Collecte intelligente et adaptative d'applications Web pour l'archivage du Web

Muhammad Faheem Pierre Senellart
Institut Mines–Télécom
Télécom ParisTech ; CNRS LTCI Paris, France
firstname.lastname@telecom.paristech.fr

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Les sites Web sont par nature dynamiques, leur contenu et leur structure changeant au fil du temps. De nombreuses pages sur le Web sont produites par des systèmes de gestion de contenu (Content Management System ou CMS) tels que WordPress, vBulletin ou phpBB. Les outils actuellement utilisés par les archivistes du Web pour préserver le contenu du Web collectent et stockent de manière aveugle les pages Web, en ne tenant pas compte du CMS sur lequel le site est construit (ce qui conduit à des stratégies de collectes sub-optimales) et du contenu structuré de ces pages Web (ce qui résulte en des archives au niveau des pages dont le contenu est difficile à exploiter). Nous présentons dans cet article un *application-aware helper* (AAH) qui s'intègre à une chaine d'archivage classique pour accomplir une collecte intelligente et adaptative des applications Web (p. ex., les pages servies par un CMS). Parce que l'AAH est conscient des applications Web actuellement collectées, il est capable de raffiner la liste des URL à traiter et d'ajouter à l'archive de l'information sémantique sur le contenu extrait. Afin de traiter les changements possible de structure des applications Web, notre AAH inclut un module d'adaptation qui rend la collecte résistante aux petits changements de structure du site Web. Nous démontrons la valeur de notre approche en comparant la sortie et l'efficacité du AAH par rapport à des robots Web traditionnels, également en présence de changement.

1 Introduction

Social Web Archiving The World Wide Web has become an active publishing system and is a rich source of information, thanks to contributions of hundreds of millions of Web users, who use the social Web as a medium for broadcasting their emotions, publishing content, discussing political issues, sharing videos, posting comments, and also stating their personal opinion in ongoing discussions. Part of this public expression is carried out on social networking and social sharing sites (Twitter, Facebook, Youtube, etc.), part of it on independent Web sites powered by content management systems (CMSs, including blogs, wikis, news sites with comment systems, Web forums). Content published on this range of *Web applications* does not only include the ramblings of common Web users but also pieces of information that are newsworthy today or will be valuable to tomorrow's historians. Barack Obama thus first announced his 2012 reelection as US president on Twitter [20] ; blogs are more and more used by politicians both to advertise their political platform and to listen to citizens' feedback [8] ; Web forums have become a common way for political dissidents to discuss their agenda [30] ; initiatives like the Polymath Project [1] transform blogs into collaborative research whiteboards [31] ; user-contributed wikis such as Wikipedia contain quality information to the level of traditional reference materials [16].

Because Web content is distributed, perpetually changing, often stored in proprietary platforms without any long-term access guarantee, it is critical to preserve this valuable material for historians, journalists, or social scientists of future generations. This is the objective of the field of *Web archiving* [28], which deals with discovering, crawling, storing, indexing, and ensuring long-term access to Web data.

Application-Aware Archiving Current archival crawlers, such as Internet Archive's Heritrix [36], function in a conceptually simple manner. They start from a *seed* list of the URLs to be stored in a queue (e.g., the starting URL may be the homepage of a Web site). Web pages are then fetched from this queue one after the other (respecting crawling ethics, limiting the number of requests per server), stored as is, and links are extracted from them. If these links are in the scope of the archiving task, the newly extracted URLs are added to the queue. This process ends after a specified time or when no new interesting URL can be found.

This approach does not confront the challenges of modern Web application crawling : the nature of the Web application crawled is not taken into account to decide the crawling strategy or the content to be stored ; Web applications with dynamic content (e.g., Web forums, blogs, etc.) may be crawled inefficiently, in terms of the number of HTTP requests required to archive a given site ; content stored in the archive may be redundant, and typically does not have any structure (it consists of flat HTML files), which makes access to the archive cumbersome.

The aim of this work is to address this challenge by introducing a new *application-aware* approach to archival Web crawling. Our system, the *application-aware helper* (AAH for short) relies on a knowledge base of known Web applications. A *Web application* is any HTTP-based application that utilizes the Web and Web browser technologies to publish information using a specific template. We focus in particular on social aspects of the Web, which are heavily based on user-generated content, social interaction, and networking, as can be found for instance in Web forums, blogs, or on social networking sites. Our proposed AAH only harvests the important content of a Web application (i.e., the content that will be valuable in a Web archive) and avoids duplicates, uninteresting URLs and templates that just serve a presentational purpose. In

1. `http://polymathprojects.org/`

addition the application-aware helper extracts from Web pages individual items of information (such as blog post content, author, timestamp), etc., that can be stored using semantic Web technologies for richer and semantic access to the Web archive.

To illustrate, consider the example of a Web forum, say, powered by a content management system such as vBulletin. On the server side, forum threads and posts are stored in a database ; when a user requests a given Web page, the response page is automatically generated from this database content, using a predefined template. Frequently, access to two different URLs will end up presenting the same or overlapping content. For instance, a given user's posts can be accessed both through the classical threaded view of forum posts or through the list of all his or her post displayed on the user profile. This redundancy means that an archive built by a classical Web crawler will contain duplicated information, and that many requests to the server do not result in novel pieces of content. In extreme cases, the crawler can fall into a *spider trap* because it has infinitely many links to crawl. There are also several noisy links such as to a print-friendly page or advertisement, etc., which would be better to avoid during the constitution of the archive. On the contrary, a Web crawler that is aware of the information to be crawled can determine an optimal path to crawl all posts of a forum, without any useless requests, and can store individual posts, together with their authors and timestamps, in a structured form that archivists and archive users can benefit of.

