# Technical Report: An Asynchronous Call Graph for JavaScript

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## ABSTRACT

This Technical Report serves as a supplementary document to the "An Asynchronous Call Graph for JavaScript" article. It provides extra background information and showcases results.

## CCS CONCEPTS

• **Software and its engineering → Concurrent programming structures**.

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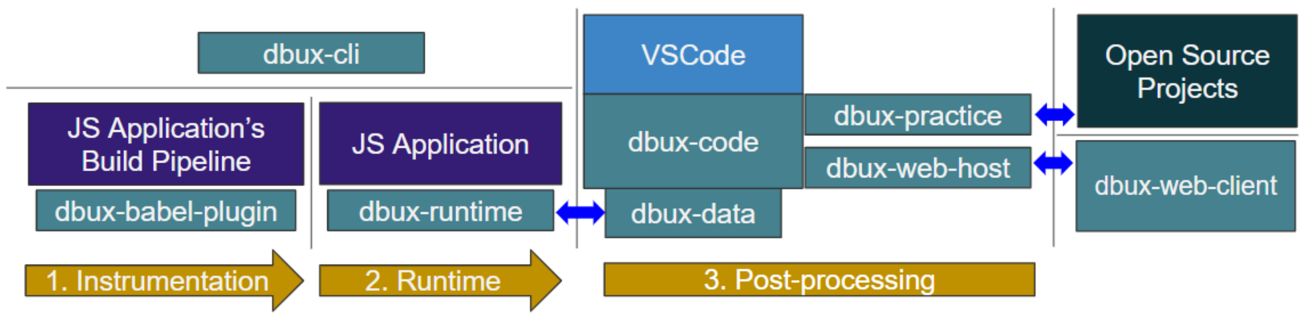


**Figure 1: Dbux Architecture.**

# 1 A BRIEF INTRODUCTION TO DBUX

## 1.1 Architecture

Dbux has four applications and several supplementary modules, as depicted in Fig. 1 (several shared modules, such as the `dbux-common*`, modules are not shown).

Dbux's three stages *instrument*, *runtime* and *post-processing* are implemented in four collaborating applications:

- `dbux-babel-plugin` instruments the target application and injects the `dbux-runtime`. It requires to be run with "Babel".
- `dbux-runtime`, when injected into a target application, records the target application's execution trace and streams it to a server in real time.
- `dbux-code` is a one-click-installable extension to VSCode, available on the VSCode Marketplace, complete with extensive documentation. It also has prepared several real-world projects, bugs and experiments to try it out on. Upon activation, it starts a server to wait for the execution data produced by `dbux-runtime`. When received, it *post-processes* it with the help of the `dbux-data` module before presenting it to the user. Data is processed and presented as soon as it is received, meaning that applications can be debugged while they are still running.
- `dbux-cli` is to Dbux, what "nyc" is to the coverage reporter Istanbul [1], that is: a convenient command line tool that makes it easier for developers to execute a JS application with Dbux enabled, without having to prepare a build pipeline. Instead, it uses a modified version of `@babel/register` [2] to inject `dbux-babel-plugin` on the fly.

## 1.2 Call Graph Assembly

*NOTE: In the following, we refer to the "dynamic call graph" just as "call graph". Dbux does not have a static call graph.*

We model the call graph as follows:

(1) We refer to a call graph node, that is the recorded execution of a file or function, as an "executionContext", or **context** for short. Given a function $f$, we denote the context that represents the $i$'th execution of some function $f$ as $f_i$.
(2) Edges represent the caller - callee relationship. For uninterruptible functions: if during it's $i$'th execution, $f$ calls some function $g$, then, for some $j$, $g_j$ is a child —or **callee**— of $f_i$, and $f_i$ is a parent —or **caller**— of $g_j$.
(3) Any function execution $f_i$ is considered a Call Graph Root (CGR), if it has no parent caller.
(4) Traditionally the above rule set was sufficient to build a JavaScript dynamic call graph. However, ES2017 introduced `async` functions, which need special attention due to their property of interruptibility: we refer to the $i^{th}$ execution of some `async` function $h$ as $h_i$. The context $h_i$ is considered a **real context**. When executed, a **virtual context** $h_i^1$ is added as a child to $h_i$. Furthermore, any `await p;` expression tells the scheduler to **interrupt** the current control flow for one tick of the asynchronous queue, or, if `p` is a promise, until that promise has been settled. Right after an `await` has concluded, that is, after the promise has settled, execution of $h_i$ continues. At this point, our instrumentation adds a new virtual context $h_i^k$. That context represents the asynchronous continuation of the interrupted real context $h_i$ at a later point in time. It is ensured that each virtual context $h_i^k, i > 1$ is also a CGR.

