Smart Caching for Web Browsers

Kaimin Zhang
University of Science and Technology of China, Hefei, China
coming@mail.ustc.edu.cn

Lu Wang
Hong Kong University of Science and Technology, Hong Kong
luwang@cse.ust.hk

Aimin Pan, Bin B. Zhu
Microsoft Research Asia, Beijing, China
{aiminp, binzhu} @microsoft.com

ABSTRACT

In modern Web applications, style formatting and layout calculation often account for a substantial amount of local Web page processing time. In this paper[1], we present two novel caching schemes, the smart style caching and the layout caching, for Web browsers. They cache stable style data and layout data for DOM (Document Object Model) elements, and apply directly without re-calculation when the same data is subsequently processed, possibly across different visits of a Web page. Redundant computations in both style formatting and layout calculation could be eliminated, resulting in more efficient local Web page processing. The proposed caching schemes are still applicable and effective even there are changes in the DOM structure or style rules of a Web page. The experiments on the homepages of the Top 25 Web sites show that on average, in a subsequent visit of the same Web page, the smart style caching could reduce the style formatting time by about 64%, and the combination of both caching schemes could reduce the layout calculation time by about 61%, with about 46% overall performance improvement on the local Web page processing time. For the overall performance when networking, Web servers, and local Web page processing were all included, our caching schemes could improve up to 56% when browsing these Web sites on a desktop PC and up to 60% when browsing on a netbook.

Categories and Subject Descriptors

H.4.3 [**Communications Applications**]: Information Browsers; I.7.m [**Document and Text Processing**]: Miscellaneous.

General Terms

Performance, Algorithms.

Keywords

Web, Browser, CSS, cascade style sheet, caching, JavaScript.

1. INTRODUCTION

Web tends to become a platform for modern applications. An increasing amount of data has been moved to the cloud as cloud computing is becoming a reality. In Web applications, the client side is a Web browser or a thin application with a Web browser engine embedded. Modern Web applications, e.g., Bing Maps [1] and Google Docs [2], have become increasingly complex and powerful that can rival desktop applications. This poses a challenge to Web browsers. A Web browser with a lousy performance would not be able to provide a user experience comparable to desktop applications. Current Web browsers may not meet this demanding performance requirement yet, particularly when rendering complex Web pages.

In loading a Web page, a Web browser does basically two tasks: fetching the Web content through the Internet and performing local computations to process the content. Networking is a performance bottleneck if data transmission is slower than local processing. This occurs typically when a lot of data need to be fetched over a network of limited bandwidth available. Network bandwidths have been improved dramatically in recent years. For example, 3.5G mobile networks, already available in some countries, provide a bandwidth up to 14.4Mbps for mobile Internet users. In addition, HTTP caching has been widely used by modern Web browsers to reduce the amount of data that needs to be fetched over the Internet. On the other hand, Web pages become increasingly more complex that substantial computation resources are required to parse, format, and render properly [3]. Local Web content processing may not get much benefit from recent advances of hardware processing power which is mainly through parallel processing by including multiple cores in a single chip but the chip frequency remains the same or is even reduced as compared to single-core chips. Web content is processed essentially in a single thread manner in order to get a proper result. It is still unclear in practice how to use parallelization capacity in a chip to render Web content, which is a new research topic [3]. In conclusion, the trend is that local Web content processing plays an increasingly important role in the performance of a Web browser at the cost of diminished impact from networking. In other words, Web browsing tends to be computation-intensive instead of network-intensive.

The results reported in [4] by profiling popular Web sites as well as our own experiments with the Webkit web browser engine [5] indicate that the combination of layout calculation and style formatting accounts for more than half of the total computation time in local Web page processing. Many modern Web pages use the cascade style sheet (CSS) [6] heavily due to its flexibility in supporting various visual effects. Computing style properties and applying them to the Document Object Model (DOM) [7] elements are essentially a recursive, time-consuming process. Current Web browsers have to perform both tasks every time when a Web page is browsed. In addition, any change in style properties of an HTML element leads to re-calculation of its layout, which may affect its descendant elements in the DOM tree.

Existing efforts to reduce style computation include providing a guideline for writing JavaScript [8][9] and optimizing layout engines [10]. These approaches can minimize the effects of DOM modifications and localize the reflow scope, particularly when JavaScript code manipulates DOM elements [11].

In this paper, we propose a novel method to improve Web browsing performance by caching intermediate results in vital

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[1] This work was done when Kaimin Zhang and Lu Wang were working as interns at Microsoft Research Asia.

stages of Web page processing and applying the cached results whenever applicable in subsequent processing of the same data to avoid redundant local computations. Repeated local computations typically occur when revisiting a Web page. They may also occur when processing a new Web page due to redundancy in the Web page. In particular, we construct both style cache and layout cache to record the stable results of style formatting and layout calculation, and apply directly without re-calculation when the same data is subsequently used for style formatting or layout calculation. As we have mentioned, style formatting and layout calculation together typically account for a substantial portion of the local Web page processing time in a modern Web application. Our caching schemes can effectively eliminate redundant calculations in those operations, resulting in much improved browsing performance.

There are two challenges in our method: 1. What information is stable across different visits of a same page and also requires heavy computations to generate? 2. How to make cache still effective when there are changes in a Web page? Our caching schemes address these two challenges well. These schemes can identify when cached data can be applied, and update the caches dynamically. The caches are still effective when there is a reasonably large gap in time between two visits of a same Web page, and also when there are changes in the DOM structure or style rules of a Web page.

We have implemented a prototype of the proposed caching schemes based on Webkit [5], an open-source web browser engine. Our experimental results on the Web pages of the Top 25 Web sites from comscore.com (2008) show that on average, in a subsequent visit of the same Web page, the smart style caching could reduce the style formatting time by about 64%, and the combination of both caching schemes could reduce the layout calculation time by about 61%, with about 46% overall performance improvement on the local Web page processing time. For the overall performance when networking, Web servers, and local Web page processing were all included, our caching schemes could improve up to 56% when browsing these Web sites on a desktop PC and up to 60% when browsing them on a netbook. The experiments on two typical dynamically changed Web sites show that most cached data can be valid for several hours. For some Web sites, they may be valid for several days to several weeks, or even longer.