Template Change Web applications are dynamic in nature ; not only their content changes over time, but their structure and template does as well. Content management systems provide several templates that one can use for generating wiki articles, blog posts, forum messages, etc. These systems usually provide a way for changing the template (which ultimately changes the structure of Web pages) without altering the informational content, to adapt to the requirements of a specific site. The layout may also change as a new version of the CMS is installed.

All these layout changes result in possible changes in the DOM tree of the Web page, usually minor. This makes it more challenging to recognize and process in an intelligent manner all instances of a given content management systems, as it is hopeless to hope to manually describe all possible variations of the template in a Web application knowledge base. Another goal of the work is to produce an intelligent crawling approach that is resilient to minor template changes, and, especially, automatically adapts its behavior to these changes, updating its knowledge of CMSs in the process. Our adaptation technique relies on both relaxing the crawling and extraction patterns present in the knowledge base, and on comparing successive versions of the same Web page.

Outline We next present the state of the art on Web application crawling and adaptation to structure change. After giving some preliminary definitions in Section 3, we describe our knowledge base of Web applications in Section 4. The methodology that our application-aware helper implements is then presented in Section 5. We discuss the specific problem of adaptation to template changes and related algorithms in Section 6 before covering implementation issues and explaining how the AAH fits into a crawl processing chain in Section 7. We finally compare the efficiency and effectiveness of our AAH with respect to classical crawling approach in crawling blogs and Web forums in Section 8.

This article is an extended version of a work accepted for publication at the ICWE 2013 conference [12]. Initial ideas leading to this work have also first been presented as a PhD workshop article in [11].

2 Related work

Web crawling Web crawling is a well-studied problem with still ongoing challenges. A survey of the field of Web archiving and archival Web crawling is available in [28].

A *focused*, or *goal-directed*, crawler, crawls the Web according to a predefined set of topics [6]. This approach is a different way of influencing the crawler behavior, not based on the structure of Web applications as is our aim, but on the content of Web pages. Our approach does not have the same purpose as focused crawling : it aims instead at a better archiving of known Web applications. Both strategies for improving a conventional crawler are thus complementary.

Content in Web applications or *content management systems* is arranged with respect to a template (template components may for example include left or right sidebar of the Web page, navigation bar, header and footer, main content, etc.). Among the various works on template extraction, Gibson, Punera, and Tomkins [15] have performed an analysis of the extent of template-based content on the Web. They have found that 40–50% of the Web content (in 2005) is template-based, i.e., part of some Web application. Their findings also suggested that template-based Web pages are growing at the rate of 6–8% per year. This research is a strong hint at the benefit of handling Web application crawling in a specific manner.

Forum crawling Though application-aware crawling in general has not yet been addressed, there have been some efforts on content extraction from Web forums [18, 5].

The first approach [18], dubbed Board Forum Crawling (BFC), leverages the organized structure of Web forums and simulates user behavior in the extraction process. BFC deals with the problem effectively, but is still confronted to limitations as it is based on simple rules and can only deal with forums with some specific organized structure.

The second approach [5], however, does not depend on the specific structure of the Web forum. The iRobot system assists the extraction process by providing the sitemap of the Web application being crawled. The sitemap is constructed by randomly crawling a few pages from the Web application. This process helps in identifying the rich repetitive regions that are then further clustered according to their layouts [45]. After sitemap generation, iRobot obtains the structure of the Web forum in the form of a directed graph consisting of vertices (Web pages) and directed arcs (links between different Web pages). Furthermore a path analysis is performed to provide an optimal traversal path which leads the extraction process in order to avoid duplicate and invalid pages. A later effort [44] analyzed iRobot and identified a few drawbacks. [44] extends over the original system in a number of way : a better minimum spanning tree discovery technique [10], a better measure of the cost of an edge in the crawling process as an estimation of its approximate depth in the site, and a refinement of the detection of duplicate pages.

iRobot [5, 44] is probably the work closest to ours. In contrast with that system, the AAH we propose is applicable to any kind of Web application, as long as it is described in our knowledge base. Also differently from [5, 44], where the analysis of the structure of a forum has to be done independently for each site, the AAH exploits the fact that several sites may share the same content management system. Our system also extracts structured and semantic information from the Web pages, where iRobot stores plain HTML files and leaves the extraction for future work. We finally give in Section 8 a comparison of the performance of iRobot vs AAH to highlight the superior efficiency of our approach. On the other hand, iRobot aims at a fully automatic means of crawling a Web forum, while the AAH relies on a knowledge base (manually constructed but automatically maintained) of known Web applications or CMSs.

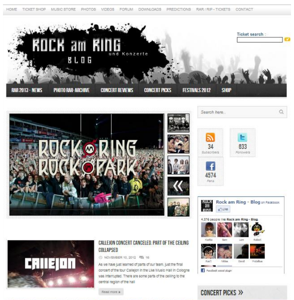
Web application detection As we shall explain, our approach relies on a generic mechanism for detecting the kind of Web application currently crawled. Again there has been some work in the particular cases of blogs or forums. In particular, [21] uses support vector machines (SVM) to detect whether a given page is a blog page. Support vector machines [4, 32] are widely used for text classification problems. In [21], SVMs are trained using various traditional feature vectors formed of the content's bag of words or bag of n-grams, and some new features for blog detection are introduced such as the bag of linked URLs and the bag of anchors. Relative entropy is used for feature selection.

More generally, a few works [1, 27, 26] aim at identifying a general category (e.g., blog, academic, personal, etc.) for a given Web site, using classifiers based on structural features of Web pages that attempt to detect the *functionalities* of these Web sites. This is not directly applicable to our setting, first because the classification is very coarse, and second because these techniques function at the Web site level (e.g., based on the home page) and not at the level of individual Web pages.

