Comenius University in Bratislava
Faculty of Mathematics, Physics and Informatics

Trusted Types integration into open source frameworks and libraries

Masters Thesis

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Study Programme:	Computer Science
Field of Study:	Computer Science
Department:	FMFI.KAI - Department of Applied Informatics
Supervisor:	RNDr. Peter Borovanský, PhD.
Consultant:	Krzysztof Kotowicz

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THESIS ASSIGNMENT

Name and Surname:	Bc. Emanuel Tesař
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Title: Trusted Types integration into open source frameworks and libraries

Annotation: Trusted Types is a modern Web API which aims to reduce DOM XSS attack surface in web applications.
They give you the tools to write and maintain applications free of DOM XSS vulnerabilities by making
the dangerous web API secure by default. Currently, they are supported in Chrome, Edge and Opera.

Integrating Trusted Types in web applications and libraries requires code changes. The major problem
is when these changes need to be made in third party code which you don't have access to and you
can't easily modify. Trusted Types support in open source projects is gradually improving and our
plan is to analyze these integrations and implement one or more of the challenging ones.

Aim: Main goals of the thesis are the following:
- Review of Trusted Types integrations on various open source projects
- Design and verification of a Trusted Types library integrated into one or more projects
- Open sourcing the integration changes, ideally merging directly into the project sources
- Illustration of the newly created integrations on a real world project

Keywords: Trusted Types, Web APIs

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Abstrakt

Trusted Types je moderná webová knižnica, ktorá má za cieľ zredukovať riziko DOM XSS zraniteľností vo webových aplikáciách. Táto knižnica poskytuje nástroje a umožňuje implementáciu aplikácii bez DOM XSS zraniteľností vďaka obmedzeniu prístupu k nebezpečným funkciám a atribútom voľne dostupných v DOM. V súčasnosti je knižnica podporovaná v prehliadačoch Chrome, Edge a Opera.

Integrácia knižnice Trusted Types do webových aplikácií a knižníc vyžaduje zmeny v kóde. Obrovský problém nastáva, keď tieto zmeny musia byť implementované v kóde tretích strán, ku ktorému nemá autor prístup. Trusted Types podpora vo voľne dostupných knižniciach postupne stúpa a naším plánom je analyzovať existujúce integrácie a implementovať jednu alebo viac náročných integrácií.

Kľúčové slová: Trusted Types, Web APIs

Abstract

Trusted Types is a modern Web API which aims to reduce DOM XSS attack surface in web applications. They give you the tools to write and maintain applications free of DOM XSS vulnerabilities by making the dangerous web API secure by default. Currently, they are supported in Chrome, Edge and Opera.

Integrating Trusted Types in web applications and libraries requires code changes. The major problem is when these changes need to be made in third party code which you don't have access to and you can't easily modify. Trusted Types support in open source projects is gradually improving and our plan is to analyze these integrations and implement one or more of the challenging ones.

Keywords: Trusted Types, Web APIs

Contents

Concepts and definitions

These are the common terms used in this paper that should be understood by the reader before reading the paper. Advanced readers may skip this section and start with the first chapter (1).

1. **DOM source and sink** - In the context of XSS, a DOM source is the location from which untrusted data is taken by the application (which can be controlled by user input) and passed on to the sink (e.g. location, cookies). Sinks are the places where untrusted data coming from the sources is actually getting executed resulting in DOM XSS (e.g. eval, element.innerHTML) [1]. We might also refer to sink as injection sink, because the untrusted value is injected into the sink by the attacked.

2. **Hot module reload** - The concept of live or hot module reload (HMR) is that the running application running in development mode is automatically restarted after code changes are made. The former restarts the whole app, the latter only patches the running application with code changed and preserves the application state.

Chapter 1

Introduction

In this chapter we give a brief overview of Cross site scripting (XSS), which is one of the most common web application vulnerabilities. We mainly focus on DOM based XSS for which Trusted Types are the most effective. We then explain the design of Trusted Types and how it helps to mitigate and prevent these vulnerabilities. Lastly, we describe the motivation and background for our work.

1.1 Cross site scripting

Cross site scripting (XSS) is one of the most prevalent vulnerabilities on the web. It is an attack of web applications taking untrusted user input and interpreting is as code without sanitization or escaping. There are multiple categories of XSS. Most experts distinguish at least between non-persistent *(reflected)* and persistent *(stored)* XSS. There is also a third category, *DOM based XSS*, which will be explained in more depth as this is the threat model under which Trusted Types operate.

- Stored – A malicious injected script is permanently saved in a server database. The client *(user's browser)* will then ask the server for the requested page and the response from the server will contain the malicious script.
- Reflected – Typically delivered via email or a neutral web site. It occurs when a malicious script is reflected off of a web application to the victim's browser [10].
- DOM based – The vulnerability appears in the DOM by executing a malicious code. In reflected and stored XSS attacks you can see the vulnerability payload in the server response. However in a DOM based XSS, the attack payload is executed as a result of modifying the DOM environment in the victim's browser so that the client side code runs in an unexpected manner.

Cross site scripting vulnerability became more widespread with the boom of single page applications (SPA) where most of the behaviour is achieved by modifying the

DOM using JavaScript. There are many functions, element attributes and properties in the DOM API which interpret the arguments as an executable code. We call these DOM sinks (1). These sinks make it easy for developers to accidentally introduce this vulnerability [27].

```
document.write()
element.innerHTML
element.insertAdjacentHTML
DomParser.parseFromString
frame.srcdoc
eval()
script.src
Worker()
```

Listing 1.1: Examples of most common DOM XSS sinks [28] [27]

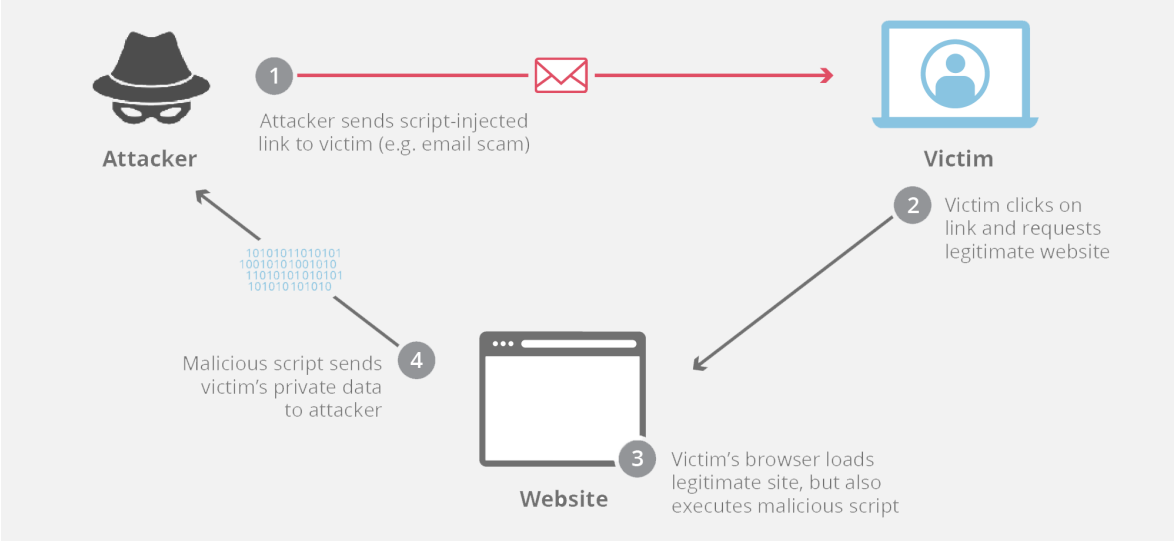

Figure 1.1: Common XSS vulnerability flow

One of the most basic examples of XSS is the interpolation of URL parameters in the DOM. The attacker can prepare a malicious URL which he sends to a victim. The victim executes the payload just by navigating to the site sent by the attacker.

```
<!--
Assume this page is on https://example.com.
It can be misused by the following attack payload:
https://example.com?<img%20src=x%20onerror="alert(1)"></img>
-->
<!DOCTYPE html>
<html lang="en">
  <body>
```

```
    <div id="content"></div>
    <script type="text/javascript">
      const content = decodeURIComponent(location.search.substr(1))
      document.getElementById('content').innerHTML = 'URL content: ' +
    content
    </script>
  </body>
</html>
```

