Generation of TypeScript Declaration Files from JavaScript Code

Fernando Cristiani Hochschule Karlsruhe Karlsruhe, Germany fernando.cristiani@hs-karlsruhe.de Peter Thiemann Albert-Ludwigs-Universität Freiburg Freiburg, Germany thiemann@informatik.uni-freiburg.de

Abstract

Developers are starting to write large and complex applications in TypeScript, a typed dialect of JavaScript. TypeScript applications integrate JavaScript libraries via typed descriptions of their APIs called declaration files. DefinitelyTyped is the standard public repository for these files. The repository is populated and maintained manually by volunteers, which is error-prone and time consuming. Discrepancies between a declaration file and the JavaScript implementation lead to incorrect feedback from the TypeScript IDE and, thus, to incorrect uses of the underlying JavaScript library.

This work presents dts-generate, a tool that generates TypeScript declaration files for JavaScript libraries uploaded to the NPM registry. It extracts code examples from the documentation written by the developer, executes the library driven by the examples, gathers run-time information, and generates a declaration file based on this information. To evaluate the tool, 249 declaration files were generated directly from an NPM module and 111 of these were compared with the corresponding declaration file provided on DefinitelyTyped. All these files either exhibited no differences at all or differences that can be resolved by extending the developer-provided examples.

CCS Concepts: • Software and its engineering \rightarrow *General programming languages*; Development frameworks and environments.

Keywords: JavaScript, TypeScript, Dynamic Analysis, Declaration Files

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1 Introduction

JavaScript is the most popular language for writing web applications [7]. It is also increasingly used for back-end applications running in NodeJS, a JavaScript-based server-side platform. JavaScript is appealing to developers because its forgiving dynamic typing enables them to create simple pieces of code very quickly and proceed on a trial-and-error basis.

JavaScript was never intended to be more than a scripting language and, thus, lacks features for maintaining and evolving large codebases. However, nowadays developers create large and complex applications in JavaScript. Mistakes such as mistyped property names and misunderstood or unexpected type coercions cause developers to spend a significant amount of time in debugging. There is ample evidence for such mishaps. For example, a JavaScript code blog¹ collects experiences from developers facing unexpected situations while programming in JavaScript. Listing ¹ exposes some of these unintuitive JavaScript behaviors.

The cognitive load produced by these behaviors is mitigated in languages that use build tools based on type information. This insight motivated the creation of TypeScript, a superset of JavaScript with expressive type annotations [15]. It has become a widely used alternative among JavaScript developers, because it incorporates features that are helpful for developing and maintaining large applications [6]. TypeScript enables the early detection of several kinds of run-time errors and the integration of code intelligence tools like autocompletion in an IDE.

Despite the advantages, it is unrealistic to expect the world to switch to TypeScript in a day. Therefore, existing JavaScript libraries can be used in a TypeScript project by adding a declaration file that describes the library's API in terms of types. The DefinitelyTyped repository [3] has been created as a community effort to collect declaration files for popular JavaScript libraries. At the time of writing it contains declaration files for more than 6000 libraries.

¹https://wtfjs.com

Unfortunately, creation and maintenance of most declaration files in DefinitelyTyped is conducted manually, which is time consuming and error-prone. Errors are aggravated because TypeScript takes a declaration file at face value. Discrepancies between declaration and implementing JavaScript library are not detected at compile time and result in incorrect behavior (e.g., autocompletion hints) of the IDE. As TypeScript does not perform any run-time checking of types, these discrepancies can lead to unexpected behavior and crashes. This kind of experience can lead to longish debugging sessions, developer frustration, and decreasing confidence in the tool chain.

1.1 Approach

We aim to improve on this situation by providing a tool that generates TypeScript declaration files automatically. To do so, we rely on run-time information gathered from the examples provided by the developer as part of the documentation of a library. If these examples are sufficiently rich, then our toolchain can generate high-quality declaration files for the library. This way we take advantage of best practices in the dynamic languages community which favors examples and tests over writing out type signatures.

As an example, consider the NPM² module abs that "computes the absolute path of an input". Its documentation contains the following three examples³.

```
const abs = require("abs");

console.log(abs("/foo"));

// => "/foo"

console.log(abs("foo"));

// => "/path/to/where/you/are/foo"
```

Listing 1. Unintuitive JavaScript behavior: Falsy values, null vs. undefined, typeof, and type coercion

```
console.log(abs("~/foo"));
// => "/home/username/foo"
```

From the examples, our tool generates the following Type-Script declaration file.

```
export = Abs;
declare function Abs(input: string): string;
```

It used to be equivalent to the declaration file provided in the DefinitelyTyped repository⁴, but the maintainer indicates (since May 10, 2021) that the parameter is optional:

```
declare function abs(input?: string): string;
export = abs;
```

This case is quite frequent. The information in our declaration file is correct, but incomplete, because the developers did not document the fact that the input is optional. If the developer had provided the call <code>abs()</code> as an additional example, then our tool would have generated exactly the declaration on DefinitelyTyped! We call this case a solvable difference between our tool's output and the DefinitelyTyped declaration file.

Our tool dts-generate is a first step to explore the possibilities for generating useful declaration files from run-time information.

dts-generate comes with a framework that supports the generation of declaration files for an existing JavaScript library published to the NPM registry. The tool gathers data flow and type information at run time to generate a declaration file based on that information.

The main contribution of our tool is twofold:

- 1. We do not rely on static analysis, which is hard to implement soundly and precisely. It is also prone to maintenance problems when keeping up with JavaScript's frequent language updates.
- 2. We extract example code from the programmer's library documentation and rely on dynamic analysis to extract typed usage patterns for the library from the example runs.

Our implementation of code instrumentation to gather data flow information and type information at run time is based on Jalangi [14], a configurable framework for dynamic analysis for JavaScript. The implementation and the results are available in the following repositories.

