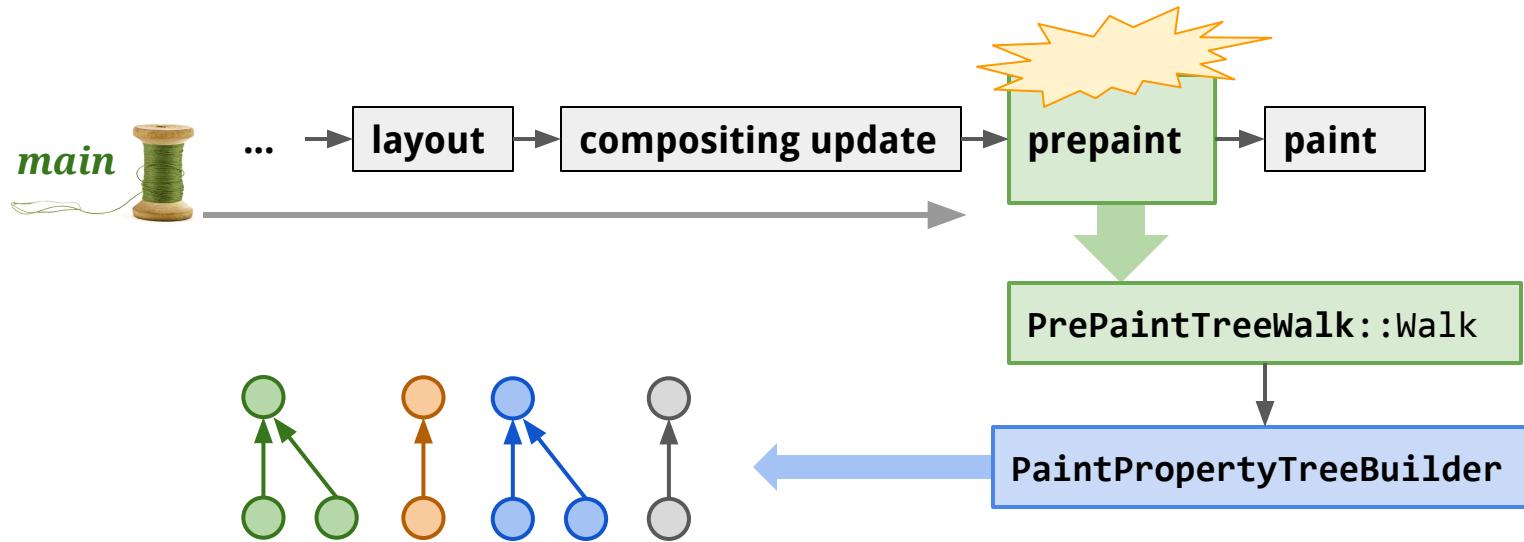


*scroll  
tree*



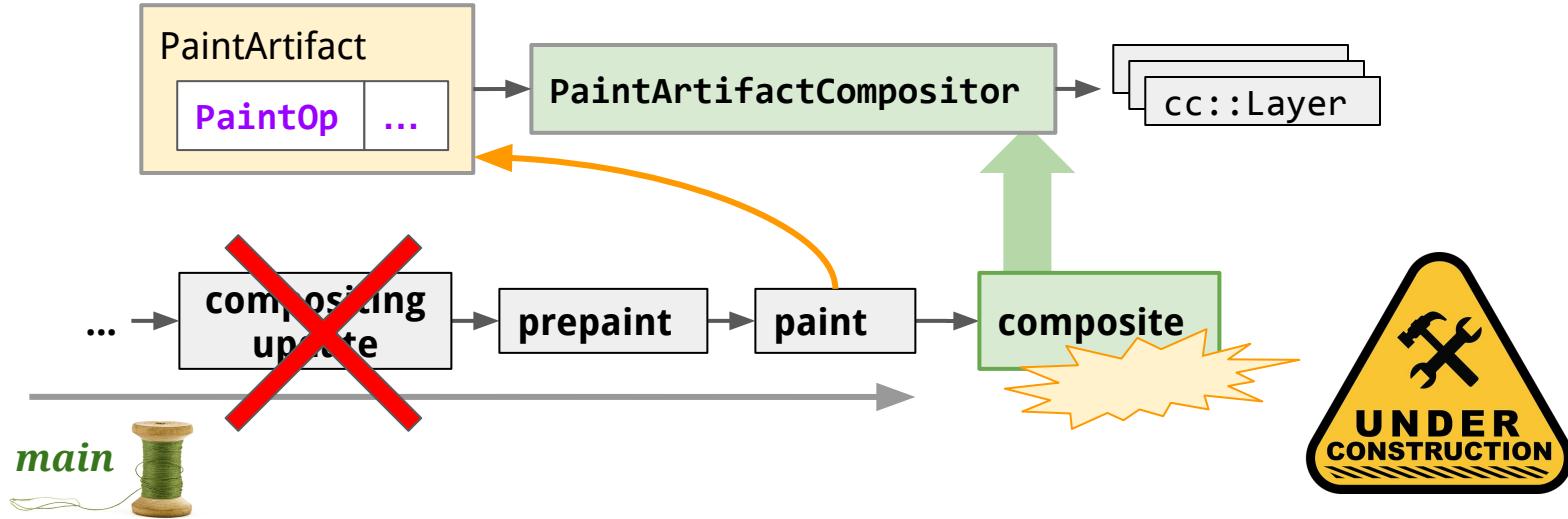
*The compositor can apply some **paint