Listing 1.2: Basic example of XSS via unsafe URL parameter interpolation

The consequences of XSS vary a lot. Their severity can range from benign annoyances to unrecoverable damages such as full account compromise, disclosure of user's cookies, storage, secrets or session. Other attacks may use XSS to change the application content and present falsy information to the user.

There are many attempts to reduce the risk of DOM XSS either by dynamic or static checkers. The former usually suffer from performance and scalability issues when applied on large codebases while the latter provide suboptimal results due to JavaScript dynamic nature [27] [25].

1.2 Trusted Types

Trusted Types is a relatively modern web API designed by Google based on a long history of mitigating XSS [3].

It is a browser security feature that limits access to dangerous DOM APIs to protect against DOM XSS. Trusted Types provide type guarantees to all frontend code by enforcing security type checks directly in the web browser. They are delivered through a CSP header and have a report-only mode that does not change the application behavior and an enforcement mode that may cause user-observable breakages [14].

When enforced, Trusted Types block dangerous injection sinks (1) from being called with values that have not passed through a Trusted Types policy [14]. If an untrusted value is passed to sink a Trusted Types violation is raised and the DOM is unaffected. In practice this means that a potential DOM XSS has been prevented.

There are many other resources which can be used to explore Trusted Types in details [16].

1.2.1 Threat model

Trusted Types is a powerful API with a well scoped threat model. The main goals of the API are to [18]:

- reduce the risk of client side vulnerabilities caused by injection sinks.

- replace the insecure by default APIs with safer alternatives which are harder to misuse.
- encourage a design where the code affecting the application security is encapsulated in a small part of an application.
- reduce the security review surface for applications and libraries.

The main idea behind Trusted Types is to make the dangerous DOM APIs secure by default and motivate application authors to use safer APIs. This model is very effective for preventing DOM based XSS, however there are still areas where Trusted Types are not effective enough and other security measures are needed. Some of the non goals of Trusted Types are [19]:

- preventing or mitigating server side generated markup attacks – Defending against XSS on both client and server can be really complex, especially for applications where parts of the code can run on both client and server, such as NextJS (**??**). To address these attacks, use the existing recommended solutions like templating systems or CSP *script-src*.
- controling subresource loading – Trusted Types deal with code running in realm of the current document and does not guard subresources.
- guarding cross origin JavaScript execution, for example loading new documents via *data:* URLs – Trusted Types do not guard cross origin executions as all
- protecting against malicious developers of the web application – It is implicitly assumed that untrusted developer can cause much severe damages. Attempting to guard against malicious developer would lead to complex and impractical design.

1.2.2 Content Security Policy

Content Security Policy (CSP) is an added layer of security that helps to detect and mitigate certain types of attacks, including XSS and data injection attacks [8]. CSP provides a way for browsers to create safer APIs in a backwards compatible manner, since the API has to be opt in explicitely by the application server by sending the CSP response header or using the CSP inside the HTML meta tag in the response body. If the browser does not support the CSP directive, the directive is ignored and standard browser behaviour applies.

Trusted Types are enabled through a CSP using two different directives:

- *require-trusted-types-for* – This directive instructs user agents to control the data passed to DOM XSS sink functions ([20]).

```
Content-Security-Policy: require-trusted-types-for 'script';
```

Listing 1.3: Syntax of require-trusted-types-for directive

- *trusted-types* – This directive instructs user agents to restrict the creation of Trusted Types policies ([21]). Syntax:

```
Content-Security-Policy: trusted-types;
Content-Security-Policy: trusted-types 'none';
Content-Security-Policy: trusted-types <policyName>;
Content-Security-Policy: trusted-types <policyName> <policyName>
    'allow-duplicates';
```

Listing 1.4: Syntax of trusted-types directive

These directives together enable and configure Trusted Types behaviour for the particular web application. They allow the application authors to define rules guarding write access to the DOM sinks and thus reducing the DOM XSS attack surface to small, isolated parts of the web application. This smaller parts can be modularized where they can be more easily monitored, reviewed and maintained.

Apart from the standard *Content-Security-Policy* header there is also *Content-Security-Policy-Report-Only* which can be used to enable Trusted Types in report only mode. Trusted Types violations are only interpreted as warnings in this mode. This way the application can gradually work on Trusted Types compliance without breaking the existing users. It is also recommended to use the report only mode in production for some time to make sure the integration is working as expected [27].

Once Trusted Types are enabled, the browser changes the behaviour of insecure DOM API sinks and expects "trusted" values instead of regular strings. These trusted values are created via Trusted Types policies.

1.2.3 Trusted Types policies

The core part of Trusted Types API are policies which are factory functions for creating "trusted" values which can be assigned to DOM sinks when Trusted Types are enabled. The policies are created by the application and access to them should be restricted. In javascript this can be easily achieved by encapsulating a policy in its own module and exporting only a very specific functions which use this policy internally.

```
const allowAll = (value) => value
const createHTMLCallback = allowAll;
const createScriptCallback = allowAll;
```

```
const createScriptURLCallback = allowAll;
const myPolicy = window.trustedTypes.createPolicy('my-policy', {
  createHTML: createHTMLCallback,
  createScript: createScriptCallback,
  createScriptURL: createScriptURLCallback,
});
```

Listing 1.5: Creating a Trusted Types policy

```
const trustedHtml = myPolicy.createHTML("<span>safe html</span>");
```

Listing 1.6: Create trusted value using a policy

The code listing 1.5 creates a Trusted Types policy using the callback functions. This callback function is called when the policy is used to create a trusted value. It receives the sink value of a string type as an argument and returns a string value that should be XSS free and thus can be trusted. In practice, this function may be implemented as identity if the payload is known to be trusted. Another good example would be to sanitize the sink value inside this callback. In case the payload should not be used or can not be sanitized, you can return *null* or *undefined* which will trigger a Trusted Types violation.

```
const myPolicy = window.trustedTypes.createPolicy('sanitize-html', {
  createHTML: (untrustedValue) => DOMPurify.sanitize(untrustedValue),
});
```

Listing 1.7: Using a policy to sanitize HTML values

1.2.4 Default policy

There is one special case for Trusted Types policies. Applications may create a policy called "default". This policy has a special behaviour. When a string value is passed to a DOM sink when Trusted Types are enabled, the user agent will implicitely flow the untrusted string value through the default policy. The callback function of the default policy receives three arguments instead of one – the string payload, sink type and a sink name respectively. This allows the application to recover from an unexpected sink usage, for example by sanitizing the untrusted value. If the default policy does not exist, returns *null* or *undefined* a CSP violation will be triggered [17]. Applications can use this policy to enable enforcement mode even though the application is not fully Trusted Types complaint.