- https://github.com/proglang/run-time-information-gathering/tree/ v1.1.0
- https://github.com/proglang/ts-declaration-file-generator/tree/v1.5.
 0
- https://github.com/proglang/ts-declaration-file-generator-service/ tree/v1 2
- https://github.com/proglang/dts-generate-method/tree/v1.3.1
- https://github.com/proglang/dts-generate-results/tree/v1.4.0

²NPM is the Node package manager, an online repository for JavaScript modules.

³https://www.npmjs.com/package/abs

⁴https://github.com/DefinitelyTyped/DefinitelyTyped/blob/master/types/

1.2 Contributions

- A framework that extracts code examples from the documentation of an NPM package and collects runtime type information from running these examples (Sections 4.1 and 4.2).
- Design and implementation of the tool dts-generate, a command line application that generates a valid TypeScript declaration file for an NPM package using run-time information (Section 4.3).
- A comparator for TypeScript declaration files (Section 5.2) for evaluating our framework and to detect incompatibilities when evolving JavaScript modules.
- An evaluation of our framework (Sections 5 and 6).
 We examined all 6029 entries in the DefinitelyTyped repository and found 249 sufficiently well documented NPM packages, on which we ran dts-generate and compared the outcome with the respective declaration file from the DefinitelyTyped repository.

2 Motivating Example

The NPM package glob-to-regexp provides functionality to turn a glob expression for matching filenames in the shell into a regular expression⁵. It has about 9.9M weekly downloads and 188 NPM packages depend on it. If a developer creates or extends TypeScript code that depends on the globto-regexp library, the TypeScript compiler and IDE require a declaration file for that library to perform static checking and code completion, respectively. With dts-generate we automatically generate a TypeScript declaration file for glob-to-regexp. Our tool downloads the NPM package, runs the examples extracted from its documentation, gathers run-time information, and generates a TypeScript declaration file. As the package is insufficiently documented, we provide one additional example to generate the result shown in Figure 1 (see discussion in Section 4.3). The interface is detected correctly. Optional parameters are detected. This declaration is ready for use in a TypeScript project: the generated file works properly with Visual Studio Code⁶. If the glob-to-regexp package gets modified in the future, a new declaration file can be generated automatically using dtsgenerate. Our comparator tool (Section 5.2) can compare the new file for incompatibilities with the previous declaration file.

3 TypeScript Declaration Files

The generated declaration file shown in Figure 1 describes a package with a single exported function. The module name is derived from the NPM module name by camlization⁷. The first parameter is of type string and the second one is an optional object described by an interface. To avoid name clashes,

```
export = GlobToRegexp;

declare function GlobToRegexp(
    glob: string,
    opts?: GlobToRegexp.I__opts): RegExp;

declare namespace GlobToRegexp {
    export interface I__opts {
        'extended'?: boolean;
        'globstar'?: boolean;
        'flags'?: string;
    }
}
```

```
import globToRegExp from 'glob-to-regexp';

globToRegExp("*.min.js", {});

⊗ extended

⊗ flags (property) GlobToRe...
⊗ globstar
```

Figure 1. Generated declaration file for glob-to-regexp

```
$ ./dts-generate abs
$ cat output/abs/index.d.ts
export = Abs;

declare function Abs(input: string): string;
```

Listing 2. Example for module-function template

dts-generate creates a namespace that corresponds to the module name. This pattern is a best practice to organize types declared in a declaration file [17]. In the example, the interface I_opts is declared in namespace GlobToRegexp. Hence, its uses must be qualified by the namespace as in GlobToRegexp. I_opts. The name of the interface is derived from the name of the formal parameter.

This file is an instance of one of the standard templates for writing declaration files⁸: **module**, **module-class**, and **module-function**. Each template corresponds to a different way of organizing the exports of a JavaScript library. The choice of the template depends on the structure of the underlying JavaScript library:

```
module several exported functions,module-class a class-like structure,module-function exactly one exported function.
```

There are further templates, but most libraries fall in one of these three categories. Both libraries glob-to-regexp and abs are instances of the **module-function** template.

The TypeScript project provides a guide on how to write high-quality declaration files⁹. The guide explains the main

⁵https://www.npmjs.com/package/glob-to-regexp

⁶https://code.visualstudio.com

⁷i.e., transforming to camel case.

⁸https://www.typescriptlang.org/docs/handbook/declarationfiles/templates.html

 $^{^9} https://www.typescriptlang.org/docs/handbook/declaration-files/by-example.html\\$

```
var greet = require("./greet-settings-module");
greet({
  greeting: "hello world",
  duration: 4000
});
greet({
  greeting: "hello world",
  color: "#00ff00"
});
```

(a) Example for module-function template

```
var myLib = require("./greet-module");

var result = myLib.makeGreeting("hello, world");
console.log("The computed greeting is: " + result)
;

var goodbye = myLib.makeGoodBye();
console.log("The computed goodbye is: " + goodbye)
;
```

(c) Example for module template

```
var Greeter = require("./greet-classes-module.js")
;

var myGreeter = new Greeter("hello, world");
myGreeter.greeting = "howdy";
myGreeter.showGreeting();
```

(e) Example for module-class template

```
export = GreetSettingsModule;

declare function GreetSettingsModule(settings:
        GreetSettingsModule.I__settings): void;

declare namespace GreetSettingsModule {
    export interface I__settings {
        'greeting': string;
        'duration'?: number;
        'color'?: string;
}
```

(b) Declaration file for module-function template

```
export function makeGreeting(str: string): string;
export function makeGoodBye(): string;
```

(d) Declaration file for module template

```
export = Greeter;

declare class Greeter {
  constructor(message: string);
  showGreeting(): void;
}

declare namespace Greeter {
}
```

(f) Declaration file for module-class template

Figure 2. Example uses and declaration files for different templates

concepts through examples. We selected one example for each template from the guide and used dts-generate to generate a corresponding declaration file, as shown in Figure 2.