This paper has the following major contributions: We propose the first style caching scheme and layout caching scheme, to the best of our knowledge, for Web browsers to effectively reduce redundant local style and layout computations. Both caching schemes are based on the workflow of Web page processing and the Web standards like HTML, DOM and CSS. They are therefore applicable to any standard-compliant Web browser. Furthermore, the two caching schemes are still effective even if the styles or content of a Web page is dynamically modified over time.

The rest of this paper is organized as follows. In Section 2, we introduce briefly the background of local Web page processing in a Web browser, and then describe the main ideas behind our schemes. The smart style caching scheme is presented in detail in Section 3, and the layout caching scheme is presented in Section 4. The experimental results are reported in Section 5. Discussion and future work are presented in Section 6. Related work is presented in Section 7. We conclude the paper in Section 8.

2. BACKGROUND AND OUR METHOD

Web applications are built on top of HTML along with other Web standards [12] such as CSS and DOM. Web browsers process Web pages based on the syntax and semantics specified in the standards. This leads to the result that most browsers have a similar framework and internal representation of a Web page. In this section, we introduce briefly such a general framework, and then discuss how caching mechanisms can be introduced in the framework.

2.1 Workflow of Web Page Processing

Figure 1 shows the general workflow that a Web page is processed by modern Web browsers. After receiving a Web page, either from a remote Web server or a local store, a Web browser parses the page in the form of HTML data, and represents the parsed HTML data as a DOM tree in memory. The style properties are then generated for the elements in the DOM tree. These properties determine how the elements are presented on the screen. In order to render them, the browser must trigger a process to calculate the layout for each element in the DOM tree. It can then render those elements correctly on the screen.

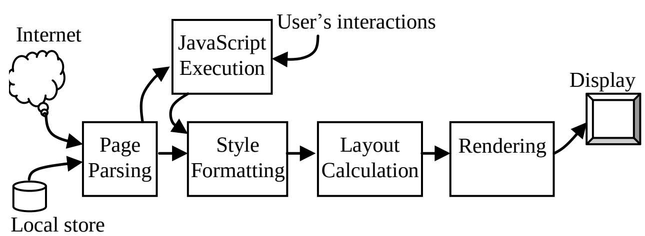


Figure 1. Workflow of Web page processing.

These stages may not be done strictly one stage after another in the order as shown in Figure 1. They may occur concurrently in order to provide a better user experience, allowing a user to see a partially rendering result before finishing download and parsing of the whole page. This processing is essentially a sequential process since any change in a previous stage will incur execution of the following stages.

Scripts in Web pages are often in the form of JavaScript code since JavaScript is supported by almost all existing Web browsers. The JavaScript code can be triggered either in the stage of page parsing or by user's actions. If the JavaScript code manipulates DOM elements, the style formatting stage and the layout calculation stage may also be triggered in order to render the elements correctly on the display. These triggered operations are most likely a reason why JavaScript code is executed inefficiently.

2.2 Caching in Web Page Processing

The data flow is formed based on the workflow of page processing in a Web browser, as shown in Figure 2. The original HTML data is parsed to form a DOM tree in memory for a Web page, which should comply with W3C DOM standard [7]. Then the styles are applied to the elements in the DOM tree after the style rules in the page are processed. This often forms a data structure separate from DOM, for example, called a render tree in Firefox [10]. Each node in the render tree has a corresponding element in the DOM tree. Its purpose is to make DOM elements visible on the screen. The render tree is further processed to calculate the layout for each node in the layout calculation stage. Finally, each node in the render tree is rendered on the screen in the rendering stage.

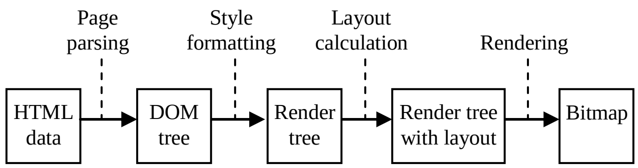


Figure 2. Data flow of Web page processing.

Now we look at possibilities to cache data in the workflow of Web page processing. One extreme case is the most straightforward HTML data caching (i.e. HTTP caching), which has been widely supported by almost all Web browsers. Another extreme case is a render caching, which caches the bitmap of the rendering result of a Web page. These two types of caching schemes are effective if the cached Web pages do not change frequently. Note that the render cache is invalid even if only the window size changes for the same URL. A large number of Web pages, however, change quickly because of real-time news, ads, and other dynamic data sources. In this case, the HTML caching may work only partially while the render caching does not work. Pages requested via a same URL at different times are typically different, but most contents of these pages may be unchanged. If we build caches in the middle of the data flow in Figure 2, the cached data may be still useful if the unchanged parts can be identified, then subsequent computations for the cached data can be eliminated. Therefore, different types of caches can be developed for different stages. They are partially effective when a Web page changes over time: only the cached data of unchanged parts is valid.

In this paper, we propose two caching schemes at two intermediate stages. One is called the Smart Style Saching (SSC), which caches results at the style formatting stage. SSC works at the granularity of a DOM element. The cached data for a DOM element is valid only if both its path to the DOM root and its style properties do not change at a subsequent calculation. The content in a DOM element is not taken into account when checking validation of the cached elements. The other is called the layout caching, which contains the intermediate results after the stage of layout calculation. Unlike SSC, the layout caching is content based. The content for a DOM element is used to both compute the cache and check validation of the cached layout data. If the cached layout data for an element is valid, it is passed to render the element without any re-calculation.

These two types of caching are chosen to save computations in style formatting and layout calculation of DOM elements. In the workflow of Web page processing, a change of style properties may trigger computations at the subsequent stages shown in Figure 1, including layout calculation and rendering when a page is processed. Thus, caching the style data can not only reduce the frequency of style calculation, but also computations at the subsequent stages. As reported in [4], the layout calculation accounts for the most of computing time among all the stages in the workflow. This agrees with our measurements with the Webkit engine. A layout cache is expected to reduce the time needed for layout calculation, which motivated us to build the layout cache.