Wrapper adaptation Wrapper adaptation, the problem of adapting a Web information extractor to (minor) changes in the structure of considered Web pages or Web sites, has received quite some attention in the research community. An early work is that of Kushmerick [23] who proposed an approach to analyze Web pages and already extracted information, so as to detect changes in structure. A "wrapper verification" method is introduced that checks whether a wrapper stops extracting data ; if so, a human supervisor is notified so as to retrain the wrapper. Chidlovskii [7] introduced some grammatical and logic-based rules to automate the maintenance of wrappers, assuming only slight changes in the structure of Web pages. Meng, Hu, and Li [29] suggested a schema-guided wrapper maintenance approach called SG-WRAM for wrapper adaptation, based on the observation that even when structure changes in Web pages, some features are preserved, such as syntactic patterns, hyperlinks, annotations, and the extracted information itself. Lerman, Minton, and Knoblock [24] developed a machine learning system for repairing wrapper for small markup changes. Their proposed system first verifies the extraction from Web pages, and if the extraction fails then it relaunches the wrapper induction for data extraction. Raposo et al. [34] collect valid query results during the use of the wrapper ; when structural changes occur in Web sources then use those results as inputs to generate a new training set of labeled examples which can be used again for wrapper induction.

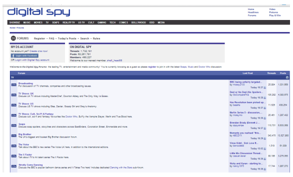
Our template adaptation technique is inspired by the previously cited works : we check whether patterns of our wrapper fail, and if so, we try fixing them assuming minor changes in Web pages, and possibly using previously crawled content on this site. One main difference with existing work is that our approach is also applicable to completely new Web sites, never crawled before, that just share the same content management system and a similar template.

Data extraction from blogs, forums, etc A number of works [43, 13, 25, 3] aim at automatic wrapper extraction from CMS-generated Web pages, looking for repeated structure and typically using tree alignment or tree matching techniques. This is out of scope of our approach, where we assume that we have a preexisting knowledge base of Web applications. Gulhane et al. [17] introduced the Vertex wrapper induction system. Vertex extracts structured information from template-based Web pages. The system cluster the pages using shingle vectors, learns extraction rules, detects site changes and relearn broken rules. Vertex detects site changes by monitoring a few sample pages per site. Any structural change can result in changes in page shingle vectors

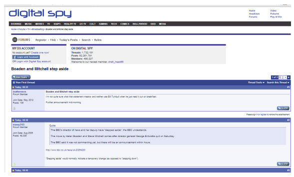


(a) Rock am Ring blog

(b) Carleton Newsroom



(c) Intermediate level



(d) Terminal level

FIGURE 1: Example Web pages of some Web applications

that may render learned rules inapplicable. In our system, we do not monitor sampled Web pages but dynamically adapt to pages as we crawl them. Our proposed crawler also applies adaptation to different versions of a content management system found on different Web sites, rather than to just a specific Web page type.

3 Preliminaries

This section introduce some terminology that we will use throughout this paper.

A *Web application* is any application or Web site that uses Web standards such as HTML and HTTP to publish information on the Web in a specific template, in a way that is accessible by Web browsers. Examples include Web forums, social networking sites, geolocation services, etc.

A *Web application type* is the content-management system or server-side technology stack (e.g., vBulletin, WordPress, the proprietary CMS of Flickr, etc.) that powers this Web application and provides interaction with it. Several different Web applications can share the same Web application type (all vBulletin forums use vBulletin), but some Web application types can be specific to a given Web application (e.g., the CMS powering Twitter is specific to that site). There can be significant differences in the appearance of Web applications of the same type ; compare for instance Figures 1a and 1b, two WordPress-powered sites.

The content presented by Web applications is typically stored in databases and predefined templates are used to generate data-rich Web pages. For intelligent crawling, our AAH needs not only to distinguish among Web application types, but among the different kinds of Web pages that can be produced by a given Web application type. For instance, a Web forum software can generate content-pages of various kinds, such as *list of forums*, *list of threads*, *list of posts*, *individual post*, *user profile*. We call such a specific template kind the *level* of the Web application.

We use a simple subset of the XPath expression language [39] to describe *patterns* in the

```
⟨expr⟩       ::= ⟨step⟩ | ⟨step⟩ "/" ⟨expr⟩
                          ⟨step⟩ "//" ⟨expr⟩
⟨step⟩       ::= ⟨nodetest⟩ | ⟨step⟩ "[" ⟨predicate⟩ "]"
⟨nodetest⟩   ::= tag | "@" tag | "*" | "@*" | "text()"
⟨predicate⟩  ::= "contains(" ⟨value⟩ "," string ")" |
                 ⟨value⟩ "=" string | integer | "last()"
⟨value⟩      ::= tag | "@" tag
```

FIGURE 2: BNF syntax of the XPath fragment used. The following tokens are used : *tag* is a valid XML identifier (or NMTOKEN [40]) ; *string* is a single- or double-quote encoded XPath character string [39] ; *integer* is any positive integer.

DOM of Web pages that serve either to identify a Web application type or level, or to determine navigation or extraction *actions* to apply to that Web page. A grammar for the subset we consider is given in Figure 2. Basically, we only allow downwards axes and very simple predicates that perform string comparisons. The semantics of these expressions is the standard one [39]. Unless otherwise specified, a leading "//" is implicit : an expression can match any node at any depth in the DOM tree. In the following, an *XPath expression* is always one of this sublanguage.

A *detection pattern* is a rule for detecting Web application types and Web application levels, based on the content of a Web page, HTTP metadata, URL components. It is implemented as an XPath expression over a virtual document that contains the HTML Web page as well as all other HTTP metadata.