The Typescript project provides a package dts-gen, which generates a template for a declaration file by analyzing the structure of the module. The resulting file is intended as a starting point for further manual development of the declaration file. Unlike dts-gen we determine the kind of declaration file by examining the *usage* of the module. If the imported entity is used solely as a function as in Figure 2a, the generated declaration file follows the **module-function** template as shown in Figure 2b. If the example only accesses properties of the imported entity as in Figure 2c, we generate the declarations according to the **module** template (Figure 2d). If the imported entity is used with new to create new instances as in Figure 2e, we generate a **module-class**

template (Figure 2f). While it is possible to create a library of undetermined category, our selection is driven by the examples in the documentation and hence reflects the developer's intent.

4 The Generation of TypeScript Declaration Files

This section gives an overview of our approach to generating TypeScript declaration files from a JavaScript library packaged in NPM. Figure 3 gives a rough picture of the inner working of our tool dts-generate. The input is an NPM package and the output is a TypeScript declaration file for the package if it is "sufficiently documented", which we substantiate in the next subsection.

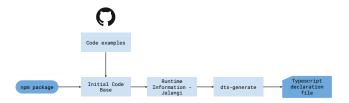


Figure 3. dts-generate - Architecture overview

As dts-generate is based on run-time information, we need code fragments that import and use the JavaScript library and we need to be able to obtain this run-time information while running the code. We explain in Section 4.1 how we obtain code fragments. To obtain run-time information, we instrument the code fragments and the entire code base of the library with Jalangi2 [14]. We extend Jalangi's analysis modules to gather data flow and type information as required for our purposes and explained in Section 4.2. dts-generate supports full ECMAScript 5.1, which is the latest JavaScript version supported by Jalangi2.

A second independent block explained in Section 4.3 uses the run-time information to generate a TypeScript declaration file. This part infers the overall structure of the JavaScript library, its interfaces, and the types from the run-time information. The resulting declaration file is ready for use in the development process. Its contents mimic the usage of the library in the example code fragments and match the structure of the JavaScript library under analysis, so that the JavaScript code generated after compiling the TypeScript code runs without interface-related errors.

The command-line interface is very simple and inspired by the dts-gen tool [4] (see Listing 2). The only required argument is the name of the module published to the NPM registry.

4.1 Initial Code Base

There are several options to obtain code fragments that exercise the library code in a meaningful way. In order to exercise library A, one might

- 1. execute code that imports library *A*;
- 2. execute the test cases that come with library *A*;
- 3. execute code fragments extracted from library *A*'s documentation.

Option 1 requires finding a library B that depends on A. While this information is straightforward to obtain from NPM, it is potentially costly to download and instrument B for use with Jalangi. Moreover, this option delegates our problem to library B, which also needs code to drive it.

We considered option 2 under the assumption that most libraries would come with test cases. However, there is no standard for testing JavaScript code so that test cases were difficult to reap from the NPM packages: they use different directory structures, employ differing (or no) testing tools,

or do not have tests at all. Moreover, developers try to cover corner cases or to trigger errors by using illegal input values in their tests. Such tests are not really useful for describing a library from the consumer's point of view. For example, a developer might write a test invoking a function with null just to validate that it throws an error in such a scenario.

In the end, option 3 was the most viable option to gather run-time information even though there is no standard for documentation, either. However, almost all repositories contain README files where the library authors briefly describe in prose what the code does, which problem it solves, how to install the application, how to build the code, etc. It is very common that developers provide code examples in the README files to show how the library works and how to use it. These code fragments showcase common use cases rather than stress-testing the implementation (a problem of option 2) because they are meant to be instructive to users of the package.

Obtaining code examples for a specific NPM package is done in three steps.

- Obtain the repository's URL with the command npm view <PACKAGE> repository.url
- Retrieve the README file from the top-level directory of the repository.
- Extract the code examples from the README file. To this end, observe that README files are written using Markdown¹⁰, a popular markup language, where most code examples are presented in code blocks labeled with the programming language. Hence, we retrieve the code examples from code blocks labeled js or javascript, which both stand for JavaScript.

Listing 3 shows the examples extracted from the README file of the glob-to-regexp package in that way.

Obtaining the code fragments from the examples provided in the README files of the repository proved to be an appropriate and pragmatic way of extracting the developer's intention. It provides an initial code base with meaningful examples.

4.2 Run-time Information Gathering

The run-time information block in Figure 3 gathers typerelated information as well as usage-related information for each function parameter. Here are some examples.

- Function f was invoked where parameter a held a value of type string and b a value of type number.
- Function foo was invoked. Its parameter hello was accessed as an object within the function. Its property
 world was found to have a string value (see Figure 4).
- Function foo was invoked. Its parameter bar was accessed as an object. Its method hello was invoked. The return value of this call was accessed as an object with property world, which returned a string (see Figure 5).

¹⁰ https://www.markdownguide.org

```
var globToRegExp = require('glob-to-regexp');
var re = globToRegExp("p*uck");
re.test("pot luck"); // true
re.test("pluck"); // true
re.test("puck"); // true
re = globToRegExp("*.min.js");
re.test("http://example.com/jquery.min.js"); //
re.test("http://example.com/jquery.min.js.map");
re = globToRegExp("*/www/*.js");
re.test("http://example.com/www/app.js"); // true
re.test("http://example.com/www/lib/factory-proxy-
    model-observer.js"); // true
re = globToRegExp("*/www/{*.js,*.html}", {
    extended: true });
re.test("http://example.com/www/app.js"); // true
re.test("http://example.com/www/index.html"); //
```

Listing 3. Code extracted from the glob-to-regexp package

• Parameter a of function f was used as operand for ==. Jalangi's configurable analysis modules enable programming custom callbacks that can get triggered with virtually any JavaScript event. Our instrumentation observes the fol-

- binary operations, like ==, +, or ===;
- variable declarations:

lowing events:

- function, method, or constructor invocations;
- access to an object's property;
- unary operations, like! or typeof.