This feature is intended to be used by applications with legacy or third party code that uses injection sinks. The policy callback functions should be defined with very

strict rules to prevent bypassing security restrictions enforced by Trusted Types API. For example, having an "accept all" default policy defeats enabled all malicious attacker payloads to reach the DOM sinks. Developers should be very cautious when using the default policy and preferably use it only for a transitional period until the offending code is refactored not to use the dangerous DOM sinks [17].

```
trustedTypes.createPolicy('default', {
  createScriptURL: (value, type, sink) => {
    return value +
      '?default-policy-used&type=' +
      encodeURIComponent(type) +
      '&sink=' +
      encodeURIComponent(sink);
  }
});
```

Listing 1.8: Creating a default policy [17]

1.2.5 Reviewability

Consider the process of security reviews for web applications, specifically reasoning about DOM based XSS. There are many tools and methodologies which can help reason about the application security, but there is no automated way that can assert the web application safety. This means that it is still necessary for security engeneers to manually review the implementation and look for potential vulnerabilities and analyze them.

When focusing on client side XSS, the engineer has to determine whether application uses dangerous DOM sinks, either implicitely and explicitely, and whether there is way for attacker to misuse them.

```
function setHtml(element, html) {
  element.innerHTML = html;
}
```

Listing 1.9: Possibly dangerous function

Is the function in the listing above safe? There is not enough information to answer this. The safety of the function depends on the context of how it is used. More generally, the safety of a function depends on both its direct and indirect callers, both present and future ones [3].

```
  function processHtml(html) {
    setHtml(document.body, html);
```

```
}

function processUserData(data) {
  log('Processing user data');
  // Is this safe? Can this call change "data.html"?
  someThirdPartyCall(data);
  processHtml(data.html);
}
```

Listing 1.10: Usage of the possibly dangerous function

Looking for the callers of the function can be difficult because of the dynamic nature of JavaScript. Also, JavaScript is a mutable language which makes it harder to reason about function calls, especially the third party ones.

When the application enforces Trusted Types, the engineer doesn't have to care about the dangerous functions and its callers. The focus of the security review shifts to reasoning about the creation of trusted values and policies. Once a trusted value is created, it is immutable and the policy which created it provides the security guarantees. When a trusted value reaches a sink, this guarantee still holds independently of how the value flew the callers. Consider the third party call in the listing 1.10 and assume *data.html* contains a TrustedHTML value. If a third party call modifies this value a violation is thrown when it is passed to a DOM sink.

1.2.6 Browser support and polyfill

Trusted Types are currently supported in Chromium family of browsers [22]. Developers creating Trusted Types compliant application should always check if Trusted Types API is available in the current execution context, which does not necessary need to be a browser. It is very common for nodeJS applications to pre render the client side code on the server to provide faster experience for the end users. This brings additional complexity and new attack vectors in forms of reflected XSS, various kinds of injection and more, which are out of Trusted Types scope.

Additional benefit of Trusted Types compliant applications is that all sinks are protected. The application can use a polyfill for browsers which do not support Trusted Types, maintaining the same security properties as in the browsers where they are supported [13].

There are multiple variants of the polyfill:

- Full – Defines the Trusted Types API, parses the *meta* tag from the HTML and enables the enforcement in the DOM.
- API only – Defines the Trusted Types API so you can use policies and create trusted values, but no enforcement rules are applied.

- Tiny – Polyfills only the most important part of the API surface with a single line of code for a minimal bundle size.

1.3 Motivation and background

Trusted Types provide opportunity to significantly reduce the risk of a client side XSS and has been proven in various projects or various scale [27] [15]. However, projects need to refactor parts of their code, which can be difficult, especially in the open source world where the software is composed by multiple dependencies which can't easily be modified. This presents a large barrier in Trusted Types adoption [27] with a "chicken and egg" problem. There is not enough pressure for library authors to migrate to Trusted Types because there is not is not enough usage. However, there is not enough usage because a lot of applications are prevented to migrate because their dependencies do not work with Trusted Types.

There is usually a knowledge gap between security engineers and software developers, the former focus on security, the latter on the application features. Trusted Types bridge this gap by providing secure by default software. The ideal scenario would be if the open source libraries used Trusted Types transparently to the application authors.

In this paper we try to analyze some of the most popular open source frameworks and libraries and show that there are workarounds for projects to use Trusted Types without too much difficulties. We want to implement some integrations and an example application to encourage application and framework authors to addopt Trusted Types to eradicate DOM based XSS.

Chapter 2

Trusted Types integration process

Integrating Trusted Types to target applications and libraries might seem as a complex task that requires good knowledge of the target inner workings. There is a small sample of already implemented integrations, which shows that the necessary code changes are relatively small [15]. Based on our experience, the integration does not require an exprteese of the projects inner workings neither. This experience is also supported by other integration authors [27]. Each integration is different, but on a high level they follow the same steps:

1. Locate all of the DOM sinks
2. Find the most suitable workaround for every sink found
3. Implement the integration and release a new version of the target

2.1 Locate all of the DOM sinks

Locating the sinks of the integration target is important for scoping the integration effort and the implementation afterwards. This task is complex since there is no bulletproof way of locating all of the sinks in a codebase. This is because JavaScript is a dynamic language and it is possible to access and set the sink values dynamically using the property element access.

Fortunately, there are a few methods and tools, which can help to catch most of the sinks:

1. Static search through the codebase
2. Static code analyzers
3. Using the target in an real world application

2.1.1 Static search through the codebase

This method is the simplest one and the least effective. Statically searching for sinks throughout the codebase produces many false positives and also false negatives. The former are produced for read only sink usage, the latter when actual sinks are missed due to implementation limitations. The output of the static search is usually cluttered with less important violations in tests and built tools, which you need to manually exclude from the search.

Nevertheless, this method is easy to reason about, fast to iterate and the final search results can provide a good estimate of the integration scope. This works well in practice since there is an assumption that the target source code is not malicious and doesn't actively use code patterns which are trying to hide or cause an XSS vulnerability.

There is not an actively maintained static search tool for finding DOM sinks. However, it is relatively easy to build a script, which uses the existing tools such as *grep* with a list of already known sinks [38].

2.1.2 Static code analyzers

A better approach at searching for the DOM sinks statically, is to search through the AST of the code. The quality of the output produced depends on the quality of the AST information. When the codebase is using TypeScript, the AST information is generally richer compared to codebases using JavaScript. One can then build and use tools like Tsec [43] which uses the compiler to parse the source code and create the AST to ultimately find the sinks in a more reliable manner and produces less false positives.

These tools have an advantage that they can be used to maintain the Trusted Types compatibility even after the violations are fixed. For example, they can be run in CI pipeline or their output can be leveraged by linters and other language plugin tools and the errors can be shown to the developers early on and directly in their IDE [44].

2.1.3 Using the target in a real world application

While static search through the codebase is fast and locates most of the sinks, it usually doesn't catch them all. If the integration target is a library, the integration author should verify the integration implementation on the applications using the target as a dependency. Also, having good test coverage in the target code greatly increases the chance that the integration is implemented correctly.