3. SMART STYLE CACHING (SSC)

Most modern Web browsers comply with CSS Standard 2.1 [6] in interpreting style information for HTML elements. In this section, we first briefly introduce the process of style formatting, and then describe SSC and its key algorithms.

3.1 Style Formatting for Web Pages

There is one CSS style sheet for each web page. A CSS style sheet consists of a set of CSS rules. Each CSS rule consists of two parts: a selector and a declaration. The selector of a CSS rule determines which kind of elements will match the rule. The selector can be either simple, such as ID selector and class selector, or complex, such as the ones that refer to any attribute of a DOM element. Therefore, developers of Web pages can define a scope of elements via a selector and then assign specific style values to them. In practice, this kind of capability can be exploited to achieve some special visible effects. However, one side effect is that a browser must deal with possible complex selectors in order to render a Web page correctly. The second part, i.e., the declaration of a CSS rule, is a set of values of pre-set style properties, which determine the way how the selected element will look like. For example, in the CSS rule "p em { color: red }", the selector part is "p em", which indicates that all the <em> elements which are a descendant of a <p> element are selected as the target elements of this rule. The declaration part, in this example, is "{ color: red }", which defines the color property of all the selected elements as red.

CSS formatting usually happens when a browser needs to determine the style of a newly created or modified element. It typically consists of two steps. First, the browser checks each CSS rule against the element. The selector of a rule determines whether the rule is a match to the element or not. Second, all the matched rules are applied to the element in a proper order defined in the CSS specification, to generate the style properties of the element. Basically, the applying process is to collect the declarations of all the matched rules and then merge them. Since one style property may appear in multiple matched rules, the value declared in the rule with highest priority is used as the final result.

There are lots of style properties which may affect the visual effect of an element. It is often tedious for Web authors to specify each property of an HTML element in CSS. Fortunately there is a mechanism called derivation in CSS, which can be used to determine the value of properties that are not explicitly declared. If a style property is not defined for an element, its value is either derived from the style of its parent element, or is set to a default value by the browser, depending on the type of that property. This requires that the style of a parent element is always determined before all of its children. Furthermore, a browser should always define a default style sheet (called UA rules).

Therefore, the process of style formatting depends on not only the set of style rules and DOM elements, but also the structure of the DOM tree. The DOM structure must be taken into account when implementing or optimizing the algorithm of style formatting.

In order to concretize the process of CSS formatting, let's look at an example. Suppose there is an HTML file as following:

```
<html>
<head>
  <style>
    p em { color : red  }
    p   { color : green }
    em  { color : blue  }
  </style>
</head>
<body>
  <p> The first part <em> The second part </em> </p>
</body>
</html>
```

In the example, there are three rules which are bracketed by the <style> and </style> tags. In order to render the <em> element, a browser needs to determine its style. The browser first checks all the CSS rules provided in the HTML file against the <em> element, and finds that both the first and the third rules are a match. Those two rules as well as the default rules provided by the browser are then merged according to the CSS specification. In this case, only the 'color' property is specified by the page author, while other style properties are set as a default value. In this example, both matched rules specify the color property, and according to the CSS specification, the value declared in the first rule is used because the first rule is more special and thus has a higher priority. Therefore the text "The second part" is in red.

3.2 Smart Style Caching Scheme

If a Web page, including its content and style sheet, does not change over time, a simple yet effective style caching algorithm is to record the style properties for each element in a page at the first visit to the page, and then to restore them at a subsequent visit to the same page. No style calculation is needed for the subsequent visit. Obviously, this is an ideal case. This simple algorithm works only for a small percentage of Web pages.

In practice, most Web pages have dynamic content, e.g. live news, search results, or ads. Therefore a practical algorithm must address possible changes in the DOM tree and CSS rules of a page. The goal is to reuse the style properties for the DOM elements that have not changed, compute the style properties only for new and modified elements in order to minimize re-calculation.

SSC takes only the following selectors into consideration: the selectors involving ID, Class, TagName attributes of a single element as well as the basic descendant and child relationship in the DOM tree. These types of selectors are referred to as *normal selectors* in this paper. This means that SSC does not cache any matched rules with non-normal selectors for a DOM element. There is nothing to prevent SSC from caching rules with non-normal selectors. It is just a tradeoff between the caching scope and the complexity of caching implementation. According to our statistical analysis of the different selectors in the homepages of the Top 25 Web sites from comscore.com (see Section 5.1 for the list), more than 95% of the selectors are normal ones. Therefore, we decided that SSC caches only the rules with normal selectors.

In order to store the cached rules for every DOM element, SSC constructs an SSC tree, which is similar to a DOM tree but stores just the structure information of the DOM tree. Each DOM element has a corresponding element in the SSC tree. Each SSC element contains a list of matched rules with normal selectors for the corresponding DOM element. The list is empty if the DOM element has no matched rule with normal selectors. In a SSC tree, sibling elements with the same <ID, class, TagName> triple are merged into one element. Figure 3 shows an example of SSC tree. In this example, the first and second <li> elements in the DOM tree share the same <li> SSC element since "foo" is not a style property that would affect identification of an SSC element. However, since the third <li> element has a special value for the "class" property, there is a separate SSC element corresponding to that element, as shown in Figure 3(c).

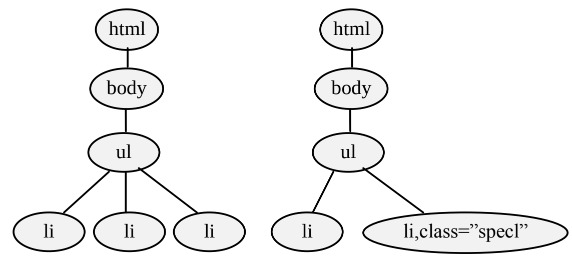
The style cache for a Web page consists of:

- The rule set of its cascading style sheet;
- The SSC tree, and the style properties and matched rule list for each element.

For any element in the SSC tree, if its matched style rules are determined to remain the same, its style properties are retrieved from the style cache without any style computation. Otherwise the style properties are re-computed.

```
<html>
<body>
  <ul>
    <li> First Line </li>
    <li foo="bar"> Second Line </li>
    <li class="specl"> Special </li>
  </ul>
</body>
</html>
```

(a) HTML



(b) DOM tree (c) SSC tree

Figure 3. A Web page and its DOM tree and SSC tree.

