Joker: A Unified Interaction Model For Web Customization

***Abstract*—Tools that enable end-users to customize websites typically use a two-stage workflow: first, users extract data into a structured form; second, they use that extracted data to augment the original website in some way. This two-stage workflow poses a usability barrier because it requires users to make upfront decisions about what data to extract, rather than allowing them to incrementally extract data as they augment it.**

In this paper, we present a new, unified interaction model for web customization that encompasses both extraction and augmentation. The key idea is to provide users with a spreadsheet-like formula language that can be used for both data extraction and augmentation. We also provide a programming-by-demonstration (PBD) interface that allows users to create data extraction formulas by clicking on elements in the website. This model allows users to naturally and iteratively move between extraction and augmentation.

To illustrate our unified interaction model, we have implemented a tool called Joker which is an extension of Wildcard, a prior web customization system. Through case studies, we show that Joker can be used to customize many real-world websites. We also present a formative user study with five participants, which showed that people with a wide range of technical backgrounds can use Joker to customize websites, and also revealed some interesting limitations of our approach. Finally, we present a heuristic evaluation of our design using the Cognitive Dimensions framework.

***Index Terms*—end-user web customization, programming-by-demonstration, spreadsheets, end-user web scraping, program synthesis**

I. Introduction

Many websites do not meet the exact needs of all of their users, so millions of people use browser extensions and userscripts [1, 2] to customize them. However, these tools only allow end-users to install customizations built by programmers. End-user web customization systems like Sifter [3], Vegemite [4] and Wildcard [5] provide a more accessible approach, allowing anyone to create bespoke customizations without performing traditional programming.

These tools each provide different useful mechanisms for end-user customization, but they share a common design limitation: they have a rigid separation between the two stages of the web customization process. First, in the *extraction* or *scraping* phase, users get data from the website into a structured, tabular format. Second, in the *augmentation* phase, users perform augmentations like adding new columns derived from the data, or sorting the data. For example, in Vegemite, a user can extract a list of addresses from a housing catalog, and then augment the data by computing a walkability score for each address.

This separation between extraction and augmentation poses an important barrier to usability. A user study [4] of Vegemite wrote that "it was confusing to use one technique to create the initial table, and another technique to add information to a new column." The creators of Sifter similarly reported [3] that "the necessity for extracting data before augmentation could take place was poorly understood, if understood at all." In Wildcard, end-users cannot augment a website at all until a programmer has written and shared extraction code for that website in Javascript [5]. These tools all impose a sequential workflow in which users must first extract all the data they need, and then perform all their desired augmentations. This workflow exemplifies the more general problem in interface design of forcing users to make premature commitments to formal structure [6, 7].

In this paper, we present a new approach to web customization that combines extraction and augmentation in a unified interaction model. Our key idea is to develop a domain specific language (DSL) that encompasses both extraction and augmentation tasks, along with a programming-by-demonstration (PBD) interface that makes it easy for end-users to program in the language. This unified interaction model allows end-users to move seamlessly between extraction and augmentation, resulting in a more iterative and free-form workflow for web customization.

To demonstrate and evaluate this model, we have built a browser extension called Joker, an extension of the Wildcard customization tool. The original Wildcard system [5] adds a spreadsheet-like table to a website and establishes a bidirectional synchronization between the website and the table. This allows users to customize a website, by filtering and sorting page elements, and adding user annotations, derived values and calls to web services. Although Wildcard offers a declarative formula language for augmenting the page, a conventional imperative language (namely JavaScript) is used for the extraction step, and the extraction code cannot be modified during augmentation.

Joker makes two primary contributions:

A unified formula language for extraction & augmentation: Wildcard's formula language only supported primitive values like strings and numbers aimed at augmentation. Joker extends this language by introducing Document Object Model (DOM) elements as a new type of value, and adding a new set of formulas for performing operations on them. This includes querying elements with Cascading Style Sheets (CSS) selectors and traversing the DOM. With this approach, a single formula language is used to express both extraction and augmentation tasks, even within a single formula expression.

A PBD interface for creating extraction formulas: Di-

rectly writing extraction formulas can be challenging for end-users, so Joker provides a PBD interface that synthesizes formulas from user demonstrations. A key aspect of our design is that the program synthesized from the demonstration is made visible as a spreadsheet formula that can be subsequently edited by the user, and is more easily understood than imperative code due to its declarative form.

Section II describes a concrete scenario, showing how Joker enables a user to complete a useful customization task. In Section III, we outline the implementation of our formula language and user interface, as well as the algorithms used by our PBD interface.

We have performed three evaluations of our approach, presented in Section IV. First, we describe a suite of case studies in which we used Joker to extract and augment a variety of websites in order to characterize its capabilities and limitations. Second, we describe a formative user study with five participants, which showed that users were generally able to use Joker to perform useful extraction and augmentation tasks, but which also uncovered limitations, particularly for less experienced users trying to extract data from more complex websites. Finally, we perform a heuristic evaluation of our design, using the Cognitive Dimensions [7] framework.

Joker relates to existing work not only in end-user web customization, but also in end-user web scraping and program synthesis, which we discuss in Section V. Finally, we discuss opportunities for future work in Section VI.

II. Example Usage Scenario

Here is an example scenario, illustrated in Figure 1, and demonstrated in the video accompanying this paper. Jen is searching for a karaoke machine on eBay, a shopping website. She wants to use Joker to sort products by price within a page of search results, a feature not supported by eBay.