That said, finding a suitable application might be challenging and it may not be an ideal way to test all edge cases. For example, when implementing an integration to React, one can find lot of real world applications using React, but most of them are

already XSS free so you can only verify if the integration doesn't break these clients.

One recommendation for the clients are to use the the report only mode of Trusted Types CSP. This allows applications to migrate their code gradually and allows them to focus on application features.

Library authors need to test how the integration works when used with applications that uses the DOM sinks and now has to produce Trusted Types values. These are done best by creating an application from scratch by the integration author.

2.2 Find the most suitable workaround for every sink found

In this section, we assume that all of the sinks discussed produce Trusted Types violations. Note, that a sink can produce a Trusted Types violation be be provably safe. For example, this happens when a constant string is assigned to an innerHTML property of an DOM element.

Generally, there are three ways how to resolve a Trusted Types violation produced by a sink:

1. Refactor the code not to use the sink value
2. Wrap the value passed to the sink in a Trusted Types policy
3. Ensure Trusted value is not altered before reaching the sink

2.2.1 Refactor the code not to use the sink value

For some dangerous sinks, there is a safer alternative that can be used. For example, for non script elements, one can use 'element.innerText' instead of 'element.innerHTML'. Another way is to create DOM nodes manually and only append the generated elements to the target element as child.

This method is only available when there is a safer API alternative, which is often not the case and this solution is not applicable.

2.2.2 Wrap the value passed to the sink in a Trusted Types policy

When there is no way to avoid using the sink and the value is trusted, one has to use a Trusted Types policy to promote the trusted value to a Trusted Types instance. One should apply the Trusted Types policy where the trusted value is created, not where it is passed to a sink. For example, the author should promote a value to Trusted Type

immediately after sanitization or escaping. This way the immutability of Trusted Types can preserve the "trust" independently of how the value flows through code until it reaches the sink.

The easy part of this method is creating a wrapping a value inside a policy, but if the application or library used to modify this value it now needs to be refactored to readonly usage of these values (2.2.2).

2.2.3 Ensure Trusted value is not altered before reaching the sink

As we mentioned, Trusted Types instances are immutable values. Previously the DOM sinks accepted a string values so the application or library might be used to call string operations on the value. Such code was valid, but now the Trusted Types values do not have string methods defined and trying to call them will result in an error. Another problem is stringification which converts the Trusted Types instance to a string, which then throws an error when the value is passed to the sink.

The integration author needs to refactor the library or application to prevent modifying the Trusted values to preserve the trust guarantees secured by Trusted Types.

2.3 Implementing the integration and releasing a new version of the target

Implementing the integration and releasing a new version of the target is undoubtedly an important part of Trusted Types integration. However, this can take long time for multiple reasons, which are described in separate sections:

1. Reasoning about the integration
2. Trusted Types compatibility in dependencies
3. Knowledge required for the integration author

2.3.1 Reasoning about the integration

Proving that the integration is correct means to determine if all sinks have been located and properly addressed. This is generally infeasible or impossible to determine. Project usually look at patches empirically. If the integration looks correct and is properly tested then it is safe to assume that the integration is indeed correct. This is especially true when the integration is tested by large scale organizations by lot of services.

That being said, Trusted Types enforcement is a breaking change and project should make this change opt-in or release a new version with breaking changes [7]. If the integration is turned on by default when Trusted Types are available in the browser, the target is risking breaking existing applications [11].

Releasing an opt-in change might be problematic if the target is not configurable. This can result in the integration being put behind a feature flag which hurts the adoption [32].

2.3.2 Trusted Types compatibility in dependencies

Implementing the integration in large projects, which consists of many dependencies can bring a lot of overhead, because to be fully Trusted Types compliant one must ensure that all of the dependencies are Trusted Types complaint as well.

When there is non compliant dependency, one has multiple options:

- Implement the integration for the dependency - This option leads to recursive integrations and has all the problems already mentioned and can possible lead to many more integrations.
- Find an alternative dependency - This option is often impossible as a viable alternative might not exist and projects might not want to use an alternative only because of Trusted Types compliance.
- Use Trusted Types default policy - This option should only be used by end applications and is more complex. The application is not fully Trusted Types compliant and it can also lead to a reduced performance.

2.3.3 Knowledge required for the integration author

The integration author can neither be a security engineer familiar with Trusted Types and neither a part of the engineering team of the target familiar with the target code. This means that the author might not be fully familiar with both of the technologies and the respective teams, which can result in both:

- Increased propability of a bug in implementation
- Harder and longer review, since the reviewers might also lack the information about Trusted Types or simply ignore the PR due to other priorities

Chapter 3

Preprocessor integrations

It is very common for web applications to depend on multiple code preprocssing tools which can perform many different things. For example, one can consider TypeScript compiler a code preprocessor which compiles TypeScript code to JavaScript. One of the most notorious code preprocessors is Babel, which takes a modern JavaScript code and transpiles it into older versions that are then compatible with a wide range of browsers and their versions. However, the biggest group of code preprocessors are bundlers which simplify developer experience by providing advanced development features such as hot reloading, debugging and source map support.

These tools are essential for web application developers and are usually configured declaratively and abstracted away from the application authors. Unfortunately, these transformations might produce non Trusted Types compliant code. To achieve Trusted Types compliance in frameworks and applications, one must ensure that the resulting code from preprocessing tools is Trusted Types compliant or implement the Trusted Types integration themselves.

There are a lot of preprocessors which do not affect the Trusted Type compliance of a code. It is hard to formally define this group, but these are usually the code transformations which do not change the semantics of the code. For example:

- TypeScript – TypeScript compiler transforms the TypeScript sources to equivalent code written in JavaScript by mostly removing the type annotations. Such transformation yields semantically equivalent code.

- Transformation to older JavaScript standard – One of the most common functionality of Babel is to transpile code written in modern JavaScript language to older standard compatible with wide range of browsers and browser versions. Many of these transformations are solved with polyfills or simple AST replacements but the code remains semantically the same.

- Minification and obfuscation – The purpose of the code minification is to reduce

the overall bundle size that needs to be sent by the server to the clients browser. In practice this includes removing dead code, changing the names of the functions, shortening expressions and statements, however the minified code is functionally equivalent to the non minified one.

There are many Trusted Types compliant preprocessors which work with Trusted Types out of the box. Unfortunately, there are also tools and preprocessors which produce non Trusted Types compliant code for which Trusted Types integration is needed.

3.1 Babel

Babel is an extremely large collection of tools and plugins for preprocessing source code. For this paper, the most interesting feature of Babel is JSX transformation. JSX is an XML-like syntax extension to ECMAScript without any defined semantics. It is intended to be used by preprocessors to transform the JSX markup into standard JavaScript. These preprocessors provide the semantics the JSX on its own does not have.

The JSX was originally designed to simplify the syntax for React applications by allowing mixing HTML, JavaScript and CSS all in the same file. However, the specification [23] is generic and can be used for multiple use cases and not only strictly UI related.