3.3 Key Algorithms in SSC

In this section, we first describe the algorithm of maintaining SSC elements for DOM elements, and then discuss how SSC tolerates changes in the DOM tree or CSS rule set of a Web page. These algorithms can guarantee correctness of the final DOM elements, i.e. the style properties for each DOM element are equivalent to the original ones when SSC is not used.

3.3.1 Maintaining SSC Elements for DOM Elements

According to the definition and generation of the SSC tree for a Web page, a DOM element has exactly one corresponding SSC element while an SSC element may correspond to one or more DOM elements. For each SSC element, we store the necessary properties (i.e. ID, Class, and TagName) that are used to find the matched DOM elements, as well as the cached style properties that would be retrieved and applied to the unchanged DOM elements in subsequent visits to the same page.

Given a DOM element, say E, the corresponding SSC element is located or created in the following way:

> *Check if E is the root of the DOM tree. If not, since E's parent, say EP, should have already been checked, we know EP's corresponding SSC element, say EP_{SSC}. Then check the child elements of EP_{SSC}. If we find an SSC element with exactly the same <ID, Class and TagName> triple as E, then E is associated with the SSC element. Otherwise, E is treated as a new element (it could also be an existing but modified element), and a new SSC element associated with E is created with E's <ID, Class and TagName> triple and attached to the SSC tree as a child of EP_{SSC}.*
>
> *If E is the root and the SSC root element does not match E, then the whole cached SSC tree is invalidated and a new SSC element is created as the new root. Otherwise, the SSC root element matches E, therefore is associated with E.*

Note that we have assumed here that any parent element in a DOM tree is always processed before its child elements. This assumption holds during generation of a DOM tree since a DOM tree is constructed with elements in pre-order.

Once we have identified the corresponding SSC element for E, the style properties are retrieved from the SSC element. If it is a newly created SSC element, then E's style properties are calculated and recorded into the new SSC element. In this way, we can ensure that all the style information of an element E that has been calculated during a visit to a Web page could always be retrieved in subsequent visits if E appears in the page again.

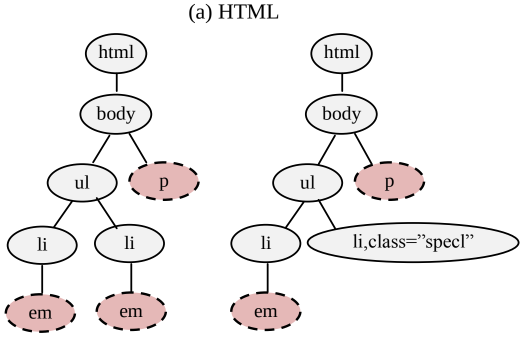
3.3.2 Tolerating Changes in DOM Tree

The maintenance algorithm described in the previous section implies that the path of a DOM element to the root of the DOM tree has not changed, so is the path of its corresponding SSC element to the root of the SSC tree. If the path of a DOM element to the root of the DOM tree has changed, the DOM element as well as its descendant elements in the DOM tree can no longer be matched in the cached SSC tree.

Let's take an example to see how SSC tolerates changes in the DOM tree. Suppose that the Web page shown in Figure 3(a) is modified to that shown in Figure 4(a). The corresponding DOM tree and SSC tree are shown in Figure 4(b) and Figure 4(c), respectively. The brown elements with dashed border in Figure 4 are new elements in the tree.

```
<html>
<body>
  <ul>
    <li> This is <em>First</em> Line </li>
    <li> <em>Second</em> Line </li>
  </ul>
  <p>
    New paragraph
  </p>
</body>
</html>
```

(a) HTML



(b) DOM tree (c) SSC tree

Figure 4. A modified Web page and its DOM tree and SSC tree.

In this example, note that:

1. The <em> and <p> DOM elements are new elements, therefore new SSC elements should be created for them;
2. The two <em> DOM elements share a same <em> SSC element, although their parents are different. In fact, they are identical from the viewpoint of style rules (including the rules along the path from the root to them);
3. The old <li> SSC element still corresponds to the two <li> elements in the new page;
4. The old <li> SSC element with a special value of the class property still exists in the SSC tree because the element, although not in the DOM tree of the modified page, may appear again in future visits. It is possible to remove unused SSC elements periodically to make the SSC tree compact.

3.3.3 Tolerating Changes in CSS Rule Set

To tolerate changes in a CSS rule set, SSC records not only the final style properties for each element but also the list of matched rules for it. Both the final style properties and the list of matched rules of a DOM element are stored in its corresponding SSC element.

In page processing, two sets of CSS rules are involved. One is the rule set retrieved from the style cache, either recorded in a previous visit to the same page or an empty set if there is no style cache. This rule set is denoted as R_{cache}. The other is the set of CSS rules for the current Web page, denoted as R_{cur}. Note that since Web pages are usually downloaded and processed incrementally, R_{cur} is also constructed incrementally. Therefore, we cannot determine the missed rules (i.e. those are in R_{cache} but not in R_{cur}) until the page is completely processed. We can, however, always identify the new rules (i.e. those are in R_{cur} but not in R_{cache}) immediately once they are added into R_{cur}. When a page is being loaded, the following process is executed for each element:

- If there are no new rules in R_{cur}, the cached style properties for the element are employed directly without any re-calculation;
- Otherwise, all the new rules are examined against the element, and the matched ones are inserted into the list of matched rules of the element at proper positions. Finally, the new list of matched rules is used to generate the style properties for the element. In this way, we can avoid re-checking the selectors of the existing rules in R_{cache} .

As soon as the page is loaded completely, we can identify which rules are missed, i.e. the rules in R_{cache} but not in R_{cur}. Then we process the elements affected by those rules as following:

- If there is no missed rule, do nothing;
- All elements whose matched rule list in the style cache contains any of missed rules need to be re-formatted. For each element, the missed rules are eliminated from its matched rule list, and then its style properties are re-computed.