In general, all events, contexts and roots are ordered by time of occurrence. Dbux's synchronous call graph implementation renders all CGRs linearly in that order.

[1] https://istanbul.js.org/
[2] https://babeljs.io/docs/en/babel-register

## 1.3 Developer Survey

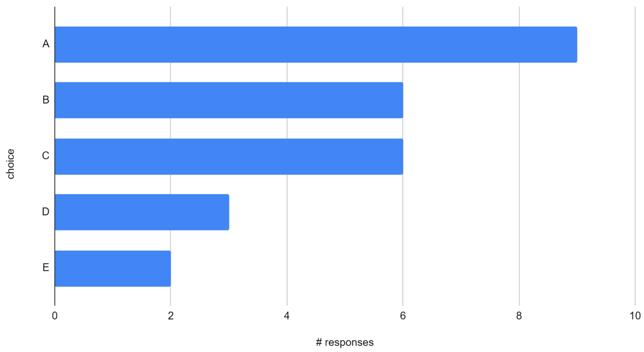


**Figure 2: Survey Results: What type of programming problems are the most difficult to deal with? (A) Asynchronous behavior (setTimeout; setInterval; Process.next; promise; async/await etc.) (B) Third-party APIs (e.g. Node API, Browser API, other people's libraries, modules etc.) (C) Programming logic (D) Syntax (E) Events.**

During a workshop in summer 2020 that introduced Dbux to 20 TAs of a local JavaScript Bootcamp provider, we asked the participants what type of bugs they found most difficult to deal with. A total of 10 participants filled out our survey. The top choice for the (multiple choice) "programming problems" was "asynchronous behavior" with 9 votes, while the second place only received 6.

```
async function send(fpath) {
  const file = await openFile(fpath);

  const cont = await readFile(file);



  await sendFile(cont);



  console.log('File sent!');
}
```

```
function send(fpath) {
 return openFile(fpath).
   then(function (file) {
     return readFile(file);
   }).
   then(function (cont) {
     return sendFile(cont);
   }).
   then(function () {
     console.log('File sent!');
   });
}
```

```
function send(fpath, cb) {
 openFile(fpath, function (file) {

   readFile(file, function (cont) {


     sendFile(cont, function () {
       cb && cb();

       console.log('File sent!');
     });
   });
 });
}
```

**Figure 3: Three types of AEs implementing a series of three operations:** openFile → readFile → sendFile

## 2 ASYNCHRONOUS SEMANTICS PRIMER

Fig. 3 illustrates the three types of Asynchronous Events (AE). In all three cases, the resulting Asynchronous Call Graph (ACG) should feature three nodes, connected by two CHAINs.

Below are several illustrations of asynchronous programs and their expected conceptual ACG.

```
let p = P().
  then(f1);

p.then(f2).
  then(f3);

p.then(f4).
  then(f5);
```

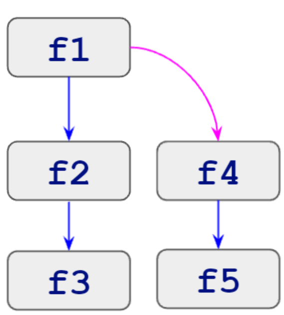


**Figure 4: Promises (CHAIN vs. FORK)**

```
let p = P().
  then(f0);

p.then(g).
  then(f3);

p.then(f4).
  then(f5);
```

```
function g() {
  G
  return P().
    then(f1);
}
```