Extracting Product Titles & Prices By Demonstration. (Figure 1 Part A): Jen initiates Joker through the browser context menu. As she hovers over the product title, Joker provides two kinds of live feedback. First, it highlights the titles of all the corresponding product listings on the page, to indicate how it has generalized Jen's intent based on her demonstration of a single example product. Second, a column of the table is populated with the values that will be extracted, giving a preview of how the extracted data would look. To commit to this extraction, Jen clicks on the product title. She repeats a similar process to extract the price.

When she clicks one of the cells in column `B`, the formula bar above the table displays the extraction formula that was generated from her demonstration:

```
=QuerySelector(rowElement,
"span.s-item__price")
```

This formula produces the values in column `B`. For each row in the table, Joker has a created a reference to the corresponding DOM element, accessible through the special identifier `rowElement`. The `QuerySelector` function runs the specified CSS selector (`span.s-item__price`) within the row element to extract the price of each item. While Jen could directly edit this formula, in this case the values in the table are correct, so there's no need to edit the formula.

Sorting Products By Price. (Figure 1 Part B): Next, Jen wants to sort the table by price, but she realizes that the column of prices is a list of strings containing the `$` symbol. She needs to *augment* this raw data by turning the strings into numbers. In the next column (`C`), Jen starts typing a formula, and uses an autocomplete dropdown to find a relevant function that extracts numeric values from strings:

```
=ExtractNumber(B)
```

Now column C contains numeric values, so Jen can sort the table by price. Because the table is synchronized with the website, the product listings become sorted as well.

Extracting Product URL With Formulas (Figure 1 Part C): While completing the previous task, Jen realizes there is another customization she would find useful: prioritizing products for which she has not yet visited the details page for the listing. To do this, she must first return to *extracting* more relevant data from the page.

Each product listing links to a page for the specific product, but because the URL is not visible in the page, it's not possible to directly extract it by demonstration. However, Jen can still achieve the goal by directly writing an extraction formula.

Jen has some basic knowledge of HTML, which she can leverage to write the formula. She opens the browser developer tools, and observes that the listing title is represented by a link tag with a heading inside:

```
<a href="LISTING PAGE URL">
  <h3>LISTING NAME</h3>
</a>
```

Since there is already a column `A` in the table representing the product's title, she can use this as a starting point to write the formula:

```
=GetAttribute(GetParent(A), "href")
```

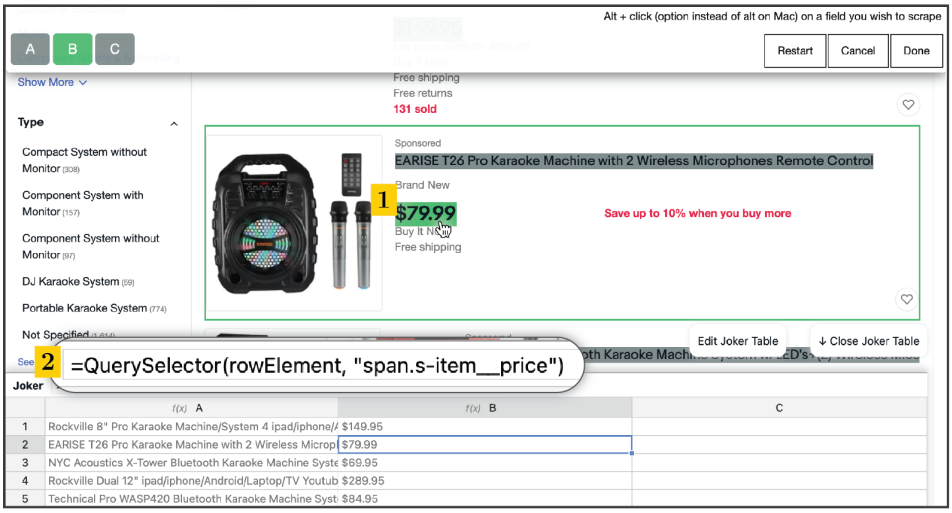
This formula first calls the `GetParent` function on column `A`, traversing up a level from the `<h3>` elements to the `<a>` elements. Then, `GetAttribute` extracts the `href` value containing the link URL. After running this formula, the table contains a column `D` with the URL for each product.

Sorting Products By Whether They Have Been Visited (Figure 1 Part C): After performing that extraction, Jen can write a final augmentation formula to indicate whether she has visited the corresponding product page:

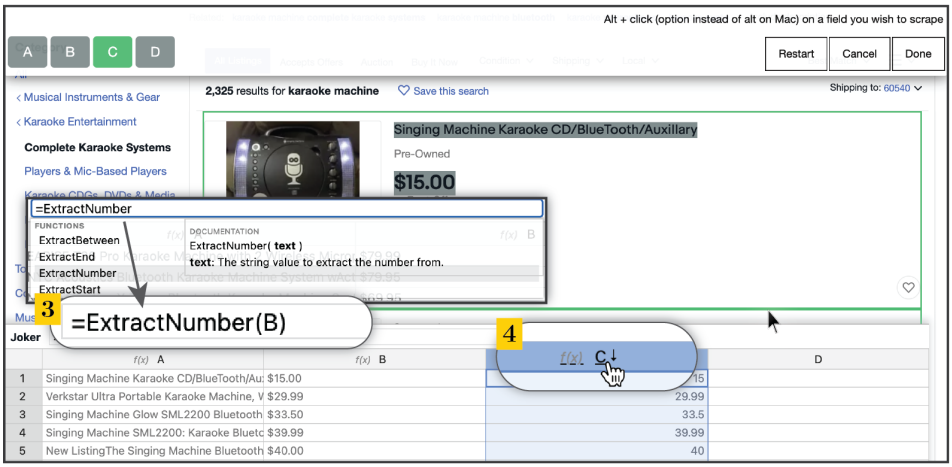
```
=Visited(D)
```

The `Visited` function checks whether a URL is present in the browser history and returns a boolean value represented by a checkbox. Jen can then sort by this column to put listings that she has not yet visited at the top of the page.