3.1.1 Solid.js JSX preprocessor

One of these non React JSX use case is the JSX preprocessing inside solid.js framework (4.3). This framework on the surface looks like React as it is component oriented, uses the JSX to for component code and supports native APIs which resemble the React hooks API. The important fact is that the translated JSX is very different under the hood. React translates the JSX to React.createElement calls but Solid.js translates the JSX markup to native HTML templates. The framework differences are not that important for this paper. However, both of them use Babel to transform the easier to more convenient JSX syntax to JavaScript compatible code. You can see the transformation in action in the code listings below (generated using Solid.js playground [29]).

```
import { createSignal, splitProps } from "solid-js";

export function Counter(props) {
  const [local] = splitProps(props, ["ref"]);
```

```
  const [count, setCount] = createSignal(0);
  const increment = () => setCount(count() + 1);

  return (
    <button ref={local.ref} type="button" onClick={increment}>
      {count()}
    </button>
  );
}
```

Listing 3.1: Example of a component in Solid.js using JSX

```
import { template, delegateEvents, insert } from 'solid-js/web';
import { splitProps, createSignal } from 'solid-js';

const _tmpl$ = template(`<button type="button"></button>`, 2);
function Counter(props) {
  const [local] = splitProps(props, ["ref"]);
  const [count, setCount] = createSignal(0);

  const increment = () => setCount(count() + 1);

  return (() => {
    const _el$ = _tmpl$.cloneNode(true);

    _el$.$$click = increment;
    const _ref$ = local.ref;
    typeof _ref$ === "function" ? _ref$(_el$) : local.ref = _el$;

    insert(_el$, count);

    return _el$;
  })();
}

delegateEvents(["click"]);

export { Counter };
```

Listing 3.2: Example of a Solid.js component after Babel transformation

The transformed Solid.js code uses template function (imported from *solid-js/web*). This function internally uses *HTMLTemplateElement.innerHTML* property when creating the template. This triggers a Trusted Types violation when the code is executed in the browser. The solution is to create a Trusted Types policy wrapping the content assigned to innerHTML property. This is secure, because the JSX transformation

only creates the templates from statically known HTML. All dynamic and interpolated markup is rendered using JavaScript without using any dangerous sinks.

```
// Example input 1
let dynamic = "<img src=x onerror='alert(1)'>"
return (
  <iframe srcdoc={dynamic}></iframe>
);

// Example output 1
const _tmpl$ = template(`<iframe srcdoc="<img src=x onerror='alert(1)
    '>"></iframe>`, 3);

// Example input 2
let dynamic = "<img src=x onerror='alert(1)'>"
dynamic += '<br />'
return (
  <iframe srcdoc={dynamic}></iframe>
);

// Example output 2
const _tmpl$ = template(`<iframe></iframe>`, 2);

// Example input 3
<form action="/action_page.php">
  <input type="text" id="fname" value={name()} />
  <input type="text" id="lname" value={lname()} />
  <input type="submit" value="Submit" />
</form>

// Example output 3
const _tmpl$ = template(`<form action="/action_page.php"><input type="
    text" id="fname"><input type="text" id="lname"><input type="submit
    " value="Submit"></form>`, 5);
```

Listing 3.3: Examples of JSX transformations

The JSX preprocessing is able to ensure only statically known JSX values are passed to the *template* function. These statically known values are coming from the source code written by the developer, so this code is implicetelly trusted. Any dynamic properties and attributes are set when the component renders and is not part of the generated template calls.

3.2 Bundlers

Bundlers deal with many different tasks such as code minification and obfuscation, loading different file types, bundling all of the source files into big chunks, hot reloading in development and more.

Many of the bundler responsibilities are Trusted Types compliant out of the box, however many of the development only features break when Trusted Types are enforced. Usually bundlers include a development server which injects some markup into DOM to provide better developer experience for the application authors. Common examples include hot reloading changed parts of the application or displaying error details in an overlay widget.

Fortunately, Trusted Types are already supported in Webpack (starting from version 5), which is the most used bundler at time of writing. However, there are some new promising ones which provide better performance or use ES modules which leads to simpler architecture and more performant design.

3.2.1 Vite

Vite is one of the modern bundlers which serves the source files via native ES modules which have many built in features and extremely fast and reliable hot module replacement (HMR) for development. It also provides a simple way to bundle production code using another common bundler called Rollup.

Vite is especially interesting to us, because it is a preferred bundler for creating applications using solid.js framework. To support development of solid applications, we needed to create a Trusted Types integration for Vite.

We followed the integration process from chapter (2) and have identified three places which cause Trusted Types violations. These can be categorized into:

- Creation of style elements – Internally, Vite used *innerHTML* of an HTML style element to create apply styles to the DOM. These two occurrences can be replaced with a safer alternative using *textContent* which does not trigger a Trusted Types violation, but works for CSS stylesheet creation.

```
if (!style) {
  style = document.createElement('style')
  style.setAttribute('type', 'text/css')
  style.innerHTML = content
  document.head.appendChild(style)
} else {
  style.innerHTML = content
}
```

Listing 3.4: Creation of style elements using innerHTML in Vite [46]

- Showing error overlay – Vite supports HMR during development and part of this feature is to display error overlay when there is an error triggered by the development server. This usually happens when there is an syntax error in the code. The overlay widget uses *innerHTML* property to inject the overlay HTML markup on top of the client's web page. The solution in this case was to introduce a Trusted Types policy to wrap the overlay code inside Trusted Types policy. Alternative solution would be to to create the overlay markup dynamically using *document.createElement*.

  In the future, the Trusted Types API might provide support for constructing trusted values from string constants via template literals, but this is not yet supported.

```
export class ErrorOverlay extends HTMLElement {
  root: ShadowRoot

  constructor(err: ErrorPayload['err']) {
    super()
    this.root = this.attachShadow({ mode: 'open' })
    this.root.innerHTML = template
    (further lines omitted for brevity...)
```

Listing 3.5: Creation of error overlay using innerHTML property [45]

```
export class ErrorOverlay extends HTMLElement {
  root: ShadowRoot

  constructor(err: ErrorPayload['err']) {
    super()

    let policy
    if (window.trustedTypes) {
      policy = window.trustedTypes.createPolicy('vite-overlay', {
        createHTML: (s) => s
      })
    }

    this.root = this.attachShadow({ mode: 'open' })
    this.root.innerHTML = policy
      ? (policy.createHTML(template) as any)
      : template
```

```
    (further lines omitted for brevity...)
```

Listing 3.6: Creation of error overlay using Trusted Types policy [39]

Chapter 4

Integrations into web frameworks and libraries

Web frameworks and libraries is a software that is designed to support development of web applications and services. They try to solve common problems faced in web development, such as building user interfaces, testing, building and bundling the application. Typical web application consists of numerous libraries and software frameworks which together create the resulting web application.

In this chapter we describe the frameworks we examined and integrations we implemented. We document each unique properties of the integration, sinks found and the respective solutions implemented.

4.1 Next.js integration

Next.js is one of the most popular frameworks for building web applications. The framework is build upon the React library which is the most used library as of 2021 [24]. Parts of a Next.js application can be rendered statically, server side or fully client side on a page by page basis. Next.js is thus not only about the client side code, but it can also handle server side logic which opens up different means of attacks such as reflected XSS, SQL injections and more.

Next.js was our initial choice for Trusted Types integration, because of the large impact this integration would have. The framework itself seemed interested in the integration of Trusted Types for a longer time [42].