A *crawling action* is an XPath expression over an HTML document that indicates which action to perform on a given Web page. Crawling actions can be of two kinds : *navigation actions* point to URLs to be added to the crawling queue ; *extraction actions* point to individual semantic objects to be extracted from the Web page (e.g., timestamp, blog post, comment). For instance, `div[contains(@class,'post')]//h2[@class='post-message']//a/@href` is a navigation action to follow certain types of links.

The application-aware helper distinguishes two main kinds of Web application levels : *intermediate* pages, such as lists of forums, lists of threads, can only be associated with navigation actions ; *terminal pages*, such as the list of posts in a forum thread, can be associated with both navigation and extraction actions. The idea is that the crawler will navigate intermediate pages until a terminal page is found, and only content from this terminal page is extracted ; the terminal page may also be navigated, e.g., in the presence of paging. To illustrate, Figure 1(c) and 1(d) show, respectively, intermediate and terminal pages in a Web forum application.

Given an XPath expression e, a *relaxed expression* for e is one where one or several of the following transformations has been performed :

- a predicate has been removed ;
- a *tag* token has been replaced with another *tag* token.

A *best-case relaxed expression* for e is one where at most one of these transformations has been performed for every step of e. A *worst-case relaxed expression* for e is one where potentially multiple transformations have been performed on any given step of e.

To illustrate, consider $e =$`div[contains(@class,'post')]//h2[@class='post-message']`. Examples of best-case relaxed expressions are `div[contains(@class,'post')]//h2` or `div[contains(@class,'post')]//h2[@id='post-content']` ; on the other hand, `div[contains(@class,'post')]//div[`

@id='post-content'] is an example worst-case relaxed expression.

4 Knowledge base

The AAH is assisted by a *knowledge base* of Web application types that describes how to crawl a Web site in an intelligent manner. This knowledge specifies how to detect specific Web applications and which crawling actions should be executed. The types are arranged in a hierarchical manner, from general categorizations to specific instances (Web sites) of this Web application. For example the social media Web sites can be categorized into blogs, Web forums, microblogs, video networks, etc. Then we can further categorize these specific types of Web applications on the basis of the content management system they are based on. For instance, WordPress, Movable Type, etc., are examples of blog content management system, whereas phpBB and vBulletin, etc., are examples of Web forum content management systems. The knowledge base also describes the different levels under a Web application type and then, based on this, we can define different crawling actions that should be executed against this specific page level.

The knowledge base is specified in a declarative language, so as to be easily shared and updated, hopefully maintained by non-programmers, and also possibly automatically learned from examples. The W3C has normalized a Web Application Description Language (WADL) [41] that allows describing resources of HTTP-based application in a machine processable format. WADL is used for describing the set of resources, their relationship with each other, the method that can be applied on each resource, resource representation formats, etc. WADL may be a candidate component and export format of our knowledge base, but does not satisfy all our needs : in particular, there is no place for the description of Web application recognition patterns. Consequently, our knowledge-based is described in custom XML format, well-adapted to the tree structure of the hierarchy of Web applications and page levels.

Web application type and level For each Web application type, and for each Web application level, the knowledge base contains a set of detection patterns that allows to recognize whether a given page is of that type or that level.

Let us take the example of the vBulletin Web forum content management system, that can for instance be identified by searching for a reference to a `vbulletin_global.js` JavaScript script with the detection pattern : `script[contains(@src,'vbulletin_global.js')]`. Pages of the "list of forums" type are identified [2] when they match the pattern `a[@class="forum"]/@href`.

Crawling actions Similarly, for each Web application type and level, a set of navigation actions and extraction actions (for the latter, only in the case of terminal levels) is provided. Navigation actions point to links (typically in an attribute `a/@href`) to follow ; extraction actions, also associated with semantic types, point to content to extract.

5 Application-aware helper (AAH)

Our main claim is that different crawling techniques should be applied to different types of Web applications. This means having different crawling strategies for different forms of social

2. The example is simplified for the sake of presentation ; in reality we have to deal with several different layouts that vBulletin can produce.

Web sites (blogs, wikis, social networks, social bookmarks, microblogs, music networks, Web forums, photo networks, video networks, etc.), for specific content management systems (e.g., WordPress, phpBB), and for specific sites (e.g., Twitter, Facebook). Figures 1a and 1b are example Web applications that are based on the WordPress CMS. Our proposed approach will detect the type of Web application (general type, content management system, or site) currently processed by the crawler, and the kind of Web pages inside this Web application (e.g., a user profile on a social network) and decide on further crawling actions (following a link, extracting structured content) accordingly. The proposed crawler is intelligent enough to crawl and store all comments related to a given blog post in one place, even if comments stays on several Web pages.

The AAH detects the Web application and Web page type before deciding which crawling strategy is appropriate for the given Web application. More precisely, AAH works in the following order :

1. it detects the Web application type ;
2. it detects the Web application level ;
3. it executes the relevant crawling actions : extract the outcome of extraction actions, and add the outcome of navigation actions to the URL queue.

Detection of Web application type and level The AAH loads the Web application type detection patterns from the knowledge base and executes them against the given Web application. If the Web application type is detected, the system executes all the possible Web application level detection patterns until it gets a match. The number of detection patterns for detecting Web application type and level will grow with the addition of knowledge about the new Web applications. To optimize this detection, the system needs to maintain an index of these patterns.

To this purpose, we have integrated the YFilter system [9] (an NFA-based filtering system for XPath expressions) with slight changes according to our requirements, for efficient indexing of detection patterns, in order to quickly find the relevant Web application types and levels. YFilter is developed as part of a publish–subscribe system that allows users to submit a set of queries that are to be executed against streaming XML pages. By compiling the queries into an automaton to index all provided patterns, the system is able to efficiently find the list of all users who submitted a query that matches the current document. In our integrated version of YFilter, the detection patterns (either for Web application type or level) will be submitted as queries ; when a document satisfy a query, the system will stop processing the document against all remaining queries (in contrast to the standard behavior of YFilter), as we do not need more than one match.