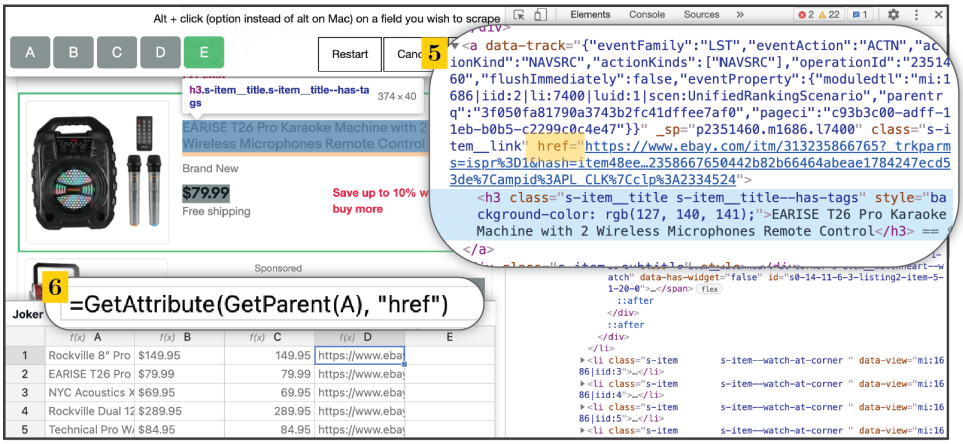
Using Joker, Jen was able to not only achieve her initial customization goal to sort the products by price but also perform a customization she did not plan to do. This was made possible by Joker's unified interaction model for web customization which enabled her to interleave extraction and augmentation. While we have described only a single illustrative scenario in this example, Joker is flexible enough to support a wide



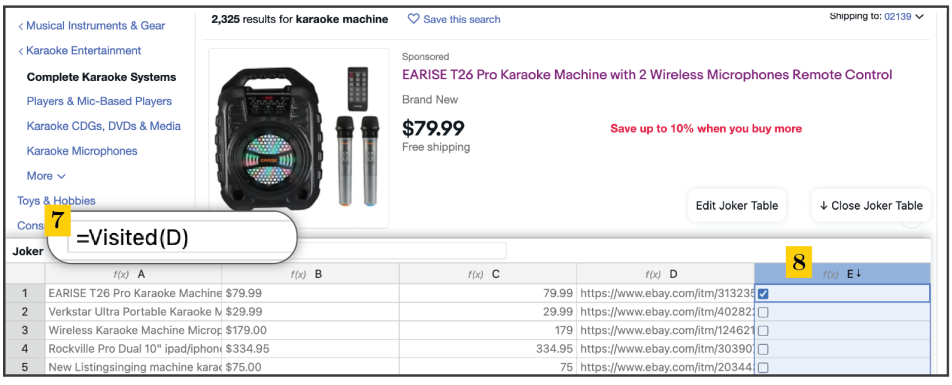
A) Extracting Names and Prices by Demonstration:
(1) The user scrapes the name and price of each listing by successively clicking on a name and price on the webpage.
(2) The table reveals the underlying formula that was synthesized to scrape this data.



B) Extracting the Number and Sorting by Price:
(3) Autocomplete with function documentation helps the user write a formula that converts the price from a string with a dollar sign into a numerical value.
(4) Now, the user can sort this column such that the rows are ordered by increasing numerical value. Correspondingly, the web page is sorted such that the lowest-cost results appear at the top.



C) Extracting Links using Formulas:
(5) The user wants to extract the link attached to the listing's name element, but the link cannot be extracted by demonstration. The user inspects the page to find that this is because the link is contained in the name element's parent.
(6) The user composes a function to get the parent element of the name element (in column A) and extract its link attribute ("href").



D) Sorting to Filter by Unread Links:
(7) The user writes a formula that determines whether a link has already been visited in the user's browser history.
(8) The user can sort this column to see all listings with unread links at the top of the page, with already-read links at the bottom.

Fig. 1. Scraping and customizing eBay by unified demonstration and formulas.

range of other useful customizations and workflows on various websites, described in more detail in Section IV.

III. System Implementation

In this section, we describe Joker's formula language in more detail. Then, we outline the *wrapper induction* [8] algorithm that Joker's PBD interface uses to synthesize the row element and column selectors presented in formulas. Figure 2 illustrates the entire process.

A. Extraction Formulas

The Wildcard customization tool includes a formula language for augmentation, including operators for basic arithmetic and string manipulation, as well as more advanced operators that fetch data from web APIs. As in other tabular interfaces like SIEUFERD [9] and Airtable [2], formulas apply to a whole column at a time rather than a single cell, and can reference other columns by name. Joker extends this base language with new constructs which enable it to apply to *data extraction* instead of just augmentation.

We added DOM elements as a data type in the language, alongside strings, numbers, and booleans. Because the language runs in a JavaScript interpreter, we simply use native JavaScript values to represent DOM elements in the language. DOM elements are displayed visually by showing their inner text contents. They can also be implicitly typecast to strings for use in other formulas; for example, a string manipulation formula like `Substring` can be called on a DOM element value, and will operate on its text contents.