The implementation stores these observations as entities called interactions, which document each operation applied. They are used for translating, modifying, and aggregating Jalangi's raw event information to get an applicationspecific data representation. Each function invocation is stored as a FunctionContainer which contains an ArgumentContainer for each argument. Each ArgumentContainer contains the name and index of the argument and a collection of interactions on the argument. As shown in Figure 4, the interaction getField gets triggered whenever a property of an object gets accessed. It tracks the name of the accessed field and the type of the returned value. The invocation of a method is tracked with the methodCall interaction. An interaction can have a following Interactions property if there are further operations on the return value of the interaction. It is used for inferring nested interfaces. That is, the followingInteractions recursively record interactions on the return value of getField or methodCall, taking care

Figure 4. Example code for getField interaction

of object identities to avoid looping. Figure 5 provides an example for both the methodCall interaction and the followingInteractions property. There is a usedAsArgument interaction (not shown) that gets triggered when an argument is used in the invocation of another function.

To obtain this information we wrap each function's argument in a wrapper object, which stores meta-information and provides the mapping of an observation to the corresponding ArgumentContainer or interaction. For operators that are aware of object identity, such as === or typeof, we use the original values because they could return different results for wrapper objects.

We also gather information to determine which module template is most appropriate. To this end the property requiredModule stores the name of the module that declared the invoked function. If a function is explicitly exported by the module, the property isExported is set to true when it is invoked. If a function of an exported object is invoked, isExported will be false and requiredModule will contain the name of the required module, as shown in Figure 6. If a function is used as a constructor, we set its isConstructor flag.

4.3 TypeScript Declaration File Generation

The next step after gathering the run-time information is the generation of the declaration file (cf. Figure 3). Contrary to dts-gen which analyzes the shape of the exported module, we choose the template based on the way the module is used. We analyze the properties isExported, requiredModule,

```
function foo(bar) {
  if (bar.hello().world) {
}
foo({
 hello: function () {
    return {
      world: "xxx",
};},});
{ functionId_1: {
  functionName: "foo",
   args: {
    0: {
        argumentName: "bar",
        interactions: [
            code: "methodCall",
            methodName: "hello",
            functionId: "functionId_2",
            followingInteractions: [
             {
                code: "getField",
                field: "world",
                followingInteractions: [],
                returnTypeOf: "string",
              }, ], },],},},}
```

Figure 5. methodCall and followingInteractions

and isConstructor from the run-time information to distinguish between **module-class** and **module-function**. If a function is invoked and it is imported from the module we are analyzing we infer the template **module-class** or **module-function**. We choose **module-class** if the function is used as a constructor. Otherwise, we choose **module-function**. If no function is invoked, we use the **module** template.

Our goal is to support the most commonly used Type-Script features first in our implementation. To this end, the selection of typing features covered in the tool is driven by an analysis of the 6648 declaration files in the Definitely-Typed repository. ¹¹ We parsed each declaration file with dts-parse and tagged it according to the features used in the file. Table 1 summarizes the results. The **Count** column indicates the number of declaration files that use a specific feature. The 3rd column shows the corresponding percentage with respect to all files in the repository.

Table 1. Usage of TypeScript features on DefinitelyTyped

F 4	C1	64
Feature	Count	%
type-string	5086	76.50%
optional-parameter	4915	73.93%
type-boolean	3891	58.53%
type-number	3699	55.64%
type-void	3548	53.37%
type-union	3456	51.99%
type-function	3286	49.43%
type-array	3264	49.10%
type-any	3127	47.04%
type-literals	1925	28.96%
alias-type	1899	28.56%
index-signature	1271	19.12%
generics-function	1145	17.22%
dot-dot-dot-token	882	13.27%
call-signature	817	12.29%
generics-interface	718	10.80%
type-object	661	9.94%
type-undefined	577	8.68%
type-intersection	431	6.48%
readonly	373	5.61%
type-tuple	355	5.34%
generics-class	265	3.99%
static	251	3.78%
private	82	1.23%
public	43	0.65%
protected	19	0.29%

We start with a limited scope on the features with the highest number of occurrences. Thus, we focus our effort on building an end-to-end solution that generates useful declaration files. We choose the types string, number, boolean, unions thereof, arrays, function callbacks, and optional elements are considered both for function parameters and interface properties. We also treat aliases and overloaded functions. Some common types such as any, literals, generics, and index signatures are not yet implemented. Rare types such as tuples and intersections (that is, types formed using the intersection operator &) were not considered.

Interfaces are created by exploring getField and method-Call interactions from the run-time information. We gather the interactions for a specific argument and build the interface by incrementally adding new properties. Interactions within the followingInteractions field are recursively traversed, building a new interface at each level up to a predefined depth. Interfaces that turn out to be equivalent are merged.

To construct the type signature for a function, we inspect the primitive types of each argument as well as the interface created from interactions on the argument in the function body. We do the same for the return type of the function.

¹¹As of commit da93d7b13094bacb170ead3f4a289f3b8687e4e5 (April 4, 2020)

```
const foo = require('foo');
foo.doSomething();
```

(a) Example code for module template

```
const foo = require('foo');
foo();
```

(c) Example code for module-function template

```
functionId_1: {
   functionName: 'doSomething',
   //...
   isExported: false,
   requiredModule: 'foo'
}
```

(b) Run-time information fragment for module template

```
functionId_1: {
   functionName: 'foo',
   //...
   isExported: true,
   requiredModule: 'foo'
}
```

(d) Run-time information for module-function template

Figure 6. Example code for properties is Exported and required Module - Property is Exported is false for module and true for module-function. Additionally, required Module is foo for both cases.

This procedure yields a candidate type for each function call observed during the execution. For instance, for the globToRegExp examples shown in Listing 3 we obtain the following observed candidate types

These types are correct, but underapproximate the best possible type for the package. Our comparison tool (see Section 5.2) classifies the differences as solvable, hence we provide one more code example:

```
re = globToRegExp("*/www/{*.js,*.html}", {
  flags: "i",
  globstar: true,
});
```

From this additional example, we obtain the following type:

As the type for the argument glob and the return type RegExp are the same, we collapse the type for opts into a union type. The union with the undefined type is special and converted into an optional argument. Moreover, the union of object types proceeds componentwise. Altogether, we arrive at a single collapsed candidate type.