6 Adaptation to Template Change

Two types of changes can occur in a Web page : Web content changes, and Web structure changes. Change in the rating of a movie, a new comment under a post, the deletion of a comment, etc., are examples of Web content changes. These kind of changes are easy to identify by simply comparing the current Web page with a recently crawled version. An example of Web structure change is a change to the presentational template of a Web site template change, which is more complicated to identify and adapt. Our adaptation approach deals with this challenge.

Structural changes with respect to the knowledge base may come from varying versions of the content management system, or from alternative templates proposed by the CMS or developed for specific Web applications, If the template of a Web page is not the one given in the Web application knowledge base, Web application detection patterns and crawling actions may fail on a Web page. The AAH aims at determining when a change has occurred and adapting patterns and actions. In the process, it also automatically maintains the knowledge base with the newly discovered patterns and actions.

Detection patterns for determining the Web application type are most of the time detected by looking for a reference to script files, stylesheets, HTTP metadata (such as cookie names) or even textual content (e.g., a "Powered by" text fragment), which are quite robust to template changes. Accordingly, we will assume in the following that our Web application type detection patterns never fail. We did not see any instance where this would happen in our experiments. On the other hand, we consider that Web application level detection patterns and crawling actions may become inapplicable after structural changes.

We deal with two different cases of adaptation : first, when (part of) a Web application has been crawled before the template change and a recrawl is carried out after that (a common situation in real-world crawl campaigns) ; second, when crawling a new Web application that matches the Web application type detection patterns but for which (some of) the actions are inapplicable.

6.1 Recrawl of a Web Application

We first consider the case when part of a Web application has been crawled successfully using the patterns and actions of the knowledge base. The template of this Web application then changes (because of an update of the content management system, or a redesign of the site) and it is recrawled. Our core adaptation technique relearns appropriate crawling actions for each crawlable object ; the knowledge base is then updated by adding newly relearned actions to it (since the existing actions may work on an other instance of this Web application type, we do not replace existing ones).

As later described in Section 7, crawled Web pages with their Web objects and metadata are stored in the form of RDF triples into a RDF store. Our proposed system detects structural changes for already crawled Web applications by looking for the content (stored in RDF store) in the Web pages with the crawling actions used during the previous crawl. If the system fails to extract the content with the exact same actions, then it means the structure of the Web site has changed.

Input: a URL u, sets of Web application detection patterns D and crawling actions A
if $\mathit{alreadyCrawled}(u)$ **then**
    if $\mathit{hasChanged}(u)$ **then**
        $\mathit{markedActions} \leftarrow \mathit{detectAndMarkStructuralChanges}(u, A)$;
        $\mathit{newActions} \leftarrow \mathit{alignCrawlingActions}(u, D, \mathit{markedActions})$;
        $\mathit{addToKnowledgeBase}(\mathit{newActions})$;

Algorithm 1: Adaptation to template change (recrawl of a Web application)

Algorithm 1 gives a high-level view of the template adaptation mechanism in the case of a recrawl. The system processes each relevant Web page of a given Web application. Any Web page that has been crawled before but now fails to crawl will be passed to Algorithm 1 for structural adaptation. This algorithm only fix failed crawling actions for already crawled Web pages ; however, since newly learned crawling actions are added to the knowledge base, the system will still be able to process pages from the same Web application that were not crawled before. Note that in any case the system does not blindly try to relearn the failed crawling actions for each Web page, but rather first checks whether already fixed crawling actions for the same Web application level still works.

Algorithm 1 first checks whether a given URL has already been crawled by calling the *alreadyCrawled* Boolean function, which just looks for the existence of the URL in the RDF store. An already crawled Web page will then be checked for structured changes with the *hasChanged* Boolean function.

Structural changes are detected by searching for already crawled content (URLs corresponding to navigation actions, Web objects, etc.) in a Web page by using the existing and already learned crawling actions (if any) for the corresponding Web application level. The *hasChanged* function takes care of the fact that failure to extract deleted information should not be consider as a structural change. For instance, a Web object such as a Web forum's *comment* that was crawled before may not exist anymore. This scenario is very likely to occur as an administrator or even a comment's author himself may remove it from the Web forum. For that reason, the system will always check the existence of a Web object with all of its metadata in the current version of a Web page ; if the Web object has disappeared, it is not considered for detecting structural changes.

In the presence of structural changes, the system calls the *detectAndMarkStructuralChanges* function which detects inapplicable crawling actions and mark them as "failed". The *detectAndMarkStructuralChanges* returns a set of marked crawling actions. All crawling actions which are marked as failed will be aligned according to structural changes. The *alignCrawlingActions* function will relearn the failed crawling actions.

If a Web application level detection pattern also fails then the system will apply an approach similar to that later described in Section 6.2 for adapting the level detection pattern.

6.2 Crawl of a New Web Application

We are now in the case where we crawl a completely new Web applications whose template is (slightly) different from that present in the knowledge base. We assume that the Web application type detection patterns fired, but either the application level detection patterns or the crawling actions do not work on this specific Web application. In this situation, we cannot rely on previously crawled content from the knowledge base.

Let us first consider the case where the Web application level detection pattern works.

Web application level detected Recall that there are two classes of Web application levels : intermediate and terminal. We make the assumption that on intermediate levels, crawling actions (that are solely navigation actions) do not fail – on that level, navigations actions are usually fairly simple (they typically are simple extensions of the application level detection patterns, e.g., `//div[contains(@class,'post')]` for the detection pattern and `//div[contains(@class,'post')]//a/@href` for the navigation action). In our experiments we never needed to adapt them. We leave the case where they might fail to future work. On the other hand, we consider that both navigation actions and extraction actions from terminal pages may need to be adapted.