We also added several functions to the formula language for traversing the DOM and performing extractions, summarized below with their types:

- `QuerySelector(el: Element, sel: string): Element`. Executes the CSS selector `sel` inside of element `el`, and returns the first matching element.
- `GetAttribute(el: Element, attribute: string): string`. Returns the value for an attribute on an element.
- `GetParent(el: Element): Element`. Returns the parent of a given element.

To extract data from a row, formulas need a way to reference the current row, so we added a construct to support this use case. Every row in the table maps to one DOM element in the page; we allow formulas to access this DOM element via a special keyword, `rowElement`. In some sense, `rowElement` can be seen as a hidden extra column of data in the table containing DOM elements.

While many more functions could be added to expose more of the underlying DOM API, we found that in practice these three functions provided ample power through composition. For example, in Section II we showed how `GetParent` and `GetAttribute` can be composed to traverse the DOM and extract the URL associated with a product listing.

By providing a single formula language to express extractions and augmentations, Joker enables a *unified interaction model* that supports interleaving the two. Furthermore, the formula language enables users to specify logic using pure, stateless functions that reactively update in response to upstream changes. This *functional reactive paradigm* is easier to reason about than traditional imperative programming, as demonstrated by the use of formulas by millions of end users in spreadsheet programs and end-user programming environments [2, 10, 11, 12, 13, 14].

B. Wrapper Induction

When users demonstrate a specific column value to extract, Joker must synthesize a program that reflects the user's general intent. This is an instance of the *wrapper induction* problem of synthesizing a web data extraction query from examples. Prior work on this topic [8, 15] prioritizes accuracy and robustness to future changes, which makes sense for a fully automated system, but can lead to very complex queries. In our work, we chose to prioritize the readability of queries by less sophisticated users, so that users can more easily author queries and repair them when they break. We implemented a set of heuristics inspired by Vegemite [4] for wrapper induction, described below.

1) Determining Row Elements: The user starts by demonstrating an element v, representing a value that should be in the table. From that demonstration, we must find a set of *row elements* that represent the rows of the table. We could naively assume that $parent(v)$ is the row containing v, but often v is deeply nested inside its containing row; we must determine which ancestor of v is likely to be the row.

Intuitively, we solve this problem by assuming that all rows share some similar internal structure. In particular, we expect most rows to contain a value for the demonstrated column. (If there were no missing data, we'd expect *all* rows to contain data for this column.)

Formally: assume a function $select(el, s)$ which runs a CSS selector that returns the set of elements matching s within el. We generate a set of plausible candidates P, consisting of pairs of a row element and a CSS selector:

$$P = \{(r, s) \mid r \in ancestors(v) \wedge select(r, s) = \{v\}\}$$

For each candidate $(r, s) \in P$, we compute a weight function w, which is based on the number of siblings of r that have "similar structure", defined by checking whether running s within the sibling also returns a unique element.

$$w(r, s) = |\{r' \mid r' \in siblings(r) \wedge |select(r', s)| = 1\}|$$

We then choose the candidate with the highest weight. In case of ties, the candidate closer to v in the tree (i.e., lower in the tree) wins. Given a winning candidate (r, s), the full set of row elements is $\{r\} \cup siblings(r)$.

2) Synthesizing CSS Selectors For Column Values: Once we have determined the row elements, next we must choose a CSS selector that will be used to identify the demonstrated value within its row.

Given a demonstrated value v within a row element r, we generate two kinds of plausible selectors:

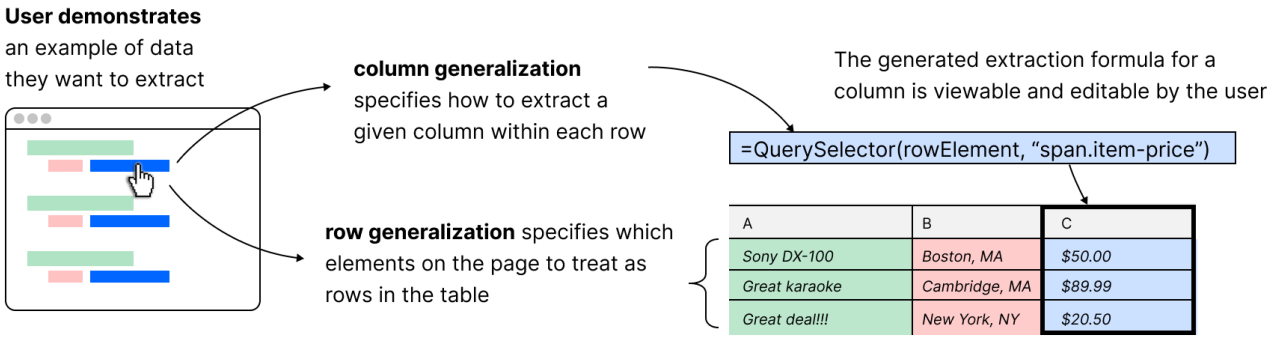


Fig. 2. An overview of Joker's interaction model and wrapper induction process.

- selectors using CSS classes, which are manual annotations on DOM elements added by the website's programmers, typically for styling purposes (e.g. "item__price")
- selectors using positional indexes within the tree, using the `nth-child` CSS selector (e.g. `nth-child(2)`, representing the second child of an element)

The minimum criteria for a plausible selector s is that it uniquely identifies the value within the row: $select(r, s) = \{v\}$. But there may be many plausible selectors, so we must pick a best one.

We first prioritize selectors using classes, because they tend to be more robust to changes on the website. A single selector can combine multiple classes, but we prefer using fewer classes when possible. If no plausible class-based selector can be generated (for example, if the relevant elements don't have any classes to query), we fall back to using a positional index selector. This kind of selector can always be generated regardless of the contents of the page, but tends to be less accurate and robust.