We proceed in this way with merging further candidate types until we reach a set of non-mergable types for the function. If this set contains more than one candidate type, then we generate an overloaded definition. For example, the candidate types

```
f(string): string
f(number): number
f(boolean): boolean
```

cannot be merged as the return types are different. They give rise to an overloaded definition with three alternatives. However, given the candidate types

```
g(string): string
g(number): string
g(boolean): boolean
```

we can merge the first two types on the first argument (because all remaining arguments and the return types are equal) by collecting string and number into a union type. The resulting set of non-mergable types has two elements.

```
g(string|number): string
g(boolean): boolean
```

5 Evaluation

After generating a declaration file for an NPM package, we need to evaluate its quality. Clearly, the quality of the generated declaration file is heavily dependent on the quality

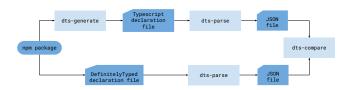


Figure 7. Evaluation of generated declaration files

of the examples provided by the developers. For example, if there is no code example exploring an execution path that would access a particular property, then that property will not appear in the gathered run-time data and consequently will not appear in the generated declaration file.

As a measure of the quality of a generated file we use its distance to the declaration file provided for the same module on DefinitelyTyped. In other words, we use DefinitelyTyped as our ground truth, because it is the only available reference against we can compare our results. To this end, we created dts-compare, a tool to compute the differences between two TypeScript declaration files.

For each module, we applied dts-compare to the generated declaration file and the one uploaded to the Definitely-Typed repository for the same module as shown in Figure 7. While this approach does not provide an absolute measure of quality, it gives us at least an indication of the usefulness of dts-generate: The files on DefinitelyTyped are perceived to be valuable to the community. If the accuracy of the generated files is comparable with the accuracy of the files on DefinitelyTyped, then dts-generate is a viable alternative to hand-crafted definition files.

5.1 dts-parse

We are not interested in a textual comparison of declaration files, but in a comparison of the structures described by the files. dts-parse receives the file as an input parameter and returns an AST serialized in JSON.

The first step is to parse the declaration files using the TypeScript compiler API to build and traverse the abstract syntax tree of a TypeScript program [16]. This step also performs a sanity check of the generated declaration files as it rejects files with syntactic or semantic errors. The output of dts-parse is a structure similar to a symbol table where declared interfaces, functions, classes, and namespaces are stored separately. Function arguments are described, identifying complex types like union types or callbacks. Optional parameters are also identified. For classes, a distinction between constructors and methods is made. Declaration files are tagged according to their features to identify and filter out declaration files that contain unimplemented features.

5.2 dts-compare

The compare tool takes two declaration files as input and returns a JSON file containing the result of the comparison as

```
$ dts-compare -e expected.d.ts -a actual.d.ts --
    module-name "my-module"
{
    "module": "my-module",
    "template": "module",
    "differences": [],
    "tags": []
}
```

Listing 4. Comparing declaration files without differences

shown in Listing 4. Following the naming convention of unit testing frameworks, the input files are marked as expected or actual. We use expected for the DefinitelyTyped declaration files

dts-compare applies dts-parse internally to both files to get normalized structures that are easy to compare. The result of the comparison is an array of an abstract entity Difference. We classify a difference as solvable if it can be resolved by adding more code examples. For example, we might add a function invocation with different parameters so that a missing interface property gets accessed. Otherwise it is classified as unsolvable.

We consider the following differences:

- TemplateDifference: A difference between the choice of TypeScript templates. For example, if the file in DefinitelyTyped is written as a **module** but we generated the file using the **module-function** template. The comparison stops if the templates differ.
- ExportAssignmentDifference: An equality check between the export assignments of both files, that is in the expression export = XXX.
- FunctionMissingDifference: A function declaration is present in the expected file but not in the generated one. This difference applies to functions as well as methods of classes and properties of interfaces.
- FunctionExtraDifference: A function is present in the generated declaration file but not in Definitely-Typed.
- FunctionOverloadingDifference: The number of declarations for the same function is different. This difference can be due to inexperience of the author of a declaration file, who uses, e.g., multiple declarations where a union typed argument would be appropriate.
- ParameterMissingDifference: A parameter of a function or a property of an interface is not present in the generated file.
- ParameterExtraDifference: A parameter of a function or a property of an interface is present in the generated file but not in the DefinitelyTyped file.
- ParameterTypeDifference: A parameter of a function or a property of an interface is generated with a different type than in the DefinitelyTyped file. Here

we differentiate between SolvableDifference and UnsolvableDifference.

- SolvableDifference: A type difference that can be solved by writing further code examples. For example, a basic type that is converted to a union type, a function overloading, or a parameter or property that is marked as optional.
- UnsolvableDifference: Any difference not considered as SolvableDifference.

Type aliases are expanded before the comparison and thus invisible to dts-compare: the declaration type $T = string \mid number$; declare function F(a: T); is equivalent to declare function $F(a: string \mid number)$;. The same approach applies to literal interfaces. dts-compare does not contemplate differences in function return types, because interface inference of function return types is limited in the current version of dts-generate. While the return values are inspected, a proper interface inference requires further operations on the return value (cf. the explanation of interactions in Section 4.2).

6 Results

We analyzed the generated files focusing on the following aspects:

- The quality of the inferred types, interfaces, and module structure using run-time information.
- The benefits of using code examples provided by developers as a first approximation to execute the libraries.
- The usability of the generated declaration file and whether dts-generate can be used in a proper development environment.

The conducted experiments included tests that consisted of replacing a specific type definition from DefinitelyTyped [3] with the one generated in the experiments: Type-Script compilation was successful, the generated JavaScript code ran without errors and code intelligence features performed by IDEs like code completion worked as expected.

Declaration files were generated for existing modules uploaded to the NPM registry. The DefinitelyTyped repository was used as a benchmark. Each of the generated files was compared against the corresponding declaration file uploaded to the repository.