properties** to a layer.*

# property trees



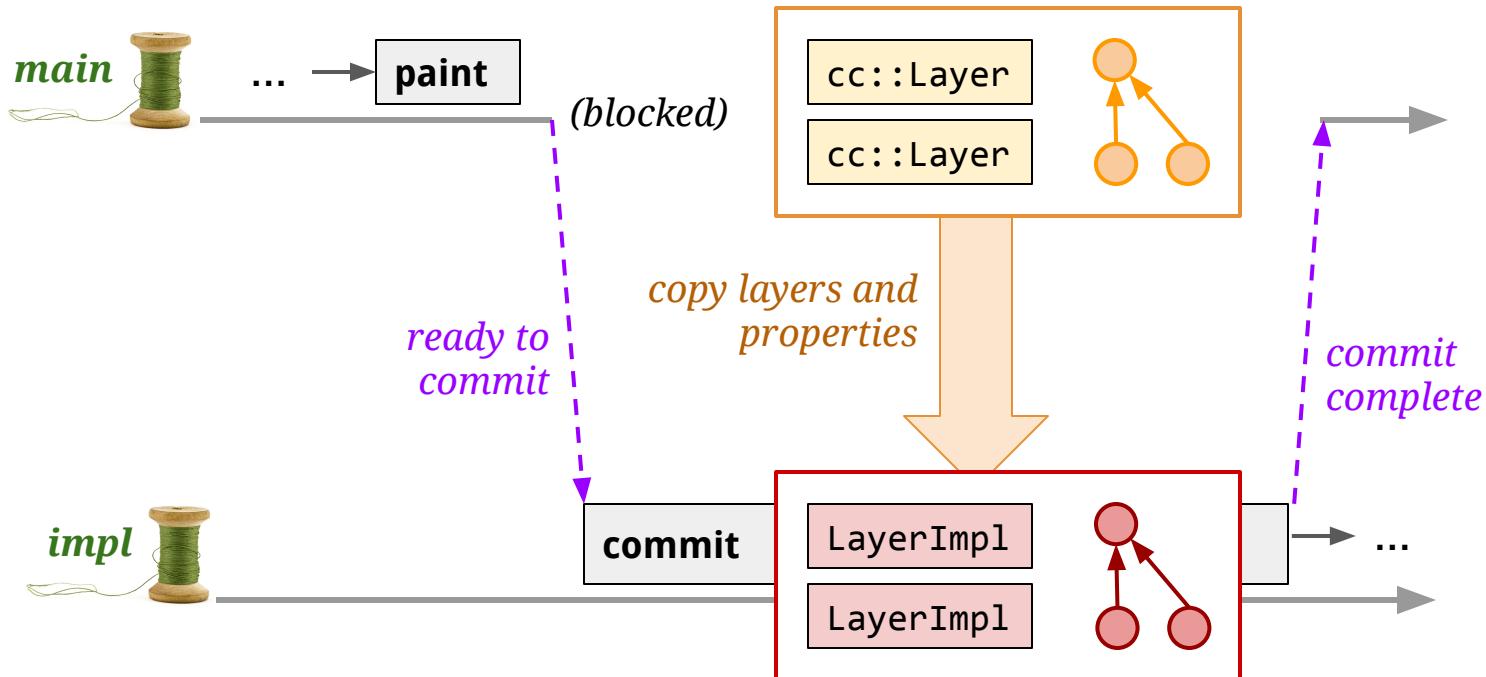
*The **prepaint** stage builds the property trees.*