In this way, we can always identify the same rules that appear in both the current visit and the last visit, and avoid duplicated calculations for the elements of which the matched rule list has not changed. Furthermore, the new CSS rules for the current visit are stored in the style cache to be retrieved for future visits to the same page.

4. LAYOUT CACHING

The layout caching is designed to reduce time-consuming layout calculation by reusing the layout results in previous visits to the same Web page. The result of layout calculation for a visible element is recorded, along with the necessary information for checking its validation later. Unlike SSC, which depends only on the style properties of each DOM element and its path to the root, the layout data of a DOM element is content-dependent. For example, in order to calculate the layout of a piece of text, the content of the text must be taken into account.

According to the data flow of Web page processing, as shown in Figure 2, the layout calculation is based on the render tree generated after style formatting. Unlike the DOM tree, the render tree is not standardized, but we can think that the render tree has a hierarchical structure similar to the DOM tree, and it includes render objects only for the visible elements in the DOM tree. Our layout cache is built atop the render tree, in a similar way that the style cache is built atop the DOM tree. In this section, we first present our layout caching scheme, and then describe its validation checking algorithm.

4.1 Layout Caching Scheme

The layout calculation for a render object is done by a certain type of layout operation. The results of layout operations are recorded by our layout caching. Therefore, when a layout operation is needed for a render object, we determine if it is recorded in the layout cache or actual execution is needed. If there is a layout operation in the layout cache which matches the current one, then its cached result can be retrieved and returned directly; otherwise, it needs actual execution. The validation checking algorithm will be described in the next section.

Like in SSC, in order to reuse the cached layout results, unchanged render objects must be first identified in the render tree. A straightforward method is to build a companying tree for the render tree like the SSC tree described in Section 3.2. However, by using the existing SSC tree, there exists a simple and efficient method without using any companying tree. Since each render object is associated with one DOM element from which it is generated, and the DOM element is associated with one SSC element, a render object is also associated with one SSC element. Therefore, we can record the render object along with its layout result in its associated SSC element. In order to identify a render object in the layout cache, we find its associated DOM element, and then use the algorithm described in Section 3.3.1 to find the SSC element associated with the DOM element. Each SSC element may associate with a set of cached render objects, but the set is usually small since there are typically only a few render objects generated from the associated DOM elements. Finally, the cached render object, if exists, can be retrieved from this set by matching its type and content.

In order to balance efficiency and complexity, the layout caching does not cache floating objects, complex render objects such as render media and render table. We only cache the layout results for several frequently used types of render objects, including render boxes, render blocks, render buttons, render text controls, render texts, render images and inline render objects. Our profiling results with Webkit for the homepages of the Top 25 Web sites (see Section 5.1 for the list) show that more than 70% of layout calculation time is spent on these types of objects.

4.2 Validation Checking for Layout

In order to determine validation of the cached result for a layout operation on a render object, there are four conditions to check against:

- **Global Information of the Browser.** This includes the size of the browser's window and the theme of the browser. If the global information changes, all cached results are invalidated.
- **Parent-Child Relations in the Render Tree.** In the render tree, the layout calculation is a top-down and recursive procedure, starting from the root of the tree. The layout calculation for a child element depends on its parent's layout result. For example, the outer box's size affects the layout of all its inner boxes, which are the children of the outer box in the render tree. Therefore, a cache miss on a render object causes cache misses on the entire sub-tree rooted at this object.
- **Style of the Render Object.** Any change on the style invalidates the cache for the render object.
- **Content of the Render Object.** The layout calculation for a render object depends on its content. However, for certain types of render objects, the layout calculation may only be sensitive to a part of their content. For example, to calculate the layout of an image, only the size of the image is concerned. Therefore, by extracting and checking only the layout-related content, the hit rate of the layout cache could be improved.

While SSC can tolerate changes in the CSS rules in a Web page with partial re-calculation. The layout caching, however, typically does not tolerate any changes, as we have seen above. This is a big difference between the two caching schemes.

5. EXPERIMENTAL RESULTS

We have implemented a prototype of the proposed caching schemes based on the Webkit web browser engine (version 1.1.5-GTK) [5] running on the Linux platform. In our experiments to compare the browsing performances with and without using our proposed caching schemes, GtkLauncher, a simple and lightweight Web browser packaged with the Webkit GTK, was used. In this section, we first describe the experimental environments and the Web sites employed in the experiments. Then we present the performance results of both SSC and the layout caching, as well as the overall performance. Finally, we report the effectiveness of our caching schemes on several typical dynamic Web pages.

5.1 Experimental Setup

The homepages of the Top 25 Web sites from comscore.com (2008) listed in Table 1 were used in our experiments. In order to study the performance of our caching schemes, we have conducted experiments both with and without networking effects. We first compared local Web page processing performance while the networking impact was removed. This was done by fetching the Web pages with the WGet utility [13] and storing them into a local disk before the experiments. During the experiments, GtkLauncher browsed the locally stored offline Web pages, with a setting in Webkit to enable or disable our caching schemes. When disabled, the original Webkit was used. Note that there might still exist some network traffic such as Ajax requests during the experiments. We believe that the impact of network variations on the performance was mostly removed. Then we compared the actual browsing performance on both desktop PC and netbook when the impact of both networking and Web servers is included. In both cases, we evaluated only the process of page loading. GtkLauncher would shut down automatically when receiving a *load-finished* signal from Webkit at the end of page loading.

The desktop PC used in our experiments was a mainstream PC with an Intel Dual Core 2.13GHz processor and 2GB of DDR2 RAM. The netbook used was a typical one with an Intel single core 1.66GHz Atom processor and 2GB DDR2 RAM. Both computers ran the 32-bit Ubuntu 9.10 Linux operating system with all the latest patches installed. Since the window size of a browser affects the performance of rendering, the window size was fixed at 800 by 600 pixels in our experiments. Each experiment was repeated 20 times. The results reported in this session were the average over the 20 measurements. For the experiments with networking, initial rounds of measurements were dropped since they typically showed a large fluctuation on the performance due to mainly the Internet cache.