The main steps of the adaptation algorithm are described in Algorithm 2. The system first checks the applicability of existing crawling actions and then fix the failed ones. The

Input: a URL u and a sets of crawling actions A

if *not alreadyCrawled*(u) **then**
  for $a \in A$ **do**
    if *hasExtractionFailed*(u, a) **then**
      relaxedExpressions $\leftarrow$ *getRelaxedExpressions*(a);
      for *candidate* $\in$ *relaxedExpressions* **do**
        if *not hasExtractionFailed*$(u, candidate)$ **then**
          addToKnowledgeBase$(candidate)$;
          break ;

Algorithm 2: Adaptation to template change (new Web application)

getRelaxedExpressions creates two set of relaxed expression (for best-case and worst-case). For each set, different variations of crawling action will be generated by relaxing predicates and tag names, enumerated by the number of relaxation needed (simple relaxations come first). Tag names are replaced with existing tag names of the DOM tree so that the relaxed expression matches. When relaxing an attribute name inside a predicate, the AAH only suggests candidates that would make the predicate true ; to do that, the AAH first collects all possible attributes and their values from the page.

When the crawling action has for prefix a detection pattern, we do not touch this prefix but only relax the latter part. As an example, if an expression like `div[contains(@class,'post')]//h2[@class='post-title']` fails to extract the post title, and `div[contains(@class,'post')]` is the detection pattern that fired, then we will try several relaxations of the second half of the expression, e.g., replacing `@class` with `@id`, `'post-title'` with `'post-head'`, `h2` with `div`, etc. We favor relaxations that use parts from crawling actions in the knowledge base for other Web application types of the same general category (e.g., Web forum).

Once the system has generated all possible relaxed expressions, it first try with best-case ones and if they do not work with worst-case ones. More generally, expressions are ordered by the number of required relaxations. Any expression which succeeds in the extraction will be still tested with a few more pages of the same Web application level before being added to the knowledge base for future crawling.

Web page level not detected If the system does not detect the Web application level, then the crawling strategy cannot be initiated. First, the system tries adapting the detection pattern before fixing crawling actions. The idea is here the same as in the previous part : the system collect all candidate attributes, values, tag names from the knowledge base for the detected Web application type (e.g., WordPress) and then creates all possible combinations of relaxed expressions, ordered by the amount of relaxation, and test them one by one until one that works is found.

To illustrate, assume that the candidate set of attributes and values are : `@class='post'`, `@id=forum`, `@class='blog'` with candidate set of tag names `article`, `div`, etc. The set of relaxed expression will be generated by trying out each possible combination :

```
//article[contains(@class,'post')]
//article[contains(@id,'forum')]
//article[contains(@class,'blog')]
```

and similarly for other tag names.

After the collection of the set of relaxed expressions, the system will attempt to detect the

Web application level by testing each relaxed expression and, if the system finally detect the Web application level, then the system will apply the crawling action adaptation as described above. If the system does not detect the Web page level then the adaptation fails.

7 System

The application-aware helper is implemented in Java. On startup, the system first loads the knowledge base and indexes detection patterns using a YFilter [9] implementation adapted from the one available at `http://yfilter.cs.umass.edu/`. Once the system receives a crawling request, it first makes a lookup to the YFilter index to detect the Web application type and level. If the Web application type is not detected, the AAH applies the adaptation strategy to find a relaxed match as previously described. If no match is found (i.e., if the Web application is unknown), a generic extraction of links is performed.

When the Web application is successfully detected, the AAH loads the corresponding crawling strategy from the knowledge base and crawls the Web application accordingly, possibly using the adaptation strategy. The crawled Web pages are stored in the form of WARC [19] files – the standard preservation format for Web archiving – whereas structured content (individual Web objects with their semantic metadata) is stored in a RDF store. For scalability and archive availability purposes, WARC files are stored in a Hadoop [3] cluster on HDFS, and the RDF store we use, H2RDF [33], is implemented on top of HBase [37]. The knowledge base is potentially updated with new detection patterns or crawling actions.

The AAH is integrated with Heritrix [36], the open-source crawler [4] developed by the Internet Archive. In the crawl processing chain, the AAH replaces the conventional link extraction module. Crawling actions determined by the AAH are fed back into the URL queue of Heritrix.

The code of the AAH (as well as the list of all sites in our experimental dataset) is available at `http://perso.telecom-paristech.fr/~faheem/aah.html` under the GPL 3.0 license.

8 Experiments

We present in this section experimental performance of our proposed system on its own and with respect to a baseline crawler, GNU wget [5] (since the scope of the crawl is quite simple – complete crawling of specific domain names – wget is as good as Heritrix here).

Experiment setup To evaluate the performance of our system, we have crawled 100 Web applications (totaling nearly 3.3 millions Web pages) of two forms of social Web sites (Web forum and blog), for three specific content management system (vBulletin, phpBB, and WordPress). The Web applications of type WordPress (33 Web applications, 1.1 million of Web pages), vBulletin (33 Web applications, 1.2 million of Web pages) and phpBB (34 Web applications, 1 million Web pages) were randomly selected from three different sources :

1. `http://rankings.big-boards.com/`, a database of popular Web forums.
2. A dataset related to European financial crisis.
3. A dataset related to the *Rock am Ring* music festival in Germany.