# composite after paint (CAP)



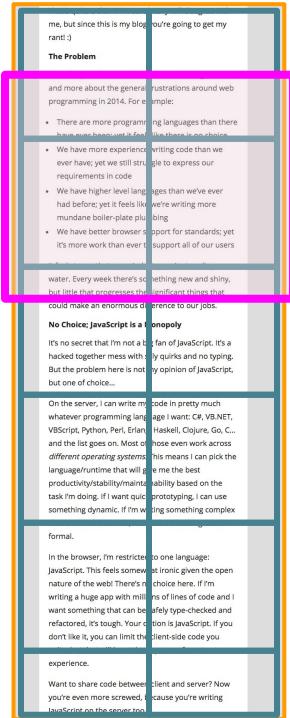
*In the future, layers will be created after paint.*

# commit



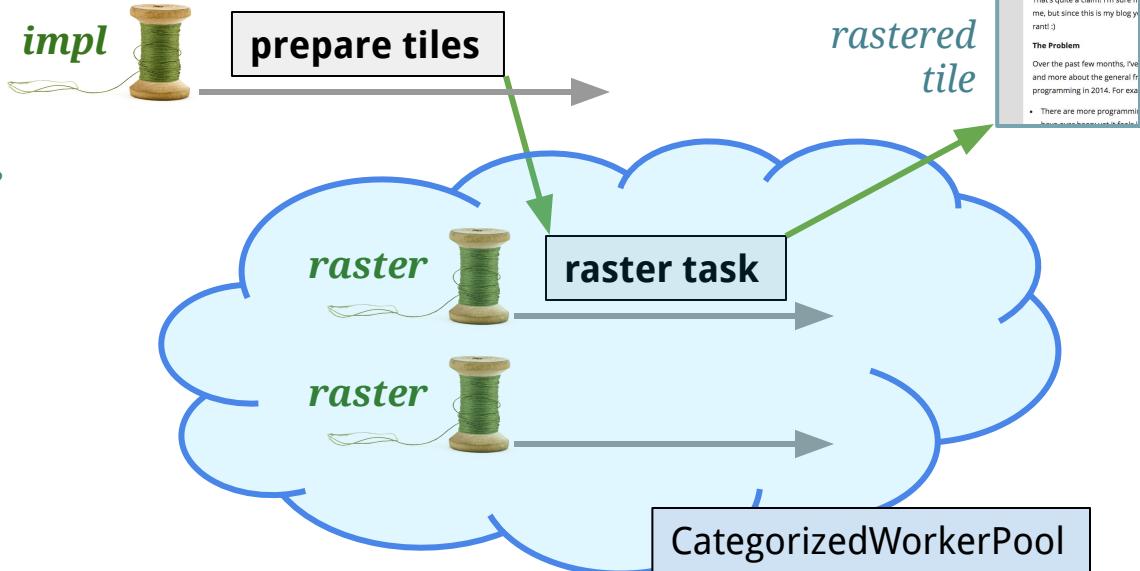