Figure 8 shows that a declaration file was generated for 249 modules out of 6029 modules on DefinitelyTyped and we identified 111 modules that have only the features implemented by dts-generate. We obtained positive results for all of them. Section 6.3 provides a detailed explanation of the overall quality of the generated files. Section 6.2 presents examples of the generated declaration files for templates module, module-class, and module-function.

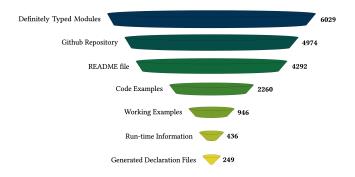


Figure 8. Number of analyzed modules at each stage

6.1 Code Examples

Retrieving the code examples for the JavaScript libraries proved to be a pragmatic way of driving the type gathering at run time. Figure 8 gives an overview of the process to extract code examples. To understand why it was only possible to obtain working code examples for 2260 packages, we explain the steps in the process and analyze the losses in each step.

The process of getting a valid code example for a module is divided in four stages:

- extracting the repository URL;
- extracting a README file;
- extracting code examples from README files;
- executing code examples and discarding failing ones.

Next, we describe the results obtained for each step.

Repository URL. The URL of the source repository could be retrieved for only 4974 packages. More than 1000 packages on NPM do not have a repository entry in their corresponding package.json file. Therefore, the npm view <module> repository.url command returns no value. Even important modules like ace provide no repository URL.

README Files. 682 packages do not have a README file in their repository, although the implementation checks for several naming conventions like readme.md or README.md.

Extraction of Code Examples. In this step, we lose another 50% of modules! This loss is mainly explained because some developers do not wrap their code in a block using the javascript or js tags. As we are still left with code examples for 2260 modules, we did not look further into code extraction as this number was considered sufficient for evaluating the generation of declaration files.

Execution of Code Examples. We executed the remaining 2260 extracted code examples by installing the required packages and running the code as a NodeJS application. Unfortunately, 1314 modules did not run correctly and had to be discarded. The code examples worked for the remaining 946 modules. Some failing samples were analyzed and there were mainly two reasons for the failure:

- The code fragment had been properly extracted but the code was faulty. It invoked the library in an unsupported (obsolete?) way, which lead to a run-time error.
- The extracted code fragment was not intended to be executed and/or it was not even valid JavaScript code.

Run-time Information. Run-time information was extracted for only 436 out of 946 modules with working code examples. As explained, to extract the run-time information, the behavior of the code under analysis was explicitly modified by wrapping the arguments. Furthermore, Jalangi's instrumentation itself caused some executions to fail, because the modules contained JavaScript features that are not supported by Jalangi. As a result, run-time information could not be extracted for 510 modules. An instrumentation without user-defined analysis modules was not applied, so it was not possible to determine which modules were failing only because of Jalangi's own limitations.

Generated Declaration Files. A declaration file was generated for 249 out of 436 modules. Despite the correct execution of the instrumented code examples, the extracted code for 138 modules did not exercise the library sufficiently. Hence, the collected run-time information was not enough for generating a declaration file.

6.2 Declaration Files Generation

This section exhibits an example of the 249 generated declaration files. Figure 9 exposes a simplified example for the **module-class** template where we highlight the most important features. We expose the results for the remaining templates **module** and **module-function** in Section A.1. The left side of the figure shows the generated declaration file with x dts-generate, the right side shows the corresponding file in the DefinitelyTyped repository.

There are no relevant differences between the files. Class methods and functions are correctly detected; input and output types are accurately inferred. We extract the parameter names from the variable names of the JavaScript code. For the getSteam2RenderedID method we correctly generate a signature that matches the type alias chosen by the author of the library. Finally, the method

from Individual Account ID is correctly located in the namespace section.

It is worth mentioning that for some libraries the declaration file in DefinitelyTyped was not correct. For module glob-base we detected that a parameter was incorrectly marked as optional. For module smart-truncate we discovered that the author incorrectly used the **module** template. We provide a more detailed explanation in Section A.3.

6.3 Evaluation

We analyzed 111 of the 249 generated files. The remaining 174 files contained at least one of the unimplemented TypeScript features so that they could not be considered.

The code examples have a direct influence on the quality of the generated declaration file. We introduced the concept of solvable and unsolvable differences in Section 5.2. Modules containing only solvable differences were considered as positive results. All of the analyzed files contained only solvable differences. We manually completed the examples for 10 of those modules. Applying dts-generate with the completed examples generates declaration files which are equivalent to the files from DefinitelyTyped. Section A.2 exhibits the manually added code examples for module github-url-to-object.

7 Discussion

How can we improve further? Given that JavaScript developers are incentivized to develop good examples rather than writing "boring" type declarations, how can we capitalize on that attitude? The main issue is that any example-driven algorithm can only come up with an under-approximation of the intended meaning, so some form of help is required when generalization is desired.

We believe that JavaScript developers can be taught to write their code examples in such a style that high-quality TypeScript signatures can be extracted from them without human intervention. In the subsequent paragraphs we survey some approaches that rely on developers using special strings and other constants in their code examples.

Literal types vs string. Many JavaScript libraries use literal strings to select options and configurations. To be concrete, 1925 DT packages rely on literal types (see Table 1). For example, the bonjour package¹² relies on strings to control events and indicate protocols in (different) interfaces:

```
removeAllListeners(event?: 'up' | 'down'):
    this;
protocol?: 'udp'|'tcp';
```

The carlo package¹³ uses literals to distinguish different events.

```
export type AppEvent = 'exit' | 'window';
```

For our framework, it is hard to distinguish a string that is meant literally from a string that just serves as an example. An automatic solution might collect typical values of literal strings and generate the corresponding literal types (or unions thereof) when the arguments used in the example are all typical. Alternatively, one might always generate literal types until the number of different examples passes some threshold, in which case the generator generalizes to type string. Both alternatives come with the problem that they

¹² https://www.npmjs.com/package/@types/bonjour

¹³ https://www.npmjs.com/package/@types/carlo

(a) steamid/index.d.ts - Generated (simplified)

(b) steamid/index.d.ts - DT (simplified)

Figure 9. Results for module-class template for module steamid

create a local over-approximation, which makes it harder to qualify the output of the generator. A further alternative that does not suffer from this drawback would be to communicate to the developer a set of typical example strings, *marker strings*, that the generator always generalizes to the string type.