3. `http://hadoop.apache.org/`
4. `http://crawler.archive.org/`
5. `http://www.gnu.org/software/wget/`

The second and third dataset were collected in the framework of ARCOMEM project [2]. In these real-world datasets corresponding to specific archival tasks, 68% of the seed URLs of Web forum type belongs to either vBulletin or phpBB, which explains while we target these two CMSs. WordPress is also a prevalent CMS : the Web as a whole has over 61 million Wordpress sites [42] out of a number of blogs indexed by Technorati [38] of around 133 million. Moreover, Wordpress has a 48% market share of the top 100 blogs [35]. All 100 Web applications were both crawled using wget and the AAH. Both crawlers are configured to retrieve only HTML documents, disregarding scripts, stylesheets, media files, etc.

The knowledge base is populated with detection patterns and crawling actions for one specific version of the three considered CMSs (other versions will be handled by the adaptation module). Adding a new Web application type to the knowledge base takes a crawl engineer of the order of 30 minutes.

Performance metrics The performance of the AAH will be mainly measured by evaluating the number of HTTP requests made by both systems vs the amount of *useful* content retrieved. Note that since wget is performing a complete, blind, retrieval of the Web site, all URLs crawled by the AAH will also be crawled by wget.

Evaluating the number of HTTP requests is easy to perform by simply counting requests made by both crawlers. Coverage of useful content is more subjective ; since it is impossible to ask for user evaluation given the volumes we consider, we use the following proxies :

1. Counting the amount of textual content that has been retrieved. For that, we compare the proportion of 2-grams (sequences of two consecutive words) in the crawl result of both systems, for every Web application.
2. Counting the number of external links (i.e., hyperlinks to another domain) found in the two crawls. The idea is that external links are a particularly important part of the content of a Web site.

Efficiency of detection patterns. We first briefly discuss the use of YFilter to speed up the indexing of detection patterns. In Fig. 3 we show the time required to determine Web application type in a synthetically generated knowledge base as the number of Web application types grows up to 5,000, with or without using YFilter indexing. The system takes a time linear in the number of detection patterns when indexing is turned off, taking up to several dozens of seconds. On the other hand, detection time is essentially constant with YFilter activated.

Crawl efficiency. We compare the number of HTTP requests required by both crawlers to crawl each set of Web applications of the same type in Fig. 4. Notice how the application-aware helper makes much fewer requests (on average 7 times fewer) than a regular blind crawl. Indeed, for blog-like Web sites, a regular crawler make redundant HTTP requests for the same Web content, accessing to a post by tag, author, year, chronological order, etc. In a Web forum, many requests end up being search boxes, edit areas, print view of a post, areas protected by authentication, etc.

Crawl effectiveness. The crawling results, in terms of coverage of useful content, are summarized in Fig. 5 and in Table 1. Figure 5 presents the distribution of the proportion of n-grams crawled by the AAH with respect to those of the full crawl. Not only are the numbers are generally very high (for the three types, the median is greater than 98%), but the results are

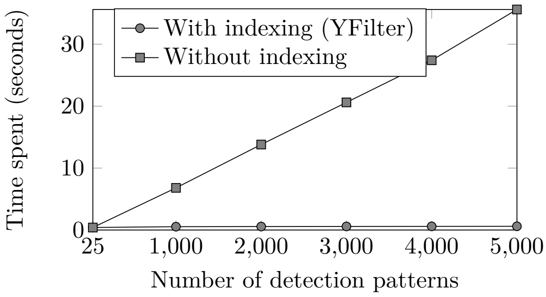


FIGURE 3: Performance of the detection module

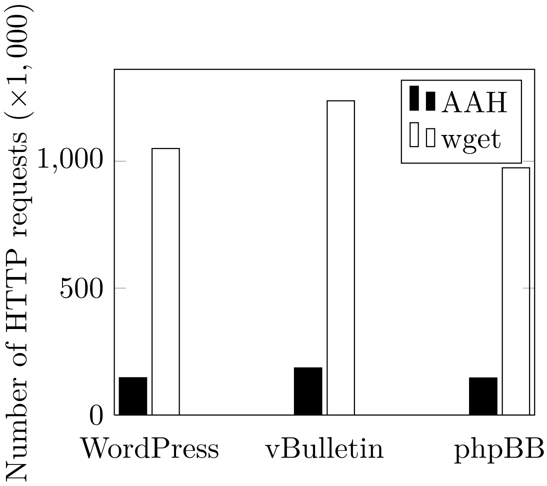


FIGURE 4: Total number of HTTP requests used to crawl the dataset

TABLE 1: Coverage of external links in the dataset crawled by the AAH

CMS	**External links**	**External links (w/o boilerplate)**
WordPress	92.7%	99.8%
vBulletin	90.5%	99.5%
phpBB	92.1%	99.6%

also very stable, with a very low variance : the worst coverage score on our whole dataset is greater than 97% (typically, lower scores are achieved for small Web sites where the amount of boilerplate text such as menus or terms of use remains non negligible). This hints at the statistical significance of the results.

The proportion of external links covered by the AAH is given in Table 1. The application-aware helper has ignored nearly 10 percent of external links since every page may use widgets, such as those of Facebook, Amazon, etc., with URLs varying from one page to another. Once we have excluded boilerplate with defined set of patters, we see that more than 99.5% of the external links are present in the content crawled by the AAH.

To reach a better understanding of how an application-aware crawl enfolds, we plot in Fig. 6 the number of distinct 2-grams discovered by the AAH and wget during one crawl (in this particular case, of a given WordPress blog), as the number of requests increase. We see that the AAH directly targets the interesting part of the Web application, with a number of newly discovered 2-grams that grows linearly with the number of requests made, to reach a final level of 98% 2-gram coverage after 1,705 requests. On the other hand, wget discovers new content with a lower rate, and, especially, spends the last 2/5 of its requests discovering very few new 2-grams.