# tiling

viewport



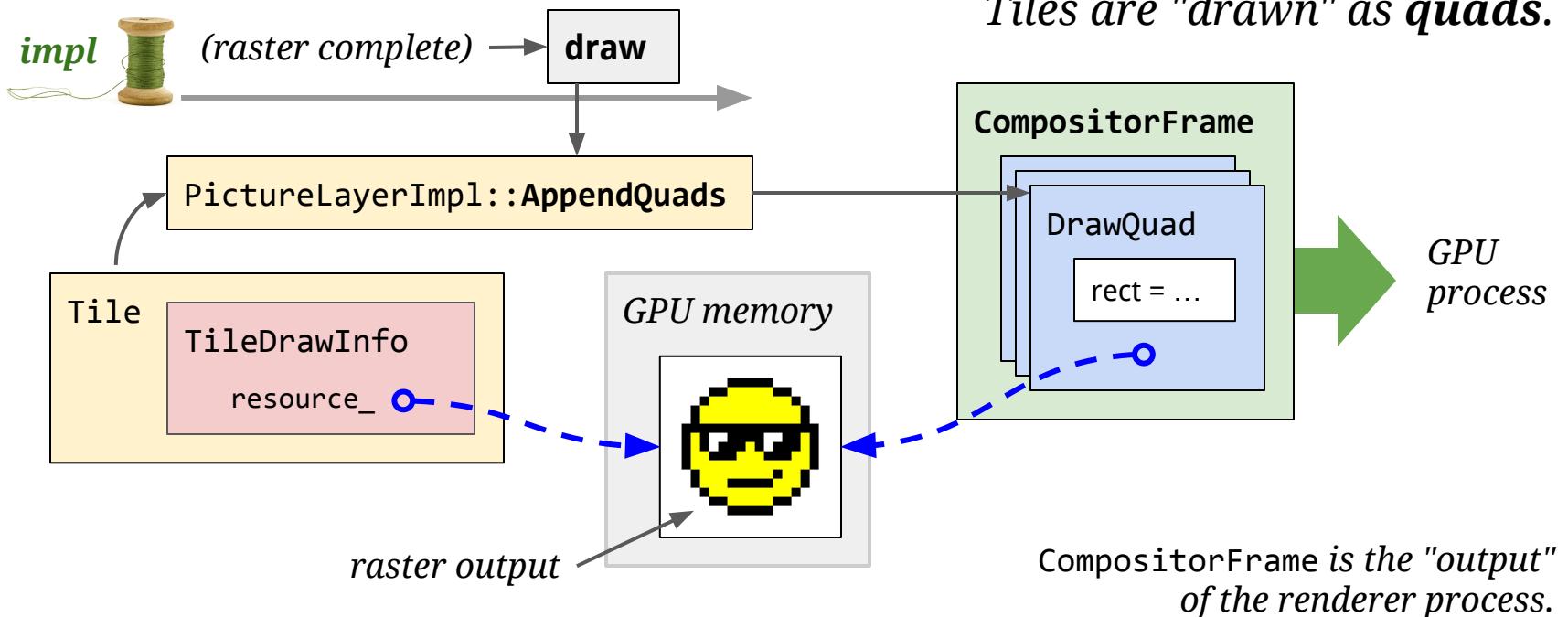
visible tiles

layer

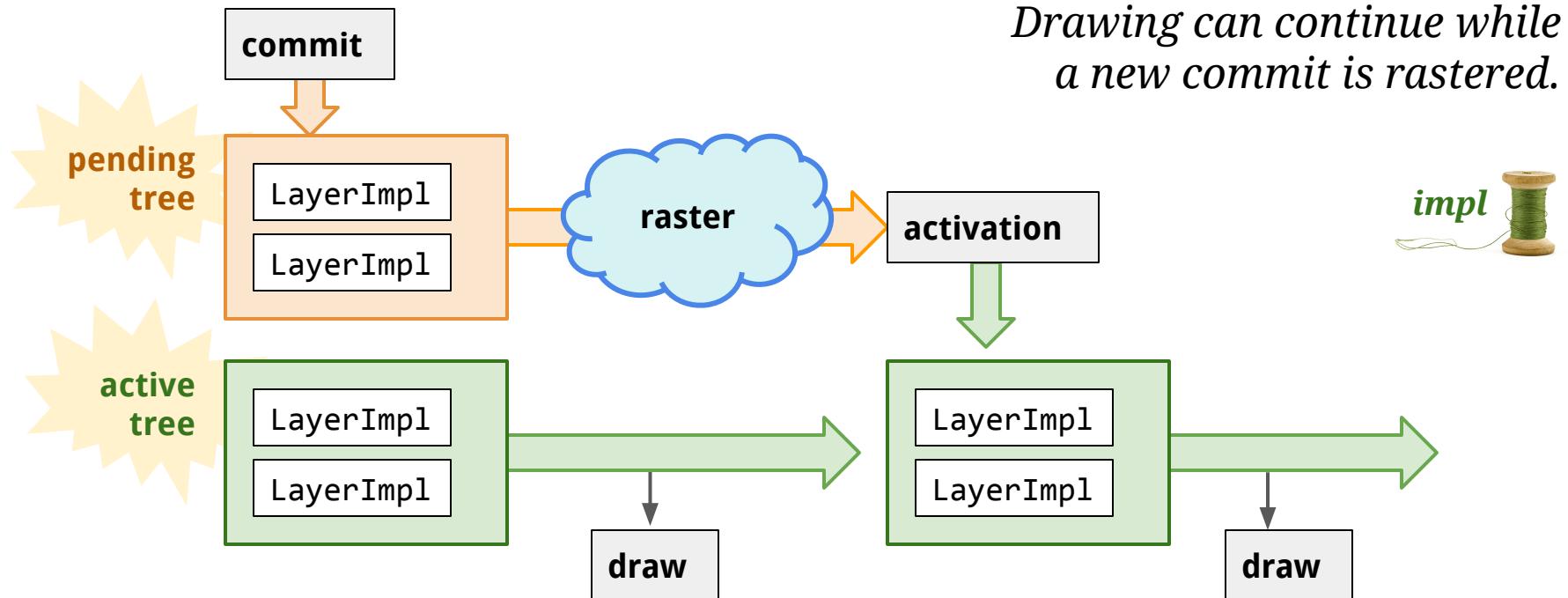