Table 1. Top 25 Web sites from comscore.com (2008)

www.google.com	en.wikipedia.org	www.mozilla.com
www.google.cn	www.myspace.com	www.apple.com
www.aol.com	www.qq.com	www.adobe.com
www.xunlei.com	buzz.blogger.com	www.amazon.com
www.facebook.com/barackobama	www.ask.com	www.microsoft.com
www.yahoo.com	www.163.com	www.sina.com.cn
www.youtube.com	www.wordpress.com	www.ebay.com
www.baidu.com	www.soso.com	
www.msn.com	www.bing.com	

The performance results of local Web page processing are reported in Sections 5.2 to 5.4, while the overall browsing performance results are reported in Sections 5.5. In those reports, the data under "*Original*" are the results with the original version of Webkit. The data under "*First*" are the results of our proposed schemes when the Web pages were visited for the first time, with empty caches. The data under "*Subsequent*" are the results of our proposed schemes when the Web pages were visited previously, therefore the caches were already constructed at the experiment. The percentage numbers under "*First*" and "*Subsequent*" are the improvements relative to the results under "*Original*".

5.2 Performance of Style Formatting

In Webkit, the main function for style formatting is CSSStyleSelector::styleForElement. We wrapped this function to measure the time of style formatting. The performance of SSC against the original Webkit for local Web processing is shown in Table 2. The data in the table is an overall performance summed over the results for the homepages of the TOP 25 Web sites listed in Table 1 due to space limitation. From Table 2, SSC improves the style formatting performance dramatically. On average, the performance is improved by 34% for the first visit and by 64% for subsequent visits. Although the style cache is empty when a Web page is visited for the first time, SSC still improves the speed by 34% on average in computing style properties for DOM elements as compared to the original Webkit engine. This is because

- The style formatting for the elements with the same styles is automatically aggregated with SSC in the first visit to a Web page since they are merged in the SSC tree. This can be considered as a kind of optimization for style formatting.
- The in-memory style cache, which is being built during the first visit to a Web page, has already been employed by SSC in processing subsequent data of the same Web page.

Our experiments show that the improvement is more significant for large and complex Web pages. For example, the performance improvement is about 80% for subsequent visits to MySpace.com or AOL.com, larger than the average improvement of 64% over the homepages of the TOP 25 Web sites.

Table 2.Time and matching operation counts of style formatting

	Original	*First*		*Subsequent*	
Time (ms)	1269	835	34.2%	453	64.3%
Count	2814713	809548	71.2%	296121	89.5%

SSC improves the style formatting performance because it eliminates duplicated or unnecessary computations, which are mainly the matching operations between DOM elements and CSS selectors. The second row in Table 2 shows the numbers of corresponding matching operations. Compared with the original Webkit, SSC eliminates about 71% of matching operations for the first visit, and about 90% for subsequent visits.

5.3 Performance of Layout Calculation

Both caching schemes can improve the performance of layout calculation, but in different ways. The layout caching is targeted to reduce the number of layout operations by reusing previously calculated layout results while SSC does not touch the logic of layout calculation directly. SSC makes the style properties of each DOM element more stable and closer to the final style results, thus layout re-calculation would be triggered less frequently than the case without SSC. Webkit has carefully maintained the dirty-bits to indicate whether a layout operation is really needed or not. Fewer style changes leads to fewer layout re-calculations. In this section, we first report the performance of layout calculation affected by SSC, and then the performance of layout caching. Again, the results were summed over the homepages of the Top 25 Web sites listed in Table 1 to save space.

5.3.1 Layout Performance with Only SSC

In order to evaluate the effects of SSC on layout calculation, we first report the layout calculation performance results with only SSC enabled. Table 3 shows the time and count of layout operations.

Table 3. Layout performance with only SSC

	Original	*First*		*Subsequent*	
Time (ms)	21895	21532	1.7%	20857	4.8%
Count	18844	16513	12.4%	14611	22.4%

We can see from the results that about 12% or 22% of layout operations were eliminated by SSC in the first or a subsequent visit. The time reduction, however, is not significant, only at a gain of 1.7% for the first visit and of 4.8% for subsequent visits. Further studies indicated that, for the unmodified Webkit, about 80% of the time for layout operations was spent on calculating element layouts for the first time, referred to as the first-time layout operation in this paper. This is also true for a single element: the first-time layout operation for a single element often consumes much more time than subsequent layout operations for the same element. Since the style cache does not carry any layout data, it is obvious that SSC cannot eliminate any first-time layout operations. Table 3 shows that 22.4% of subsequent layout operations were eliminated by SSC, the time reduction can be estimated as 22.4% * 20% = 4.48%, which is very close to the actual result of 4.8% time reduction shown in Table 3.

5.3.2 *Layout Performance with Only Layout Caching*

Table 4 shows the time and count of layout operations with the layout caching as well as those of the unmodified Webkit. Since the layout caching affects only subsequent visits to the Web pages, Table 4 does not have first visit results. Table 4 shows that both count and time consumption of layout operations are significantly reduced. About 31% of layout operations were eliminated by the layout caching. Since the eliminated operations were mainly the first-time layout operations, the time reduction was about 56%, much larger than the 31% reduction in the layout operations. This is because the first-time layout operations need more time than subsequent layout operations.

Table 4. Layout performance with only layout caching

Original		*Subsequent*			
Time	Count	Time	Improvement	Count	Improvement
21895ms	18844	9613ms	56.1%	12933	31.4%

5.3.3 *Layout Performance with Both Caches*

Both caching schemes could improve the performance of layout calculation, as we have mentioned. Table 5 shows the layout calculation performance results when both caching schemes were applied. The layout caching improves mainly the performance of the first-time layout operations and SSC mainly improves the performance of the subsequent layout operations. Therefore, the overall layout performance is approximately the sum of the above two, confirmed by the results in Table 5. For subsequent visits, the layout calculation time has been reduced by about 61%, and about 54% of the layout operations were eliminated.

Table 5. Layout performance with both caching schemes

	Original	*First*		*Subsequent*	
Time(ms)	21895	21672	1.0%	8503	61.1%
Count	18844	16513	12.4%	8687	54.0%

5.4 Performance of Page Processing

As shown in the above two sections, our caching schemes reduce the time consumption of both style formatting and layout calculation significantly. The local page processing time, which means the actual processor execution time during loading a Web page, should also be reduced notably. This is confirmed by the local page processing results shown in Table 6. With the caching schemes, the page processing time can be reduced by about 46%.