IV. Evaluation

We evaluate our interaction model and tool in terms of three research questions:

RQ1: What kinds of websites can this model operate effectively on? We evaluate this with a suite of case studies that demonstrate its capabilities and limitations.

RQ2: How are users of different backgrounds able to use the system? We evaluate this with a small formative user study.

RQ3: What are the essential design dimensions that distinguish this model from other approaches? We evaluate this with a heuristic analysis using the Cognitive Dimensions of Notation framework [7].

A. Case Studies

Our first evaluation describes the results of the authors using Joker to extract data and perform customizations on popular websites. For the websites on which Joker can be used, we provide the sequence of interactions needed to achieve the customizations; for the websites on which Joker fails, we explain the relevant limitations.

1) Successful Applications: We have used Joker to achieve a variety of customizations across many websites. Table 1 summarizes examples we have found on popular websites.

Sorting search results by price on Amazon. We have found Joker to be useful for sorting the contents of various websites. One example of a useful sort achieved by Joker is sorting search results by price within the Featured page on Amazon. (Using Amazon's sort by price feature often returns irrelevant results.) In Amazon's source code, the price is split into three HTML elements: the dollar sign, the dollar amount, and the cents amount. A user can extract by demonstration only the cents element into column `A`. Subsequently, because the parent element of the cents element contains all three of the price elements, the user can extract the full price using the formula `GetParent(A)`. Next, the user can write the formula `ExtractNumber(B)` to convert the string into a numeric value. Finally, the user can sort this column by low-to-high prices. In a similar manner, we have used Joker to extract and sort prices and ratings on the product listing pages of Target and eBay.

Filtering titles of publications on Google Scholar. We have also found Joker can be useful for filtering a website's listings based on the text content of an element in the listing. For example, we have used Joker to filter the titles of a researcher's publications on their Google Scholar profile which is not natively supported. First, a user can extract the titles into a column (`A`) by demonstration. Then, the user can write the formula `Includes(A, "compiler")` that returns whether or not the title contains the keyword "compiler". Finally, the user can sort by this column to get all of the publications that fit their constraint at the top of the page. We have also used Joker to filter other text-based directory web pages such as Google search results and the MIT course catalog, in similar ways.

Retrieving information about links on Reddit. Additionally, we have used Joker to augment web pages with external information. For example, Joker can augment Reddit's user interface, which has a list of headlines with links to articles, with the links' read times and whether the link has already been read. To achieve this customization, a user first extracts

Website	Example Customization Achieved by Joker
eBay, Amazon	Filter listings by whether they have a "Sponsored" label.
Amazon, Target	Sort search results by price and rating.
Google Scholar	Filter publications for those whose title contains a user-provided keyword.
Reddit, CNN, ABC	Sort by the read times of articles. Filter already-visited articles.
Weather.com	Filter hourly weather to find sunny times of day.
Github	Sort a user's code repositories by stars to find popular work.
Postmates, Uber Eats	Sort restaurants by delivery time and delivery fee.

TABLE I
EXAMPLES OF WEBSITES THAT JOKER CAN BE USED TO CUSTOMIZE, INCLUDING EXTRACTION AND AUGMENTATION

the headline elements into column (`A`) by demonstration. The user can then extract the link into the next column (`B`) with the formula `GetAttribute(A, "href")`. Then, the user can write the formula `ReadTimeInSeconds(B)` that calls an API that returns the links' read times. Similarly, the user can write the formula `Visited(B)`, which uses another API that returns whether that link has been visited in the user's browser history. The user can also extract elements such as the number of comments and the time of posting and sort by these values. We have performed similar customizations on websites such as ABC News and CNN.

2) Limitations: Joker is most effective on websites whose data is presented as a collection of similarly-structured HTML elements. Certain websites, however, have designs that make it difficult for Joker to extract data:

- *Heterogeneous row elements.* Some websites break their content into rows, but the rows do not have a consistent layout, and contain different types of child elements. For example, the page design of HackerNews alternates between rows containing a title and rows containing supplementary data (e.g. number of likes and the time of posting). Because Joker only chooses a single row selector, when extracting by demonstration, Joker will only select one of the types of rows, and elements in the other types of rows will not be extracted.
- *Infinite scroll.* Some websites have an "infinite scroll" feature that adds new entries to the page when a user scrolls to the bottom. Joker's table will only contain elements that were rendered when the table was first created. Additionally, for websites that render a very large number of DOM elements, the speed of the live feedback provided by Joker's PBD interface might significantly decrease. This is because the wrapper induction process used by the PBD interface queries the DOM which takes longer as the size of the DOM increases.

B. User Study

We conducted a small formative user study to understand how people would interact with Joker.

1) Participants: We recruited 5 participants with varying backgrounds. 3 participants were familiar with spreadsheet formulas. 3 participants had extensive web development experience, 1 had a small amount of prior web development experience, and 1 had no web development experience. 3 participants had previously extracted data from websites.

2) Protocol: The participants completed 7 web customization tasks across 2 websites. All participants attempted all the tasks.

First, we asked participants to customize a website with a relatively simple HTML structure: the MIT EECS course catalog website. All data *extraction* on this site can be performed with demonstrations alone in Joker, although augmentation still requires writing formulas. The specific tasks were the following: 1a) Extract course titles, 1b) Extract course prerequisites, 1c) Add a column that indicates whether a course has a prerequisite & 1d) Add a column that indicates whether a course has no prerequisites and is offered in the fall term.