*Layers are broken into **tiles** for raster.*

# draw (layers)

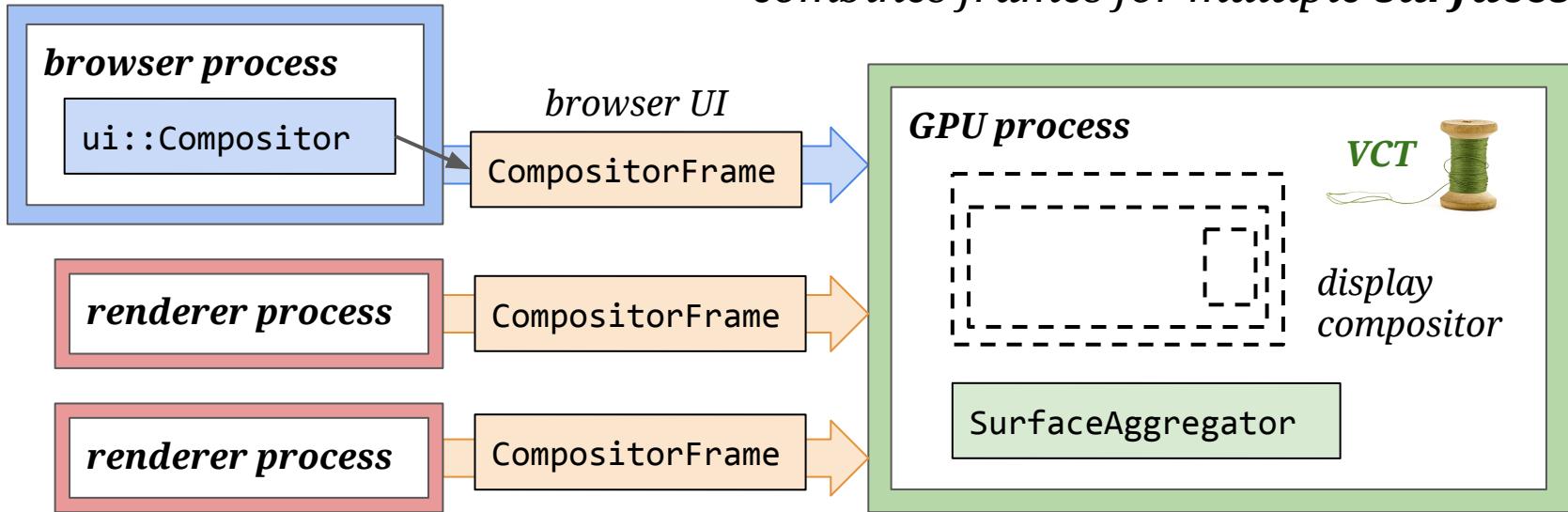


# activation

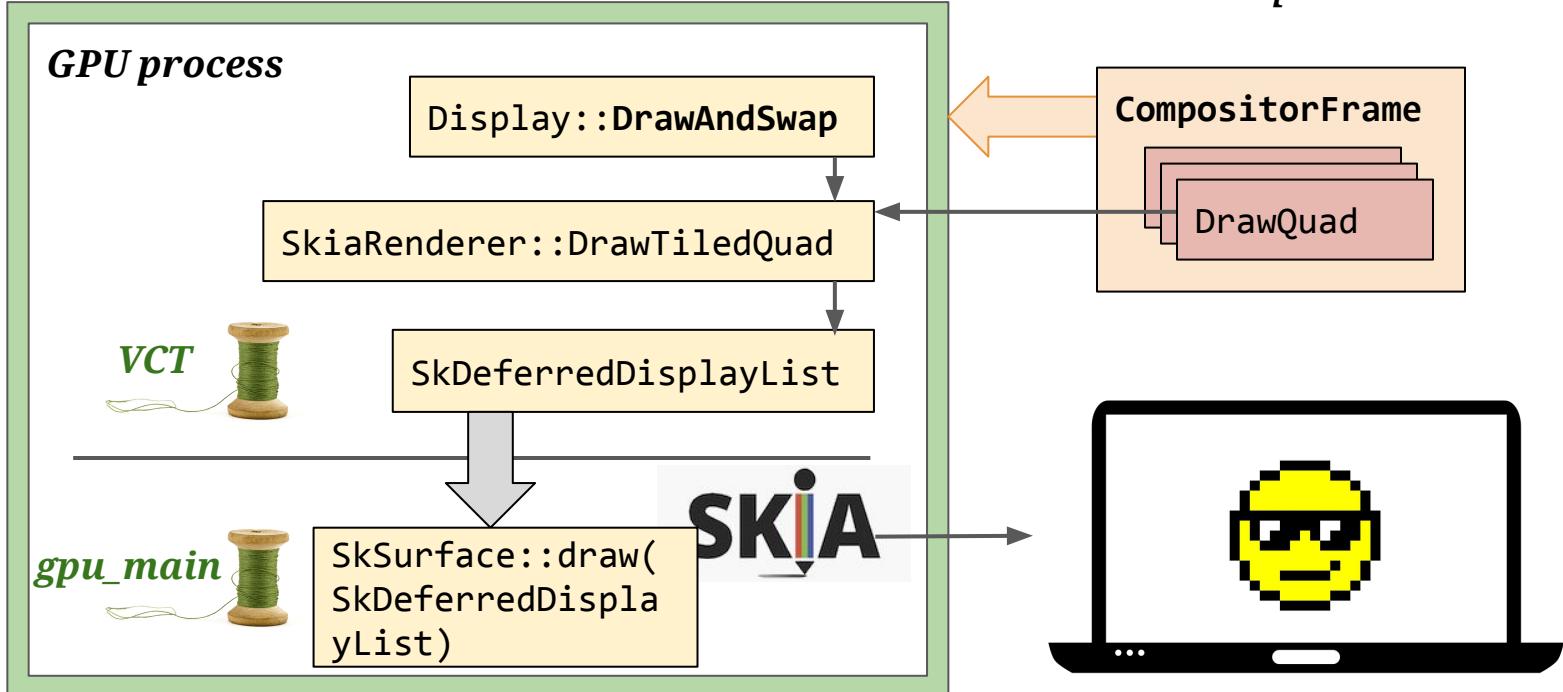