Table 6. Local page processing time (ms)

Original	*First*		*Subsequent*	
29977	29906	0.2%	16170	46.1%

5.5 Overall Performance

We also employed the page loading time to measure the overall browsing performance when networking, servers, and local Web page processing were all taken into consideration. This would be close to a user's web browsing experience in the real world. Almost all modern Web browsers support the HTTP caching, but the GtkLauncher Web browser used in our experiments is too simple to support it. To mimic a real world Web browser, we used Squid, a Web caching proxy [14] in our experiments. Table 7 shows the performance results obtained with the desktop PC on a group of Web sites selected from the TOP 25 Web sites listed in Table 1. Table 8 shows the corresponding results obtained with the netbook.

Table 7. Page loading time (ms) on Desktop PC

Sites	*Overall Page Loading Time(ms)*			
	Original	First	Subsequent	Subsequent Improvement
Baidu	978.83	992.6	863.61	11.77%
Google	1616.54	1581.68	1601.79	0.91%
Google.cn	1123.54	1056.48	1151.69	-2.51%
Soso	686.84	691.51	522.66	23.90%
ask	3616.88	3523.66	3640.06	-0.64
eBay	3258.54	3331.65	3310.19	-1.59%
Blogger	4304.16	4266.92	4124.46	4.18
MySpace	3332.88	3185.94	2218.34	33.44%
Msn	3764.09	3802.88	3650.72	3.01
Wikipedia	2294.64	2240.89	2191.71	4.49%
Sina	8122.57	8183.64	5769.79	28.97%
QQ	5318.75	5340.8	2339.21	56.02%
Xunlei	5448.7	5265.55	4533.04	16.81%
Yahoo	2376.88	2173.89	2220.96	6.56%
Youtube	3215.22	2939.68	2488.55	22.60%

Table 8. Page loading time (ms) on Netbook

Sites	*Overall Page Loading Time(ms)*			
	Original	First	Subsequent	Subsequent Improvement
Baidu	1738.99	1711.79	1372.85	21.05%
Google	2027.25	2038.15	1945.99	4.01%
Google.cn	1940.1	1967.24	1786.95	7.89%
Soso	1506.04	1523.97	990.55	34.23%
Ask	4659.01	4457.81	4398.3	5.60%
eBay	4119.29	4141.53	3959.2	3.89%
Blogger	5482.91	5178.19	5036.68	8.14%
MySpace	7773.25	7602.94	4865.85	37.40%
Msn	6781.88	6831.8	6088.81	10.22%
Wikipedia	3050.34	2968.14	2753.68	9.73%
Sina	20659.9	20893.52	14254.97	31.00%
QQ	15062.21	14716.96	5923.44	60.67%
Xunlei	11993.54	11415.57	9724.33	18.92%
Yahoo	4460.77	4306.92	4108.89	7.89%
Youtube	5381.17	5421.33	4291	20.26%

Both Table 7 and Table 8 indicate that our caching schemes could reduce the page loading time on both desktop PC and netbook for most web pages. By comparing both tables, we can find that the netbook took longer time to load a same page than as compared with the desktop PC. This gap should be due to the difference in the processing power of the two machines. The netbook had a much weaker processor than the desktop PC, therefore took more time in processing a Web page. The two machines had the same networking environment during the experiments. That means the local Web page processing contributes more to the overall performance in the netbook as compared with the desktop PC. Therefore, our caching schemes should improve more for the netbook since the caching schemes are designed to reduce the local computation, which is confirmed by Table 7 and Table 8.

Considering the complexity of the Web pages listed in Table 7 and Table 8, large and complex Web pages such as QQ.com and Sina.com tend to get more benefit from our caching schemes. This is reasonable since complex pages require more local computations. We have seen similar results in comparing the desktop PC and the netbook. Improving the page processing and loading performance for large and complex pages is more meaningful than for simple pages like Google.com and Baidu.com. In the experiments, we perceived much more significant delay for these complex pages in responding the action to load a page. Improving page loading time for complex pages would bring better user experiences for a Web browser.

We also measured the size of the cached data for each Web page. Usually, the cache size is tens to hundreds of kilobytes, depending mainly on the size of the Web page. Note that our implementation of the caching schemes has not been optimized yet. Redundancy exists in the caches. In practice, such a size of cached data should not be a concern for today's computers.

5.6 The Experiments on Dynamic Pages

The performance results of local Web page processing reported in Sections 5.2~ 5.4 were conducted mainly with the same copies of Web pages (except Ajax and other dynamic part). This is almost the best case for our caching schemes. Web pages in the real world may have much more dynamic and modified content, especially when the gap in time between two subsequent visits is large. In this section, we study the local Web page processing performance on browsing real-world dynamic Web pages with the caching schemes. We selected two Web sites from the Top 25 sites, AOL.com and YouTube.com, which could represent two popular types of Web sites. The content of both sites changed frequently. These two sites were monitored for 12 hours, and their contents were fetched every hour during the mentoring duration. 12 copies of each Web site's content were collected. The first copy was used to generate the caches. Then, we used GtkLauncher to browse all the 12 copies without updating the cached data for any of the visits. Note that in actual usage, the caches keep constantly updated. We did not update the caches to study the performance when cache miss increases. It is expected that the effectiveness of our caching schemes declines over time. In order to measure the effectiveness of the caching schemes, we counted the reductions of the CSS rule matching and layout operations for each page. The results are shown in Figure 5. From the figure, even though the Web page of AOL changed frequently, the cache effectiveness didn't decline quickly. Over the first 10 hours, reduction of the matching operations declined only by 2%, from 96% to 94%, and reduction of the layout operations declined by 4%, from 34% to 30%. At the 11th hour, however, validation checking for the SSC tree failed, thus all the cached data, including both the style cache and the layout cache, were invalidated. After the tenth hour, the layout cache was completely invalid, and the style cache performed as if it were the first visit. The results for YouTube are very different. Even though the caches were also completely invalid at the 11th hour, as shown in Figure 5, the effectiveness had been significantly declined from the 3rd hour. After the 3rd hour, the caches were mostly invalid.