Next, we asked participants to customize a website with a more complex HTML structure: the search results page for the eBay shopping website. Due to the website's complexity, demonstrations alone are not sufficient to extract data; users must also directly edit extraction formulas. The specific tasks were the following: 2a) Extract title from listings of Apple iPhones for sale, 2b) Extract the listing price for the phone, & 2c) Create a column that indicates whether a listing for a phone is sponsored.

Each session was 60 minutes long and conducted over a recorded video conference. We started each session with a description of Joker and provided a brief tutorial of its main features on a sample website not used in the tasks. There was no time limit for completing the tasks. Users were encouraged to speak aloud as they worked.

Because some of the tasks build on results of previous tasks, we wanted to ensure all participants made enough progress to gather useful feedback. Therefore, whenever a participant got stuck for several minutes, we recorded why they were stuck and then offered hints on how to proceed (such as suggestions to read formula documentation or open the browser dev tools). While all participants were able to complete all tasks with hints, this obviously does not mean they could have completed the task unassisted. Our goal was not to simply measure whether users completed the task, but rather to gain qualitative insight into the barriers they faced.

3) Results: Unified interaction model. Most participants took advantage of the unified interaction model to interleave extraction and augmentation tasks, rather than performing all extraction up front. For example, on task 1, most participants extracted the prerequisites by demonstration, added one or more columns to the table to perform some string operations on the prerequisites, and then continued on to extract more in-

formation from the web page by demonstration. Furthermore, we hypothesize that in a less controlled setting, users would be even more likely to interleave extraction and augmentation, since the task may be less well defined at the beginning.

One usability issue with the unified model was that participants sometimes got confused about how their demonstrations would affect the contents of the table. For example, multiple participants intended to add a new column by demonstrating an extraction, but instead accidentally overwrote the contents of an existing column. This poses a design challenge because the user's demonstrations occur in the website, so they cannot directly interact with the table while demonstrating; this suggests that the interface needs to do a better job indicating where the results of a demonstration will be inserted.

Extracting simple data. On the relatively simple MIT course catalog website, all participants were able to extract the relevant data from the page within seconds, simply performing demonstrations with a few clicks. This suggests that when Joker's generalization algorithm works well, it can be an effective tool for data extraction, even for users with limited programming experience. P1 said: *"you could hover and [the data] was already selected... that was very nice"*. P3, upon seeing the tutorial for extraction by demonstration, said *"that's like black magic."*

Extracting complex data. On the more complex eBay website where demonstration alone was not sufficient, results were more varied. P1, who had no prior web development experience, struggled to complete the task, saying that *"looking at HTML is a bit much"*; this suggests that more work could be done to make the experience usable for novices. However, users with more web development experience were able to use the tool to perform complex extractions, such as directly writing CSS selectors into the formula bar. P2 and P3 both reported that Joker's live feedback loop was easier to use and faster than other approaches to web extraction; P3 noted that *"[with any other approach], it would have been slower to specify and slower to validate that I specified it correctly."*

It was challenging for some participants to switch between using the browser's developer tools and the Joker interface when doing complex extraction tasks. While we chose not to build HTML inspection into the Joker UI because the browser already provides a very rich set of tools, users sometimes were not able to tell how elements in the Joker table corresponded to elements in the browser's element inspector.

Writing formulas. In general, participants were able to learn the formula language by using an autocomplete dropdown with inline documentation, which we developed as part of the Joker extension. In some cases, participants were able to immediately construct correct formulas on the first try; in other cases it took several attempts and some hints from the moderator to try a relevant function. While better documentation and error messages could help improve the learnability of the formula language, we also did not find it surprising that participants required some time to learn a completely unfamiliar formula language.

C. Cognitive Dimensions Analysis

We analyzed Joker using the Cognitive Dimensions of Notation [7], a heuristic evaluation framework that has been used to evaluate programming languages and visual programming systems [16, 17, 18]. When contrasting our tool with other scraping and customization tools, we find particularly meaningful differences along several dimensions:

Progressive evaluation. In Joker, a user can see the intermediate results of their extraction and augmentation work at any point, and adjust their future actions accordingly. The table user interface makes it easy to inspect the intermediate results and notice surprises like missing values.

In contrast, traditional extraction typically requires editing the code, manually re-running it, and inspecting the results in an unstructured textual format, making it harder to progressively evaluate the results. Also, many end-user extraction tools [4, 19] require the user to demonstrate all the data extractions they want to perform before showing any information about how those demonstrations will generalize across multiple examples.[1]

Premature commitment. Many scraping tools require making a *premature commitment* to a data schema: first, the user extracts a dataset, and then they perform augmentations using that data. Wildcard suffered from this problem: when writing code for extraction, a user would need to anticipate all future augmentations and extract the necessary data.

Joker instead supports extracting data *on demand*. The user can decide on their desired augmentations and extract data as needed to fulfill those tasks. There is never a need to eagerly guess what data will be needed in advance.

We have also borrowed a technique from spreadsheets for avoiding premature commitment: default naming. New data columns are automatically assigned a single-letter name, so that the user does not need to prematurely think of a name before extracting the data. We have not yet implemented the capability to optionally rename demonstrated columns, but it would be straightforward to do so, and would provide a way to offer the benefits of names without requiring a premature commitment.

Provisionality. Joker makes it easy to try out an extraction action without fully committing to it. When the user hovers over any element in a website, they see a preview of how that data would be extracted into the table, and then they can click if they'd like to proceed. This makes it feel very fast and lightweight to try scraping different elements on the page.