We started working on the integration and created a basic Next.js application for testing. We used a local version of Next.js as a dependency for our application. The example application was not working when Trusted Types were enforced and we needed to make some changes in the Next.js. We ended up with a working version of the integration which supported the application in dev mode with Trusted Types under

enforcement mode. We managed to accomplish this with one simply Trusted Types policy in a short timeframe.

```
let policy;

const whitelistAll = (str) => str;

// The policy getter is a private part of the module
// and cannot be used directly.
const getOrCreatePolicy = () => {
  if (policy) return policy;

  policy = window.trustedTypes?.createPolicy('next', {
    createHTML: whitelistAll('createHTML'),
    createScript: whitelistAll('createScript'),
    createScriptURL: whitelistAll('createScriptURL'),
  });
  return policy;
};

export const __unsafeAllowHtml = (html) => getOrCreatePolicy()?.
   createHTML(html) ?? html;

export const __unsafeAllowScriptUrl = (scriptUrl) => getOrCreatePolicy
   ()?.createScriptURL(scriptUrl) ?? scriptUrl;

export const __unsafeAllowScript = (script) => getOrCreatePolicy()?.
   createScript(script) ?? script;
```

Listing 4.1: Example of Next.js Trusted Types API

The fixes needed were small and the Trusted Types API specific code was encapsulated in a single small module. That said, the implementation was only a proof of concept. However, we found out that there are other engeneers working on this integration and we decided not pursue this project further. Instead we shifted our focus to a different projects and integrations.

4.1.1 Fixing violations reported by Tsec

Tsec found 8 violations [41] inside Next.js sources. Out of these 7 were indeed Trusted Types violations that needed to be fixed. Some of these could be fixed simply on a type system level since they expected a value from the user. The others needed to be explicitely allowed through a policy. The implementation for this proof of concept can be found on github [40].

Since our utmost goal was to find the sinks and create a prototype for the integration we wrapped all of these values in Trusted Types objects. This was to be revisited in the future.

4.1.2 Fixing the dev mode of an example application

Fixing the violations found by Tsec was not enough and the application still would not work under Trusted Types enforcement. This was caused by a webpack plugin used in one of the Next.js dependencies which used eval internally. The workaround for this was to use a default policy and allow all eval calls. The proper solution would be to fix the eval issue in the webpack plugin via a policy.

Apart from this, there was another violation that was triggered caused by application during hot reload (2). Tsec did not to catch this problem, since the violation came from a JavaScript file where the AST information was limited.

4.2 Create React App integration

Create React App (CRA) is a CLI and an officially recommended way to create single-page React applications. It offers an easy React application setup with no configuration. The source code of this tool does not depend on React directly. It is only used to generate the project files based on a hard coded template and then it installs the latest version of React and other necessary dependencies.

CRA was a second project we wanted to integrate Trusted Types to. Our goal was to make sure the generated project is Trusted Types compatible.

4.2.1 Using Trusted Types compatible version of React

To accomplish this, we would need to change the implementation of CRA to install Trusted Types compatible version of React. Unfortunately, such version of React is implemented only under a feature flag which needs to be turned on at build time. The published version of React contains has feature flag turned off. This means that in order to use the Trusted Types compatible version of React you need edit the React source code, turn on the feature flag and then build the framework yourself. You can then use this version of React as a dependency in your project generated by CRA.

Implementing this is non trivial, since it requires knowledge about React. More importantly though, this is harder to maintain for the application authors since you need to keep up with the new releases of React manually.

4.2.2 Using Trusted Types compliant version of Webpack

CRA internally uses webpack 5 to provide convenient development features and transfrom and bundle application for production. Some of these features, especially hot module reload breaks under Trusted Types in enforcement mode. Gladly, webpack can be configured to be Trusted Types compliant by a small configuration change [30].

The problem with CRA is that the webpack configuration is hidden from the user. Unfortunately, there is no way how to override this configuration manually. This means that there is not a simple way how to enable the Trusted Types integration. The workaround is to spy on imported JavaScript modules and change what their content. This pattern is often used when mocking or spying in unit tests. However, it is also a suitable solution for this case [2].

CRA team is reluctant to provide a convenient way to edit or override the webpack configuration, since the provided defaults are good enough for the majority of users.

```
// File 'scripts/start.js'
const rewire = require('rewire')
const defaults = rewire('react-scripts/scripts/start.js')
const webpackConfig = require('react-scripts/config/webpack.config')

// In order to override the webpack configuration without ejecting the
    create-react-app
defaults.__set__('configFactory', (webpackEnv) => {
  let config = webpackConfig(webpackEnv)

  // Customize the webpack configuration here, for reference I have
   updated webpack externals field
  config.output.trustedTypes = {
    policyName: 'webpack-policy',
  }

  return config
})
```

Listing 4.2: Script to start React application with Trusted Types enabled in webpack

The application is then started simply by running this script using *node* environment.

```
node ./scripts/start
```

Listing 4.3: Starting the CRA application

Another option is to use the *eject* command from CRA. This is a one way operation and it unwraps all of the hidden configuration and creates these files in the project.

You can then edit the webpack configuration which is now part of the project. This is not recommended and should be used only when other attempts fail. The generated webpack configuration is pretty complex and updating it in the future might not be trivial.

4.3 Solid.js

Solid.js is a simple, modern and reactive framework for building user interfaces. Framework syntax is largely inspired by React, but the internals are different. JSX internally makes use of HTML template elements. Both frameworks are component oriented. The main difference is that React uses a concept called *virtual DOM* in which the UI representation is kept in memory and synced with the "real" DOM. Solid.js does not use virtual DOM and performs all UI updates directly.

We have already described the Solid.js JSX transformation in the preprocessor chapter (3.1.1) where we implemented a Trusted Types integration. We wanted to test the changes on a real world project. Fortunately, there is fully fledged fullstack application which we used [5]. We made a few additional changes, specifically:

1. Used custom version of Vite and Solid.js
2. Added Trusted Types policies
3. Implemented e2e tests

Finally, we documented all the necessary changes needed to build the project and try the application with all the integrated projects [35].

4.3.1 Custom Vite and Solid.js

The real world project uses Rollup as a bundler, but we decided to use replace Rollup with Vite, because Vite is the preferred bundler for developing Solid.js application and we also wanted to test that our integration works properly.

The only changes we needed to implement were to use our custom version of Vite and rename the file extension for all source files from *.js* to *.jsx* in order for Vite to correctly pre process the JSX. We also used the custom version of Solid.js to generate Trusted Types compliant code after JSX transformation. You can see the code difference for these changes in [37].

4.3.2 Adding Trusted Types policies

After all of the dependencies were ready, we needed to enable the Trusted Types enforcement. We used a HTML meta tag and enabled all of the policies needed.

Because hot reloading in Vite reloads the full module, we had to use *'allow-duplicates'* to allow recreating the policy when it's module is reloaded. Having this is not be needed for production.

```
<meta
  http-equiv="Content-Security-Policy"
  content="require-trusted-types-for 'script'; trusted-types solid-dom
   -expressions trusted-article vite-overlay 'allow-duplicates';"
/>
```

Listing 4.4: Creation of style elements using innerHTML in Vite [46]

We also needed to create a Trusted Types policy for the application itself. One of the source files uses a third party API to load a HTML content and assigned that into *innerHTML* property. This could easily lead to an XSS if the API was malicious or got hacked. This means that Trusted Types helped find and prevent a possible attack vector. Since the application used this only for demonstration purposes we decided to allow this pattern via a policy.

You can see these changes in [31].