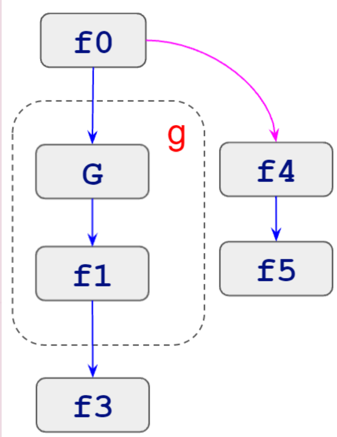


**Figure 5: Nested Promises (CHAIN vs. FORK)**

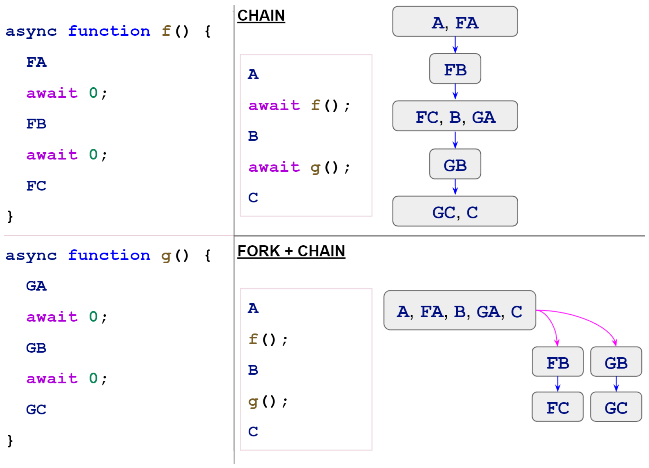


**Figure 6: AWAIT (CHAIN vs. FORK)**

## 2.1 Promise Creation Semantics

To better motivate PromiseLinks, consider the following. In JavaScript, promises can be created in four ways. Somewhat counter-intuitively, (i), (ii) and (iii) do *not* cause an asynchronous event on their own. However, all of them can nest promises:

The (i) Promise constructor takes an executor function which in turn is provided two parameters: the resolve and reject functions which are to be called to fulfill the promise. The executor function is called synchronously from the constructor. The Promise constructor is commonly used to wrap asynchronous callbacks into promises. This process is commonly referred to as “promisification”.

(ii) Promise.resolve(x) and Promise.reject(x) are equivalent to using the (i) Promise constructor and synchronously calling resolve or reject respectively. Promise.all and Promise.race can further be used to nest multiple promises into one.

When (iii) an async function is called, the runtime environment creates a new promise. Its call expression value is set to that promise. Async functions execute synchronously until the first await is encountered. This means that if an async function concluded without explicitly invoking an await expression or any of the three other types of events, it does not trigger an asynchronous event. Promises can further be nested by returning them from an async function.

(iv) promise chaining (then, catch, finally).

## 3 CONCURRENT DATA FLOW: RESULTS

These are the results from the “Concurrent Data Flow” extension on the three producer-consumer problems:

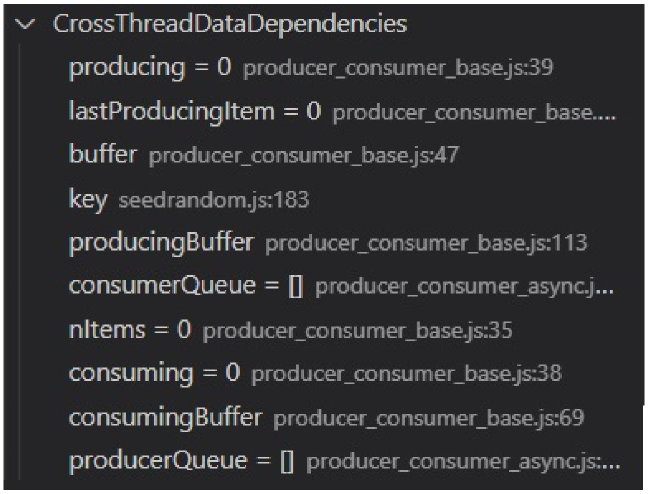


**Figure 7: Async Function Implementation**

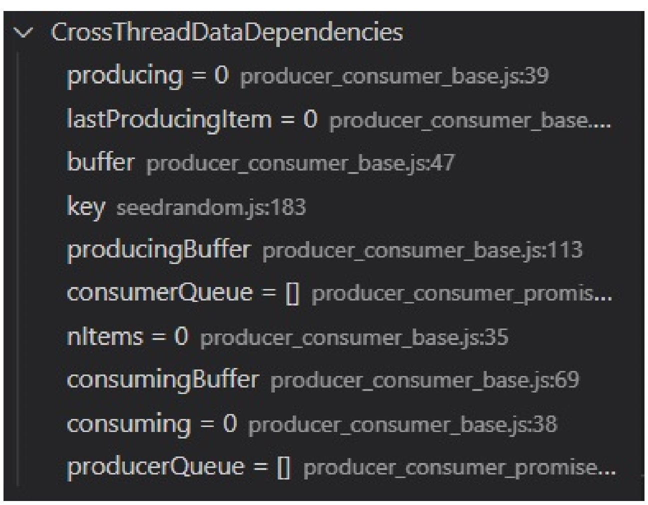


**Figure 8: Promise Implementation**

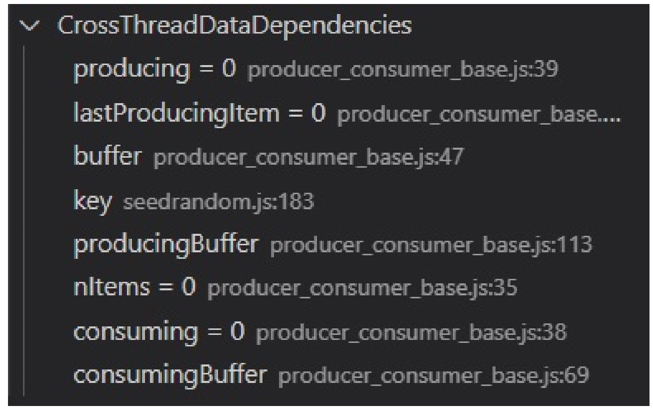


**Figure 9: Callback Implementation**

## 4 PROJECT RESULTS

In the following we share the raw ACG results of the nine projects that we had to omit from the article for brevity (enhanced for contrast).

*TODO: Editor.md screenshot is missing because the application file importer cannot deal with a special property of the Editor.md log (it created contexts that were never sent to the server; possibly due to erroneous <script> loads). The data file is Ok, but the importer needs a bit more resilience. Aiming to fix within 1-2 weeks.*