Viscosity. Some scraping tools have high viscosity: they make it difficult to change a single part of an extraction specification without modifying the global structure. For example, in Rousillon [19], changing the desired demonstration for a single column of a table requires re-demonstrating all of the columns. In contrast, Joker allows a user to change the specification

[1]This is an instance where Joker's limitation of only scraping a single page at a time proves beneficial. All the relevant data is already available on the page without further network requests, making it possible to support progressive evaluation with low latency. Other tools that support scraping across multiple pages necessarily require a slower feedback loop.

for a single column of a table without modifying the others, resulting in a lower viscosity in response to changes.

V. Related Work

Joker builds on existing work in end-user web customization, end-user web scraping and program synthesis.

A. End-user Web Customization

Joker builds on web customization ideas implemented by previous tools. Our contribution is a new interaction model that allows for interleaving extraction and augmentation, enabled by a unified formula language and a PBD interface.

Joker is an extension of the Wildcard customization system [5], and preserves its foundational idea of synchronizing a table with a website. Wildcard only allows for extraction logic to be written by programmers in Javascript; our work has substantially extended the Wildcard formula language and added an entire new system for dynamically creating data extraction logic within the user interface. We also improved the formula editing interface by adding an autocomplete dropdown and documentation popup, which proved important in our testing for allowing end-users to reliably edit and create formulas.

Vegemite [4] is a tool for end-user programming of web mashups. Like Joker, it allows users to perform demonstrations to extract data, but Vegemite only displays a table after all the demonstrations have been provided, which rules out interleaving extraction and augmentation. Vegemite does allow users to directly view and edit some of the logic generalized from demonstrations, but it only allows for editing augmentation logic, not extraction logic. The wrapper induction algorithm used in Joker is also very similar to Vegemite's algorithm.

Sifter [3] is a tool that augments websites with advanced sorting and filtering functionality. It attempts to automatically detect items and fields on the website with a variety of heuristics. If these fail, it gives the user the option of demonstrating to correct some parts of the result. In contrast, Joker makes fewer assumptions about the structure of websites, by giving control to the user from the beginning of the process and displaying an editable synthesized program. We hypothesize that focusing on a tight feedback loop rather than automation may support a scraping process that offers more expressive power and extends to a greater variety of websites, but further user testing is required to validate this hypothesis. Of course, better heuristics could benefit our model as well; the ideal system would make good guesses while giving the user full understanding and control of the extraction process.

B. End-user Web Scraping and Program Synthesis

Joker builds on insights from other tools that synthesize web scraping (i.e. data extraction) code from user demonstrations, and give users ways to inspect and modify the generated code.

Rousillon [19] is a tool that enables end-users to extract hierarchical web data across multiple linked web pages. It presents the web extraction program generated from demonstrations in an editable, high-level, block-based language called Helena [13]. While both Rousillon and Joker create an editable program, they have different focuses. Because Rousillon allows users to extract data across multiple pages (e.g., extracting details from each linked page in a list), it uses an imperative language, with nested loops as a key construct. In contrast, Joker can only extract within a single page, and therefore can use a simpler declarative formula language. Also, Rousillon only allows editing high-level control flow and treats some details of the extraction logic as opaque; Joker offers finer-grained control over details like CSS selectors.

Mayer et al propose a user interaction model called *Program Navigation* [20] which aims to give users another mechanism beside examples for guiding the generalization process of PBE tools like FlashExtract [21] and FlashFill [22]. This is important because demonstrations are an ambiguous specification for program synthesis [23]: the set of synthesized programs for a demonstration can be very large. The Program Navigation UI displays a natural language description of a space of possible programs, and lets the user choose different alternatives for parts of the generated expression. Joker shares the general idea of displaying synthesized programs, but only presents the top-ranked program; our tool might be improved by showing more candidate programs.

More broadly, Joker's use of PBD to generate editable code embodies Ravi Chugh's notion of *prodirect manipulation* [24], which aims to bridge the divide between programmatic and direct manipulation. The Sketch-N-Sketch system [25] provides prodirect manipulation by allowing users to create an SVG shape via traditional programming and then switch to modifying its size or shape via direct manipulation.

VI. Conclusion And Future Work

In this paper, we presented a unified interaction model for web customization. Our key idea is a spreadsheet formula language that encompasses both extraction and augmentation tasks, along with a programming-by-demonstration (PBD) interface that makes it easy for end-users to program to create formulas. This unified interaction model allows end-users to move seamlessly between extraction and augmentation, resulting in a more iterative and free-form workflow for web customization.

The main area of future work involves making the formula language more accessible to end-users not familiar with CSS selectors. FlashProg offers some clues through its use of natural language descriptions to explain synthesized extraction programs. One avenue for explaining CSS selectors could be by extracting semantic web content associated with the elements they select, as seen in systems like Thresher [26].

Our ultimate goal is to enable anyone that uses the web to customize websites in the course of their daily use in an intuitive and flexible way. This will in turn make the malleability of the web a reality for all of its users.