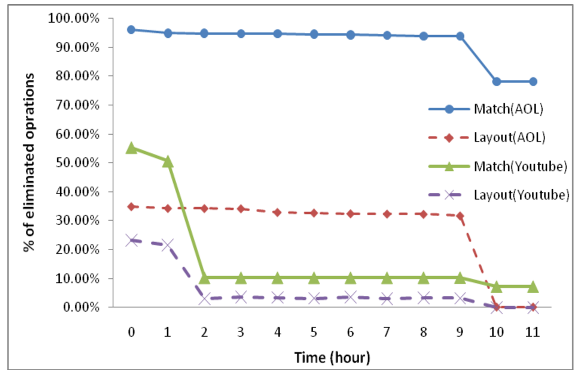


Figure 5. Reduction of the operations for YouTube and AOL.

We also conducted similar experiments on other popular Web sites. For varying Web sites such as MySpace.com, EBay.com, Sina.com, the caches could remain valid from 7 to 11 hours. For rarely changed Web sites such as Wikipedia.org and Google.com, the caches could remain valid from several days to several weeks.

6. DISCUSSIONS

In order to provide better users experiences, modern browsers usually show partially rendering results before finishing downloading and processing the whole Web page. However, since the CSS rule set and the DOM tree are incomplete at a partial processing, the style and layout results are usually updated across different rounds of partial processing. Therefore partially rendering results often change dramatically and frequently during the page loading, resulting in unpleasant users experiences. Our caching schemes can mitigate this problem. With valid caches, a DOM element can get the final layout and style results before the end of page processing, and is likely to keep intermediate results without further change. Therefore, with our caching schemes, DOM elements tend to be rendered at the right position and with the right visual effects at an early stage, typically at the very beginning of page processing. A partially rendering result is closer to the final one, resulting in fewer changes between partially rendering results and leading to smoother user experiences.

Our algorithm of maintaining the style cache can reduce unnecessary style formatting and layout calculations even with an empty style cache. Although our implementation is still rough without optimizations, the time reduced by eliminating redundant calculations exceeds the overhead of our caching schemes, as we have seen in Section 5. With the SSC tree, sibling DOM elements with the same ID, class, and TagName are merged into one SSC element, and only one style formatting is needed for these sibling DOM elements, resulting in less style formatting as compared to the case without the SSC tree that style formatting has to be executed for each DOM element. Furthermore, style formatting is typically repeated several times for a DOM element during page loading due to partially rendering for better user experiences. Therefore SSC can still improve the style formatting even with an empty style cache. Merging similar DOM elements in style formatting by the SSC tree can be considered as a type of optimization of style formatting for today's browsers.

Our caching schemes have been presented up to now to work at loading a Web page. They can be easily extended to support multiple versions of DOM elements in the style cache and layout cache, thus the cached data can be activated when a user interacts with a Web page and JavaScript code is triggered to respond to the user's actions. In this case, the extended caching schemes can still improve the responsiveness of Web applications, resulting in better user experiences, especially for complex Web applications like Google Docs and Bing Maps.

Our caching schemes can also be applied at the server side. The cacheable and stable style properties and layout results for DOM elements can be extracted from a Web page in a pre-processing stage and stored somewhere in a server. When a Web browser acquires the page, the valid cached results are sent so that the Web browser has much less data to compute during the local Web page processing. This is particularly useful for Web surfing with low-end systems such as smart phones.

7. RELATED WORK

Although the industry has been traditionally the driving force to improve the Web browsing performance, the academia has also paid attention to this issue recently. With pervasive multi-core systems and increasing Web surfing with mobile devices, researchers have tried to parallelize Web processing to speed up Web browsing. The Parallel Web Browser project in the Par Lab of UC-Berkeley attempts to parallelize different stages of Web page processing [3].

Venders of Web browsers have devoted a lot of efforts to improve the performance of Web page processing via various optimizations. Firefox contains many optimizations to reduce reflows [11], and Webkit [5] maintains a set of dirty-bits to avoid unnecessary internal re-computations. Internet Explorer 8 has tried to improve the performance from various aspects, including the memory management, the JavaScript engine, networking, and the rendering engine [4]. In addition to the layout and render engines, the JavaScript engine is another focus to improve the Web browsing performance. Chrome's V8 [15], Firefox's TraceMonkey [17] and Safari's Squalfish [18] employ Just-In-Time technologies to speed up execution of JavaScript code.

The Opera Mini [19], a popular mobile Web browser, employs a server between a mobile client and a Web site to improve user experiences. Each Web page is compressed and pre-processed in the Opera's server before sent to a mobile client, effectively reducing the networking traffic and simplifying the page to be processed by the mobile client. The approach does not actually improve the internal Web page processing in a mobile client.

In addition, some Internet companies have published guidelines to write more efficient Web pages [16]. This represents another kind of efforts to reduce the local Web page processing. These guidelines do not touch the internal logics of Web browsers. They try to take advantages of the internal processing logics in Web browsers to avoid heavy computations.

8. CONCLUSIONS

In this paper, we proposed two caching schemes to improve the performance of Web page processing. We focused on the two important stages in the workflow of Web page processing: style formatting and layout calculation. With our smart style caching and layout caching, the stable style data and layout data of DOM elements are recorded when a page is processed. The cached data are then reused when the page is revisited. Validation checking is done at the granularity of a DOM element. Therefore, the cached data is still partially valid even for dynamically changed Web pages. They can eliminate the local computations for the unchanged elements. The experiments on the homepages of the Top 25 Web sites show that on average, in a subsequent visit of the same Web page, the smart style caching could reduce the style formatting time by about 64%, and the combination of both caching schemes could reduce the layout calculation time by about 61%, with about 46% overall performance improvement on the local Web page processing time. For the overall performance when networking, Web servers, and the local Web page processing were all included, our caching schemes could improve up to 56% when browsing these Web sites on a desktop PC and up to 60% when browsing on a netbook.

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