4.3.3 Implemented e2e tests

After making sure the application works as intended both in development and production, we decided to create e2e tests to verify this. We chose Cypress as the testing framework and created our own testing plugin which is described in its own chapter (5.1). You can see the implementation of these tests in [36].

Chapter 5

Testing frameworks integrations

Trusted Types are agnostic to the testing framework used and the type of tests. It is very common for web application to have a combination of unit and end to end tests. The former are used to smaller parts of application and typically run in nodeJS environment. The latter usually test the whole application in browser environment and test the application features from the user perspective.

5.1 Cypress Trusted Types plugin

Cypress is one of the most popular frameworks for end to end testing of web applications [9]. It enjoys a rich ecosystem of plugins and supporting software. It runs the tests in real browsers and is fast and reliable due to its unique architecture. Developers can test the Trusted Types compliant applications in Cypress out of the box, because most of the Cypress commands only query the DOM which does not produce Trusted Types violations.

Even though Cypress supports Trusted Types out of the box, there are a few nuances the developer has to overcome to be able to test the application and Trusted Types violations. For this reason, we have created a Cypress plugin which abstracts the low level details and provides a nicer API for the developers to use.

5.1.1 Removed CSP header

Cypress removes the CSP header sent by the application server in order to load the application in an iframe, which could otherwise be prevented by a *scriptSrc* CSP directive. There is a workaround for now, which is to intercept the request of the initial HTML application payload and copy the CSP policy from the response headers to the response body inside a *meta* tag. [4].

This is tedious for the developers, so we have created a custom command in our plugin which does exactly this.

```
// NOTE: Based on https://glebbahmutov.com/blog/testing-csp-almost/
Cypress.Commands.add('enableCspThroughMetaTag', (options) => {
  const { urlPattern } = options ?? {};

  // Intercept all requests by default
  cy.intercept(urlPattern ?? '**/*', (req) => {
    return req.reply((res) => {
      const csp = res.headers['content-security-policy'];
      if (!csp || typeof res.body !== 'string') return;

      res.body = res.body
        .replace(
          new RegExp('<head>([\\s\\S]*)</head>'),
          new RegExp(`<head><meta http-equiv="Content-Security-Policy"
    content="${csp}">$1</head>`).toString()
        )
        // The following are needed because the regex replacement
   above inserts some characters
        .replace('/<head>', '<head>')
        .replace('<\\/head>/', '</head>');
    });
  }).as('enableCspThroughMetaTag');
});
```

Listing 5.1: Intercept requests and enable CSP header inside via meta tag

5.1.2 Testing the violations

While it is easy to test that the Trusted Types are supported (5.2) it is harder to test whether some part of the code triggered Trusted Types violation. The reason is that the violation does not produce any user visible behaviour because the DOM is unchanged and uncaught exception is thrown and Cypress automatically fails the test. The developer needs to listen to *uncaught:exception* handler from Cypress and explicitely recognize the Trusted Types violation based on the error thrown and tell Cypress that this error is intended so it doesn't fail the test.

```
it('supports TT', () => {
  expect(window.trustedTypes).not.to.be.undefined;
});
```

Listing 5.2: Test Trusted Types support

To simplify this low level handling for the developers we have created a custom command which recognizes Trusted Types violations and remembers them for the lifetime of the current test so they can be asserted later on.

```
Cypress.Commands.add('catchTrustedTypesViolations', () => {
  if (catchTrustedTypesViolationsEnabled) return;
  catchTrustedTypesViolationsEnabled = true;
  cy.clearTrustedTypesViolations();

  // https://docs.cypress.io/api/events/catalog-of-events#To-catch-a-
   single-uncaught-exception
  cy.on('uncaught:exception', (err) => {
    const type = violationTypes.find((type) => err.message.includes(
   quote(type)));
    if (type) {
      trustedTypesViolations.push({
        type,
        message: extractViolationMessage(err),
        error: err,
      });
      // Return false to prevent the error from failing this test
      return false;
    }
  });
});
```

Listing 5.3: Custom command to catch Trusted Types violations

The final part of the plugin is the API to assert the caught violations. There are multiple commands which assert that certain types of violations happened. An example of a full Cypress test which asserts the violation is listed in (5.4).

```
it('assertTrustedTypesViolations', () => {
  cy.contains('unsafe html').click();
  cy.contains('unsafe html').click();
  cy.contains('duplicate policy').click();
  cy.contains('unsafe script').click();

  cy.assertTrustedTypesViolations([
    {
      type: 'TrustedHTML',
      message:
        "Failed to set the 'srcdoc' property on 'HTMLIFrameElement':
   This document requires 'TrustedHTML' assignment.",
    },
    {}, // No assertion is made for this violation
    {
      type: 'TrustedTypePolicyFactory',
      message: `Failed to execute 'createPolicy' on '
   TrustedTypePolicyFactory': Policy with name "my-policy" already
```

```
    exists.‘,
     },
     { type: 'TrustedScript' },
  ]);
});
```

Listing 5.4: Example Trusted Types violation test

5.1.3 Releasing the plugin

The plugin is implemented in a standalone repository [33] and published as an npm package [34] for anyone to use. Together with the plugin API there is an example application and tests which showcase the plugin in action. The plugin is to be added to the cypress community list of plugins for increased visibility.

Chapter 6

Conclusion

We showed the support of Trusted Types in various open source technologies and discussed their integrations. We support the claims from the empirical research for web frameworks [27].

We discussed the Trusted Types integrations to various libraries and supporting software. We see a lot of opportunity for further research, integrations and tools to be created to make Trusted Types usage easier and more widespread.

We implemented a Trusted Types integration into Solid.js together with an example application written in this framework. We showed how integration can cascade as we needed to implement minor changes in multiple packages. The final implementation was fairly small and not that difficult. We also implemented Cypress end to end tests for the application showing that testing is not a problem with Trusted Types either with a testing plugin we created.

As a next step we would like to merge our Trusted Types Solid.js integration into the framework itself as it currently lives only on our forked repositories. It would be nice to see the integration working on multiple real life applications which run also in production. We would like to see more web platform primitives to make Trusted Types migration simpler, for example via HTMLSanitizer [12]. We would like to contribute with more open source integrations and tooling and use our knowledge to help other integration authors. All of our work is open sourced and available for anyone to see. All repositories we used during the research and implementation are used as submodules in the main repository.

Unfortunately, currently we do not see a strong demand in the open source community for Trusted Types compliant applications and libaries, but we hope this will gradually improve. We hope that our work will motivate other people to create more integrations and that together we will make the web a safe place.

Bibliography

[1] Anirudh Anand. Xss dom source and sink definition, February 2019. https://blog.0daylabs.com/2019/02/24/learning-DomXSS-with-DomGoat/#source.

[2] ashvin777. Modify webpack configuration in cra (issue comment). https://github.com/facebook/create-react-app/issues/10307#issuecomment-898889701.

[3] Multiple authors. Trusted types design history, September 2019. https://github.com/w3c/webappsec-trusted-types/wiki/design-history/8a57f5cb1a7773cfa512943e9b7560813d61a83f#why-client-side-trusted-types.

[4] Gleb Bahmutov. Figure out how to load site with content-security-policy without stripping header (github issue). https://github.com/cypress-io/cypress/issues/1030#.

[5] Ryan Carniato. Solid real world project. https://github.com/solidjs/solid-realworld.