# display (viz)

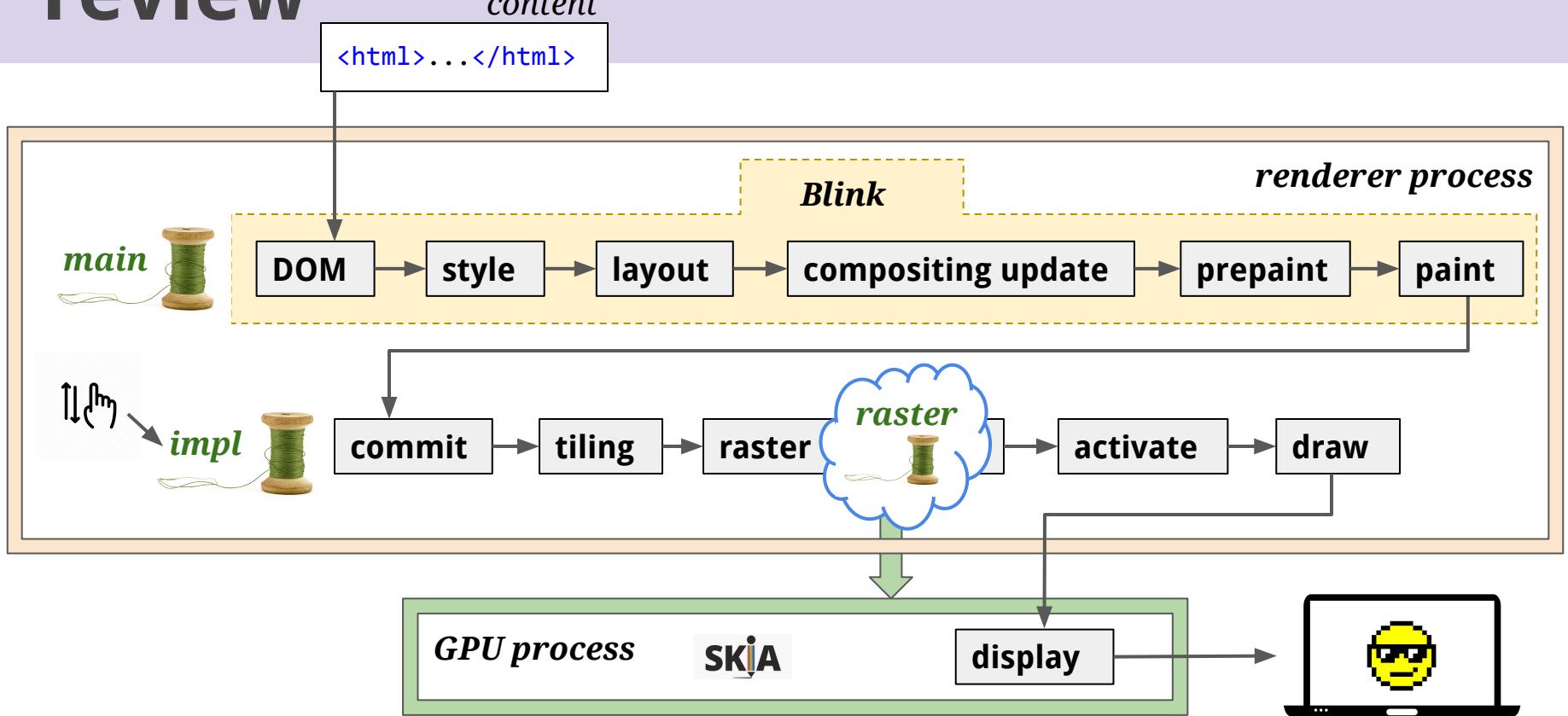
*The display compositor combines frames for multiple surfaces.*



# display (viz)



# review



end

# LIFE OF A pixel

*Latest slides:* [bit.ly/lifeofapixel](https://bit.ly/lifeofapixel)

*All versions:* [bit.ly/livesofpixels](https://bit.ly/livesofpixels)