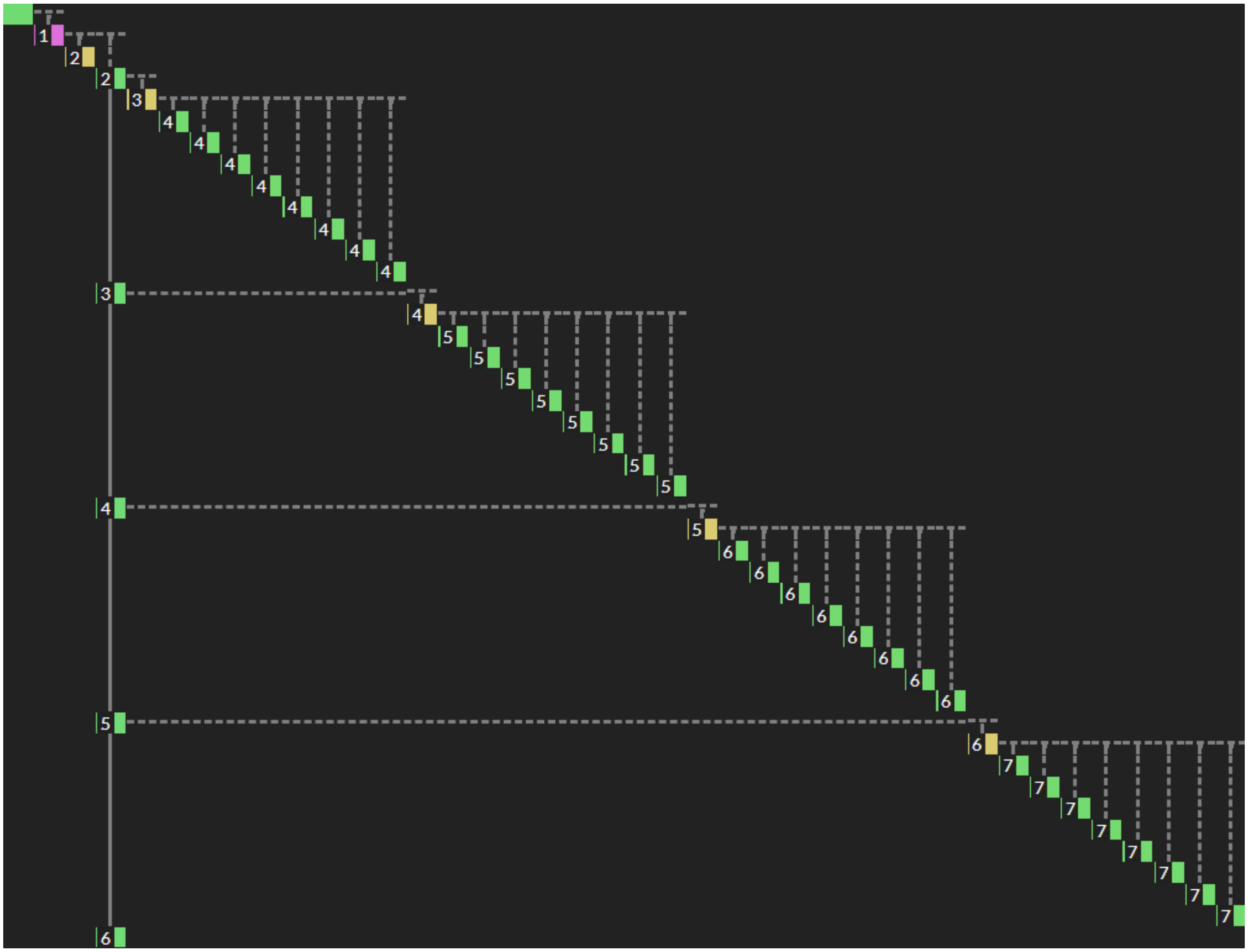


**Figure 10: 2048**

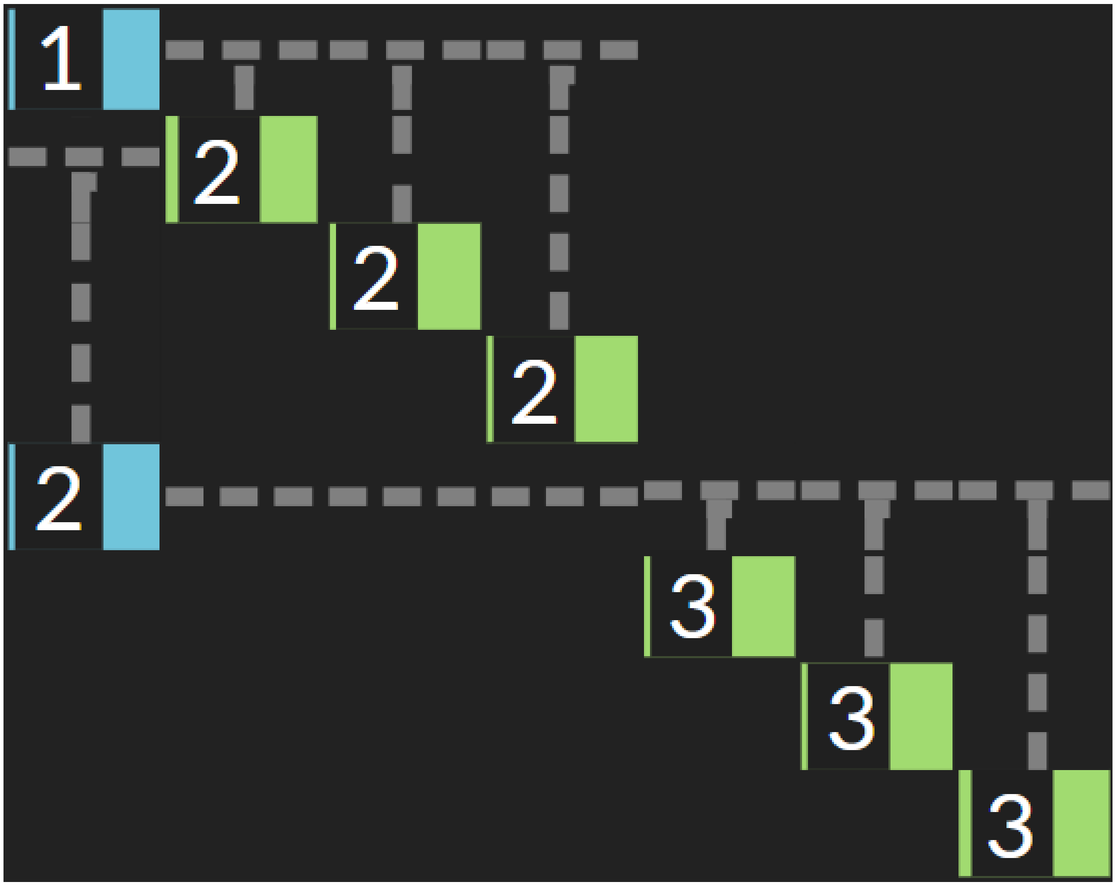