[6] Cloudflare. What is cross-site scripting. https://www.cloudflare.com/learning/security/threats/cross-site-scripting/.

[7] cure53. Dompurify 2.0.0 release. https://github.com/cure53/DOMPurify/releases/tag/2.0.0.

[8] MDN Web Docs. Content security policy (csp). https://developer.mozilla.org/en-US/docs/Web/HTTP/CSP.

[9] Sacha Greif and team. State of js 2021 - testing. https://2021.stateofjs.com/en-US/libraries/testing.

[10] Imperva. Reflected cross site scripting (xss) attacks. https://www.imperva.com/learn/application-security/reflected-xss-attacks/#:~:text=Reflected%20XSS%20attacks%2C%20also%20known,enables%20execution%20of%20malicious%20scripts.

[11] Uzlopak (DOMPurify issue #361). Trusted types breaking applications using dompurify in chrome 77. https://github.com/cure53/DOMPurify/issues/361.

[12] Krzysztof Kotowicz. Trusted types - mid 2021 report. https://storage.googleapis.com/pub-tools-public-publication-data/pdf/2cbfffc0943dabf34c499f786080ffa2cda9cb4c.pdf.

[13] Krzysztof Kotowicz. Trusted types increase security also in browsers without tt support. https://github.com/w3c/webappsec-trusted-types/wiki/FAQ#do-trusted-types-address-dom-xss-only-in-browsers-supporting-trusted-types.

[14] Krzysztof Kotowicz. Trusted types background, December 2021. https://github.com/w3c/webappsec-trusted-types/wiki/Effects-of-deploying-Trusted-Types-on-browser-extension-developers/c110df6329c46363c65e3c3de4ef24c5fbcecee9#background.

[15] Krzysztof Kotowicz. Trusted types integrations, November 2021. https://github.com/w3c/webappsec-trusted-types/wiki/Integrations/3e5ff5b7613f18c15a1895129fec063d5491ff83.

[16] Krzysztof Kotowicz. Trusted types resources, July 2021. https://github.com/w3c/webappsec-trusted-types/wiki/Resources/22dcd3a4cc55fae2e1706b47f9d26feb2aacaefb.

[17] Krzysztof Kotowicz (Google LLC) and Mike West (Google LLC). Default policy. https://w3c.github.io/webappsec-trusted-types/dist/spec/#default-policy-hdr.

[18] Krzysztof Kotowicz (Google LLC) and Mike West (Google LLC). Trusted types goals. https://w3c.github.io/webappsec-trusted-types/dist/spec/#goals.

[19] Krzysztof Kotowicz (Google LLC) and Mike West (Google LLC). Trusted types goals. https://w3c.github.io/webappsec-trusted-types/dist/spec/#non-goals.

[20] MDN. Csp: require-trusted-types-for. https://developer.mozilla.org/en-US/docs/Web/HTTP/Headers/Content-Security-Policy/require-trusted-types-for.

[21] MDN. Csp: trusted-types. https://developer.mozilla.org/en-US/docs/Web/HTTP/Headers/Content-Security-Policy/trusted-types.

[22] MDN. Trusted types compatibility. https://developer.mozilla.org/en-US/docs/Web/API/Trusted_Types_API#browser_compatibility.

[23] Inc. Meta Platforms. Jsx specification. https://facebook.github.io/jsx/.

[24] Stack overflow insights. Web frameworks statistics for 2021, 2021. https://insights.stackoverflow.com/survey/2021#section-most-popular-technologies-web-frameworks.

[25] OWASP. Cross site scripting prevention cheat sheet. https://cheatsheetseries.owasp.org/cheatsheets/Cross_Site_Scripting_Prevention_Cheat_Sheet.html.

[26] OWASP. Dom based xss. https://owasp.org/www-community/attacks/DOM_Based_XSS.

[27] Krzysztof Kotowicz Pei Wang, Bjarki Ágúst Guðmundsson. Adopting trusted types in production web frameworks to prevent dom-based cross-site scripting: A case study. https://storage.googleapis.com/pub-tools-public-publication-data/pdf/9c56e856f0ea76454f01cabec9959f7c5b31b285.pdf.

[28] Portswigger. Dom-based xss. https://portswigger.net/web-security/cross-site-scripting/dom-based.

[29] Solid.js team. Solid.js playground. https://playground.solidjs.com/.

[30] Webpack team. Webpack trusted types documentation. https://webpack.js.org/configuration/output/#outputtrustedtypes.

[31] Emanuel Tesar. Add trusted types policies for solid real worl project. https://github.com/Siegrift/solid-realworld/commit/4e0ace099712e4dd107d4cf1c817eb6686cd8a1c.

[32] Emanuel Tesar. Add trusted types to react on client side pr. https://github.com/facebook/react/pull/16157.

[33] Emanuel Tesar. cypress-trusted-types (github). https://github.com/Siegrift/cypress-trusted-types.

[34] Emanuel Tesar. cypress-trusted-types (npm). https://www.npmjs.com/package/@siegrift/cypress-trusted-types.

[35] Emanuel Tesar. Document trusted types integration for solid real worl project. https://github.com/Siegrift/solid-realworld/commit/e72662cd5b834b749e25cb08cab346c2f1efa926.

[36] Emanuel Tesar. Implement e2e tests for trusted types integration for solid real worl project. https://github.com/Siegrift/solid-realworld/commit/3de79726ed0799c3b1e908fcb9d263cff4b301be.

[37] Emanuel Tesar. Replace rollup with vite in solid real worl project. https://github.com/Siegrift/solid-realworld/commit/c087818effaf0de76bd7546800f790057de8a52d.

[38] Emanuel Tesar. Static xss code scanner. https://github.com/Siegrift/xss-sink-finder/tree/5c98c3e80e16c15bda2ccc0609288cc536601a83.

[39] Emanuel Tesar. Vite usage of trusted types policy to create error overlay. https://github.com/Siegrift/vite/blob/8134f9244a5916a090a55e5c5c690061c0c36633/packages/vite/src/client/overlay.ts#L125.

[40] Emanuel Tesar. Fix tsec violations in next.js, October 2021. https://github.com/Siegrift/next.js/commit/a45df82d5e86f7cbaa9f0e327f1b4ea0e956fbdf.

[41] Emanuel Tesar. Tsec output for next.js, October 2021. https://github.com/Siegrift/next.js/blob/a45df82d5e86f7cbaa9f0e327f1b4ea0e956fbdf/tsec-packages-next-output.

[42] TyMick. Add trusted types policy (next.js pr), 2020. https://github.com/vercel/next.js/pull/13509.

[43] Google (unofficial product). Tsec. https://github.com/google/tsec/commit/a57933da74af5aef5fd2342f207b03c4fe305003.

[44] Google (unofficial product). Tsec language service plugin documentation. https://github.com/google/tsec/tree/a57933da74af5aef5fd2342f207b03c4fe305003#language-service-plugin.

[45] Vite. Vite usage of innerhtml to create error overlay. https://github.com/Siegrift/vite/blob/788d2ec1dc9853be4ecdef67d1a458a2b46ec9bf/packages/vite/src/client/overlay.ts#L124.

[46] Vite. Vite usage of innerhtml to create style elements. https://github.com/Siegrift/vite/blob/788d2ec1dc9853be4ecdef67d1a458a2b46ec9bf/packages/vite/src/client/client.ts#L259.