REFERENCES

[1] Greasespot. [Online]. Available: https://www.greasespot.net/

[2] Tampermonkey for Chrome. [Online]. Available: http://www.tampermonkey.net

[3] D. F. Huynh, R. C. Miller, and D. R. Karger, "Enabling web browsers to augment web sites' filtering and sorting functionalities," in *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology - UIST '06*. ACM Press, p. 125. [Online]. Available: http://dl.acm.org/citation.cfm?doid=1166253.1166274

[4] J. Lin, J. Wong, J. Nichols, A. Cypher, and T. A. Lau, "End-user programming of mashups with vegemite," in *Proceedings of the 14th International Conference on Intelligent User Interfaces*, ser. IUI '09. Association for Computing Machinery, pp. 97–106. [Online]. Available: http://doi.org/10.1145/1502650.1502667

[5] G. Litt, D. Jackson, T. Millis, and J. Quaye, "End-user Software Customization by Direct Manipulation of Tabular Data," in *Proceedings of the 2020 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software*. ACM, pp. 18–33. [Online]. Available: https://dl.acm.org/doi/10.1145/3426428.3426914

[6] F. M. Shipman and C. C. Marshall, "Formality Considered Harmful: Experiences, Emerging Themes, and Directions on the Use of Formal Representations in Interactive Systems," vol. 8, no. 4, pp. 333–352. [Online]. Available: http://link.springer.com/10.1023/A:1008716330212

[7] A. F. Blackwell, C. Britton, A. Cox, T. R. G. Green, C. Gurr, G. Kadoda, M. S. Kutar, M. Loomes, C. L. Nehaniv, M. Petre, C. Roast, C. Roe, A. Wong, and R. M. Young, "Cognitive Dimensions of Notations: Design Tools for Cognitive Technology," in *Cognitive Technology: Instruments of Mind*, M. Beynon, C. L. Nehaniv, and K. Dautenhahn, Eds. Springer Berlin Heidelberg, pp. 325–341.

[8] N. Kushmerick, "Wrapper induction: Efficiency and expressiveness," vol. 118, no. 1, pp. 15–68. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0004370299001009

[9] E. Bakke and D. R. Karger, "Expressive Query Construction through Direct Manipulation of Nested Relational Results," in *Proceedings of the 2016 International Conference on Management of Data*. ACM, pp. 1377–1392. [Online]. Available: https://dl.acm.org/doi/10.1145/2882903.2915210

[10] What is Microsoft Power Fx? [Online]. Available: https://powerapps.microsoft.com/en-us/blog/what-is-microsoft-power-fx/

[11] AppSheet: No-code App Development — Google Cloud. [Online]. Available: https://cloud.google.com/appsheet

[12] Build an app from a Google Sheet in five minutes, for free • Glide. [Online]. Available: https://www.glideapps.com/

[13] Coda — A new doc for teams. Coda — A new doc for teams. [Online]. Available: https://coda.io/welcome

[14] K. S.-P. Chang and B. A. Myers, "Creating interactive web data applications with spreadsheets," in *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. ACM, pp. 87–96. [Online]. Available: https://dl.acm.org/doi/10.1145/2642918.2647371

[15] T. Furche, J. Guo, S. Maneth, and C. Schallhart, "Robust and Noise Resistant Wrapper Induction," in *Proceedings of the 2016 International Conference on Management of Data*, ser. SIGMOD '16. Association for Computing Machinery, pp. 773–784. [Online]. Available: http://doi.org/10.1145/2882903.2915214

[16] A. Satyanarayan and J. Heer, "Lyra: An Interactive Visualization Design Environment: Lyra: An Interactive Visualization Design Environment," vol. 33, no. 3, pp. 351–360. [Online]. Available: http://doi.wiley.com/10.1111/cgf.12391

[17] A. Satyanarayan, K. Wongsuphasawat, and J. Heer, "Declarative interaction design for data visualization," in *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. ACM, pp. 669–678. [Online]. Available: https://dl.acm.org/doi/10.1145/2642918.2647360

[18] D. Ledo, S. Houben, J. Vermeulen, N. Marquardt, L. Oehlberg, and S. Greenberg, "Evaluation Strategies for HCI Toolkit Research," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–17. [Online]. Available: https://dl.acm.org/doi/10.1145/3173574.3173610

[19] S. E. Chasins, M. Mueller, and R. Bodik, "Rousillon: Scraping Distributed Hierarchical Web Data," in *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18*. ACM Press, pp. 963–975. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3242587.3242661

[20] M. Mayer, G. Soares, M. Grechkin, V. Le, M. Marron, O. Polozov, R. Singh, B. Zorn, and S. Gulwani, "User Interaction Models for Disambiguation in Programming by Example," in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, pp. 291–301. [Online]. Available: https://dl.acm.org/doi/10.1145/2807442.2807459

[21] V. Le and S. Gulwani, "FlashExtract: A framework for data extraction by examples," in *Proceedings of the 35th ACM SIGPLAN Conference on Programming Language Design and Implementation*. ACM, pp. 542–553. [Online]. Available: https://dl.acm.org/doi/10.1145/2594291.2594333

[22] W. R. Harris and S. Gulwani, "Spreadsheet table transformations from examples," p. 12.

[23] H. Peleg, S. Shoham, and E. Yahav, "Programming not only by example," in *Proceedings of the 40th International Conference on Software Engineering*. ACM, pp. 1114–1124. [Online]. Available: https://dl.acm.org/doi/10.1145/3180155.3180189

[24] R. Chugh, "Prodirect manipulation: Bidirectional programming for the masses," in *Proceedings of the 38th International Conference on Software Engineering Companion*. ACM, pp. 781–784. [Online]. Available: https://dl.acm.org/doi/10.1145/2889160.2889210

[25] R. Chugh, B. Hempel, M. Spradlin, and J. Albers, "Programmatic and direct manipulation, together at last," in *Proceedings of the 37th ACM SIGPLAN Conference on Programming Language Design and Implementation*. ACM, pp. 341–354. [Online]. Available: https://dl.acm.org/doi/10.1145/2908080.2908103

[26] A. Hogue and D. Karger, "Thresher: Automating the unwrapping of semantic content from the World Wide Web," in *Proceedings of the 14th International Conference on World Wide Web - WWW '05*. ACM Press, p. 86. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1060745.1060762