Any. Suppose the programmer supplies examples that use number, bool, and string at the same argument position. In this case, our tool calculates the union type number|bool|string. But what if the programmer wants to advertise the type any for an argument? This intent is hard to communicate with a finite number of examples.

We propose that the programmer relies on marker strings like "any" to indicate the any type for an argument position.

Further types. Similar approaches could be conceived for indexed types, polymorphic types, dependent types, etc. At present we believe incorporating these features in a tool to be of limited value because they are not widely used in DefinitelyTyped (see Table 1).

8 Related Work

Dynamic analysis techniques. Trace Typing [2] is a framework for evaluating retrofitted type systems. It involves gathering traces of JavaScript program executions, just like in our system. However, the goal of the type systems that they study is quite different from ours. They are interested in type information to improve run-time performance and

traditional compilation, giving information about object layout and tag tests. Contrary to their approach, we do not just observe the types of arguments and return values. In addition, we also trace property accesses which translate to requirements on objects. We have no generalization step to infer polymorphic types.

Hummingbird [12] is a system for type checking Ruby programs at run time in the presence of metaprogramming. Metaprograms additionally generate type annotations for the generated code. Once a generated method is called, the method's body is statically checked against the actual argument types as well as the generated annotations. This system does not involve run-time tracing.

Rubydust [1] implements dynamic constraint-based type inference for Ruby. Rubydust runs an instrumented Ruby program that gathers subtyping constraints for parameters and return types of methods as well as for fields, which is quite different from the interaction that we collect. After completion, the solution of these constraints is proposed as a typing for the program. These types are sound if the runs cover sufficiently many paths in the program. Rubydust is reasonably effective because Ruby's type system is nominal. For JavaScript, this approach is much less effective as (runtime) typing is structural [10].

JSTrace [13] performs dynamic type inference for JavaScript by gathering information at run time. It inspects run-time types of arguments and return values of suitably wrapped functions. While the resulting information is treated similarly as in our work, we gather interactions from property accesses and method calls and derive further typing constraints from those. Moreover, JSTrace performs an (expensive) deep inspection of the types of objects and arrays whereas our inspection is shallow and thus more efficient.

None of the works tackles the question how to obtain a sufficient sample of run-time information. One part of our contribution is to systematically uncover the README files as a driver for running the JavaScript code under inspection.

Data Type Inference. Petricek and coworkers describe a mechanism to infer a datatype from an example input in JSON, XML, or CSV format [11]. Their implementation relies on type providers, a metaprogramming facility of F#. The type provider reads the example input at compile time and translates it into a static type. The approach is purely datacentric—the shape of the sample data determines what is legal in the program. Our approach analyzes the program's behavior on sample data and generalizes these observations to a type.

dts-gen. TypeScript comes with dts-gen, a tool that creates declaration files for JavaScript libraries [4]. Its documentation states that the result is intended to be used as a starting point for the development of a declaration file. The outcome needs to be refined afterwards by the developer.

The tool analyzes the shape of the objects at run time after initialization without executing the library. This results in most parameters and results being inferred as any.

In contrast, our tool dts-generate is intended to generate declaration files that are ready to be uploaded to DefinitelyTyped without further manual intervention. Any amount of manual work that a developer needs to do on a declaration file after updating JavaScript code increases the risk of discrepancies between the declaration file and the implementation.

TSInfer & TSEvolve. TSInfer and TSEvolve are presented as part of TSTools [8]. Both tools are the continuation of TSCheck [5], a tool for detecting mismatches between a declaration file and the implementation of the module.

TSInfer proceeds in a similar way than TSCheck. It initializes the library in a browser and records a snapshot of the resulting state. Then it performs a lightweight static analysis on all the functions and objects stored in the snapshot.

The abstraction and the constraints introduced as part of the static analysis tools for inferring the types have room for improvement. A run-time based approach like the one presented in our work will provide more accurate information, thus generating more precise declaration files.

TSInfer faces the problem of including internal methods and private properties from the snapshot in the declaration file. Run-time information would have shown that the developer has no intention of exposing these methods.

Moreover, TSEvolve performs a differential analysis on the changes made to a JavaScript library to determine intentional discrepancies between the declaration files of two consecutive versions. However, a differential analysis may not be needed. If the developer's intention were accurately represented by the extracted code, then the generated declaration file would already describe the newer version of a library without the need of a differential analysis.

TSTest. TSTest is a tool that checks for mismatches between a declaration file and the JavaScript implementation of the module [9]. It applies feedback-directed random testing for generating type test scripts. These scripts execute the library with random arguments with the typings from the declarations file and check whether the output matches the prescribed type. TSTest thus provides concrete counterexamples if it detects mismatches.

TSTest could be used to extend our tool with a feedback loop. If TSTest detects a problem with a declaration file generated by dts-generate, then we would add the resulting counterexamples to the example code and restart the generation process.

9 Conclusions and Future Work

We have presented dts-generate, a tool for generating a TypeScript declaration file for a specific JavaScript library. It downloads the developer's code examples from the library's repository. It uses these examples to execute the library and gather data flow and type information. The tool generates a TypeScript declaration file based on the information gathered at run time.

Building an end-to-end solution for the generation of Type-Script declaration files was prioritized over type inference accuracy. Hence, types were taken over from the values at run time. Developers express their intent how a library should be used with example code in the documentation. Obtaining the types from the code examples extracted from the repositories proved to be a pragmatic and effective approximation, enabling to work on specific aspects regarding the TypeScript declaration file generation itself.

We built a mechanism to automatically create declaration files for potentially every module uploaded to Definitely-Typed. We managed to generate declaration files for 249 modules. We compared the results against the corresponding files uploaded to DefinitelyTyped by creating dts-parse, a TypeScript declaration files parser and dts-compare, a comparator.