Comparison to iRobot. The iRobot system [5] that we discussed in Sect. 2 is not available for testing because of intellectual property reasons. The experiments of [5] are somewhat limited

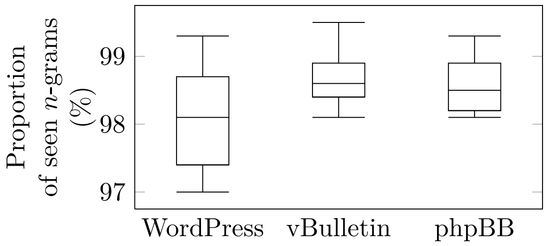


FIGURE 5: Box chart of the proportion of seen n-grams for the three considered CMSs. We show in each case the minimum and maximum values (whiskers), first and third quartiles (box) and median (horizontal rule).

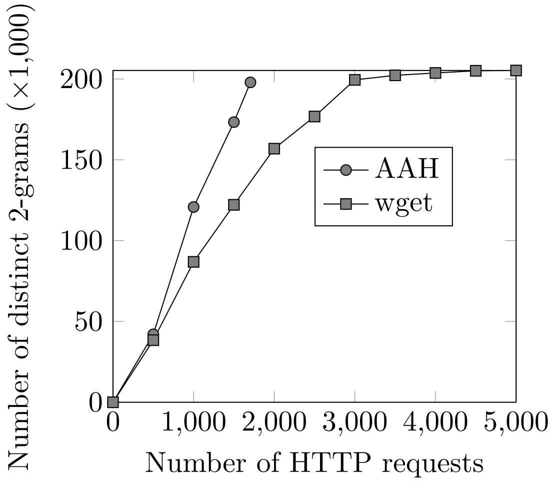


FIGURE 6: Crawling `http://www.rockamring-blog.de/`

TABLE 2: Examples of structural pattern changes : desktop vs mobile version of `http://www.androidpolice.com/`

Desktop version	**Mobile version**
div[@class='post_title']/**h3**/a	div[@class='post_title']/**h2**/a
div[@class='post_info']	div[@class='post_author']
div[@class='post_content']	div[@class='content']

in scope, since only 50,000 Web pages are considered, over 10 different forum Web sites (to compare with our evaluation, on 3.3 million Web pages, over 100 different forum or blog Web sites). To compare the AAH to iRobot, we have crawled one of the same Web forum used in [5] : `http://forums.asp.net/` (over 50,000 Web pages). The completeness of content of the AAH (in terms of both 2-grams and external links, boilerplate excluded) is over 99 percent ; iRobot has a coverage of *valuable pages* (as evaluated by a human being) of 93 percent on the same Web application. The number of HTTP requests for iRobot is claimed in [5] to be 1.73 times less than a regular Web crawler ; on the `http://forums.asp.net/` Web application, the AAH makes 10 times fewer requests than wget does.

Adaptation when recrawling a Web application. To test our adaptation technique in the case of a recrawl of a Web application in a realistic environment (without having to wait for Web sites actually to change), we have considered sites that have both a desktop and mobile version with different HTML content. These sites use two different templates to present what is essentially the same content. We simulated a recrawl by first crawling the Web site with a `User-Agent:` HTTP header indicating a regular Web spider (the desktop version is then served) and then recrawling the mobile version using a mobile browser `User-Agent:`.

Our system was not only able to detect the structural changes from one version to another, but also, using already crawled content, to fix the failed crawling actions. Table 2 presents one exemplary Web application that has both a desktop and mobile versions, with a partial list of the structural changes in the patterns across the two versions. Our system was able to automatically correct these structure changes in both navigation and extraction, reaching a perfect agreement between the content extracted by the two crawls.

Adaptation for a new Web application. As stated earlier, we have experimented our system with 100 Web applications, starting from a straightforward knowledge base containing information about one specific version of the three considered content management systems. Among the 100 applications, 77 did not require any adaptation, which illustrates that many Web applications share common templates. The 23 remaining ones had a structure that did not match the crawling actions in the knowledge base ; the AAH has applied adaptation successfully to these 23 cases. Most of the adaptation consisted in relaxing the class or id attribute rather than replacing the tag name of an element. When there was a tag name change, it was most often from span to div to article or vice versa, which is fairly straightforward to adapt. There was no case in the dataset when more than one relaxation for a given step of an XPath expression was needed ; in other words, only best-case relaxed expressions were used. In 2 cases, the AAH was unable to adapt all extraction actions, but navigation actions still worked or could be adapted, which means the Web site could still be crawled, but some structured content was missing.

As an example of relaxation, from the Web application `http://talesfromanopenbook.wordpress.com/`, the extraction of the post title by the action `div[@class='post']/h2[@class='post-title']` failed, but the relaxation `div[@class='post']/h2[@class='storytitle']` was found.

9 Conclusions

In Web archiving, scarce resources are bandwidth, crawling time, and storage space rather than computation time [28]. We have shown how application-aware crawling can help reduce bandwidth, time, and storage (by requiring less HTTP requests to crawl an entire Web application, avoiding duplicates) using limited computational resources in the process (to apply crawling actions on Web pages). Application-aware crawling also helps adding semantics to Web archives, increasing their value to users.

Our work can be extended in several ways, that we shall explore in future work. First, we can enrich the pattern language we use to allow for more complex detection and extraction rules, moving to the full support of XPath or even more powerful Web navigation languages such as OXPath [14], allowing to crawl complex Web applications making use of AJAX or Web forms. There is a trade-off, however, between the expressive power of the language and the simplicity of template adaptations. Second, we want to move towards an automatically constructed knowledge base of Web applications, either by asking a human being to automatically annotate the part of a Web application to extract or crawl [22], using semi-supervised machine learning techniques, or even by discovering in a fully unsupervised manner new Web application types (i.e., new CMSs) by comparing the structure of different Web sites, determining the optimal way to crawl them by sampling, in the spirit of iRobot [5].

10 Acknowledgments

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