Return types could be defined more accurately by analyzing the interactions tracked on them. We consider that enhancing the run-time information by executing tests already present in the codebase is an approach worth following as future work.

```
var smartTruncate = require('smart-truncate');

var string = 'To iterate is human, to recurse
    divine.';

// Append an ellipsis at the end of the
    truncated string.

var truncated = smartTruncate(string, 15);
```

Listing 5. Code example for smart-truncate module exporting a function

A Results

A.1 Templates

A.1.1 module-function. Figure 10 shows the generated declaration files for simple modules like abs, dirname-regex, and escape-html. All of them were generated using the module-function template.

The different names in the export assignment by modules dirname-regex and escape-html do not matter because the module can be named arbitrarily when it is imported: in import Abs = require('abs'); the identifier Abs can be chosen by the programmer. We generate the name in the export assignment by transforming the module name into camel case form, following TypeScript guidelines.

A difference in the names of the function parameters does not affect the correctness of the declaration file. Furthermore, neither the order of declarations nor unused namespaces (as in module escape-html) matter.

A.1.2 module. Figure 11 contains an example for the **module** template, the declaration for the is-uuid module. The generated file only contain methods that were executed by the extracted examples. All invoked functions are correctly detected; the additional functions declared on Definitely-Typed are not used in the example code. It would be easy to generate a perfectly matching declaration file by adding two examples using functions nil and anyNonNil.

A.2 Manually completed examples

Figure 12 exhibits the manually expanded code examples for module github-url-to-object.

A.3 Errors in DefinitelyTyped

For module glob-base the parameter basePath is declared as optional in DefinitelyTyped. However, when invoking the function without the basePath parameter, an error is thrown at run time. The file generated by dts-generate does not mark this parameter as optional, as shown in Figure 13. Function return type interfaces are not inferred by dts-generate.

We also discovered errors in the selected template in DefinitelyTyped. The module smart-truncate in DefinitelyTyped uses the **module** template, but dts-generate generates a file using the **module-function** template. Listing 5 shows that the module is indeed exported as a function, as inferred by dts-generate.

(e) escape-html/index.d.ts - Generated

(f) escape-html/index.d.ts - DT

```
export = Abs;
                                                          declare function Abs(input: string): string;
                                                          export = Abs;
declare function Abs(input: string): string;
                                                                            (b) abs/index.d.ts - DT
              (a) abs/index.d.ts - Generated
export = DirnameRegex;
                                                          export = dirnameRegex;
declare function DirnameRegex(): RegExp;
                                                          declare function dirnameRegex(): RegExp;
          (c) dirname-regex/index.d.ts - Generated
                                                                        (d) dirname-regex/index.d.ts - DT
                                                          declare function escapeHTML(text: string): string;
export = EscapeHtml;
                                                          declare namespace escapeHTML { }
declare function EscapeHtml(string: string):
  string;
                                                          export = escapeHTML;
```

Figure 10. Results for module-function template

```
export function v1(str: string): boolean;
export function v2(str: string): boolean;
export function v2(str: string): boolean;
export function v3(str: string): boolean;
export function v3(str: string): boolean;
export function v4(str: string): boolean;
export function v4(str: string): boolean;
export function v5(str: string): boolean;
export function v5(str: string): boolean;
export function v1(value: string): boolean;
export function anyNonNil(value: string): boolean;
export function anyNonNil(value: string): boolean;
```

Figure 11. Results for **module** is-uuid

```
declare namespace gh {
   interface Options {
      enterprise?: boolean;
   }
   interface Result {
      ...
   }
}
declare function gh(url: string | {url: string
      }, options?: gh.Options): gh.Result | null;
export = gh;
```

(a) github-url-to-object/index.d.ts - DefinitelyTyped. Properties of interface Result were ignored for readability, since return types were not considered.

```
export = GithubUrlToObject;

declare function GithubUrlToObject(repoUrl:
    string | GithubUrlToObject.I__repoUrl, opts
    ?: GithubUrlToObject.I__opts): object |
    null;

declare namespace GithubUrlToObject {
    export interface I__repoUrl {
        'url'?: string;
    }

    export interface I__opts {
        'enterprise'?: boolean;
    }
}
```

(b) github-url-to-object/index.d.ts - Generated with manually expanded code example

```
var gh = require('github-url-to-object')

gh('github:monkey/business');
gh('https://github.com/monkey/business/tree/master');
gh('https://github.com/monkey/business/tree/master/nested/file.js');
gh('https://github.com/monkey/business.git');
gh('http://github.com/monkey/business');
gh('git://github.com/monkey/business');
gh('git://github.com/monkey/business.git');

// Manually added:
gh('git+https://githuuub.com/monkey/business.git', {});
gh('git+https://githuuub.com/monkey/business.git', {enterprise: true});
gh({url: 'git://github.com/monkey/business.git'});
gh('this is not a proper url');
gh({url: 'this is not a proper url'});
```

(c) Code example for module github-url-to-object.

Figure 12. Manually expanded code example for github-url-to-object to match DefinitelyTyped declaration file. The literal interface in DefinitelyTyped is replaced by a declared interface. Return types are not considered.

```
'use strict';

// ...

module.exports = function globBase(pattern) {
  if (typeof pattern !== 'string') {
    throw new TypeError('glob-base expects a string.
        ');
}

// ...
}
```

(a) glob-base/index.js - Excerpt of JS implementation that throws an error when input parameter is not a string

```
var globBase = require('glob-base');
globBase();
// Throws: TypeError: glob-base expects a string.
```

(c) Code example invoking the exported function without the first parameter, as specified in DefinitelyTyped

```
declare function globbase(basePath?: string):
    globbase.GlobBaseResult;

declare namespace globbase {
    interface GlobBaseResult {
       base: string;
       isGlob: boolean;
       glob: string;
    }
}
export = globbase;
```

(b) glob-base/index.d.ts - DefinitelyTyped

```
export = GlobBase;

declare function GlobBase(pattern: string): object
;
```

(d) glob-base/index.d.ts - Generated

Figure 13. Incorrect optional parameter for module glob-base

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