Figure 11: Bluebird

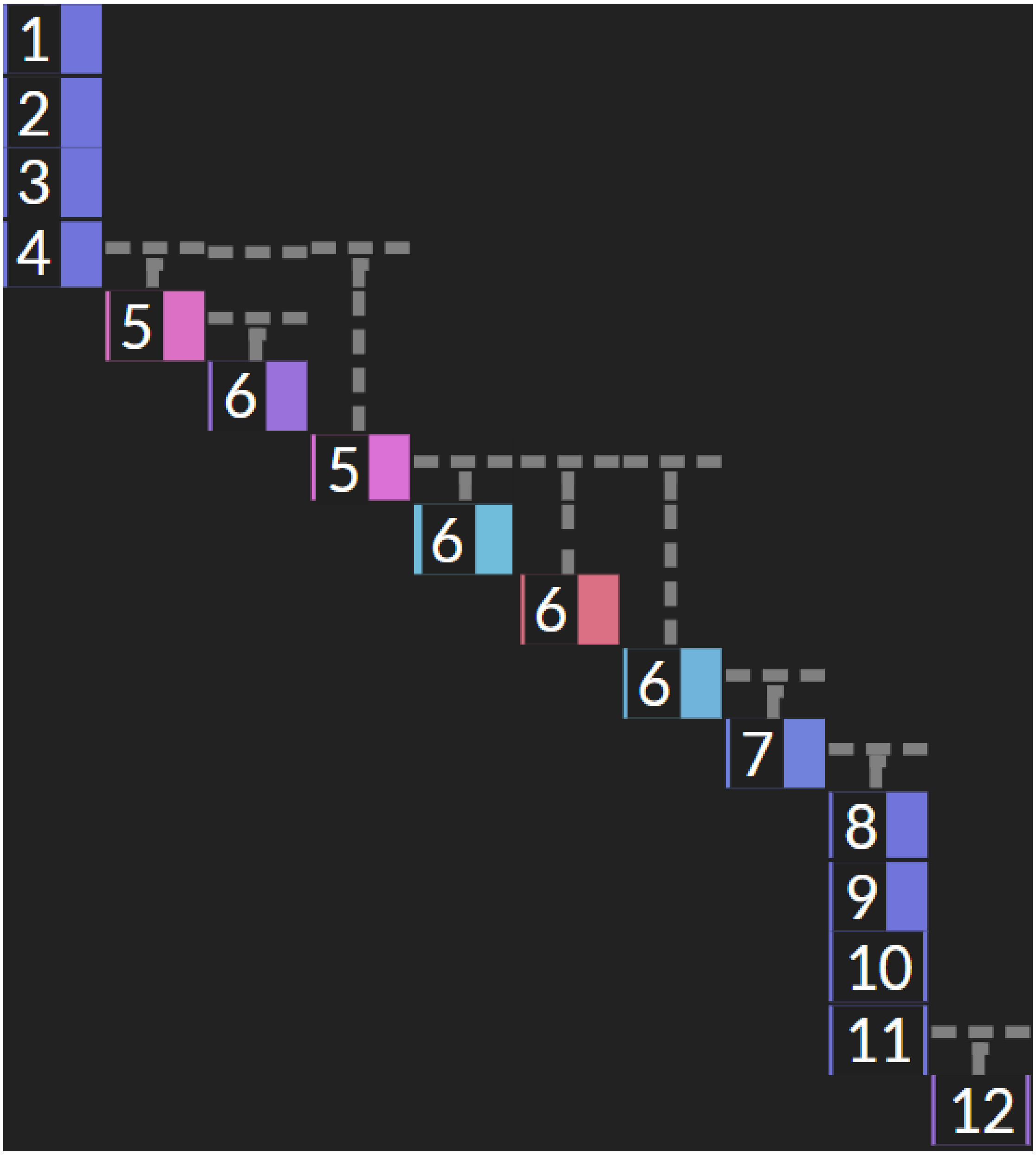


**Figure 12: Express**

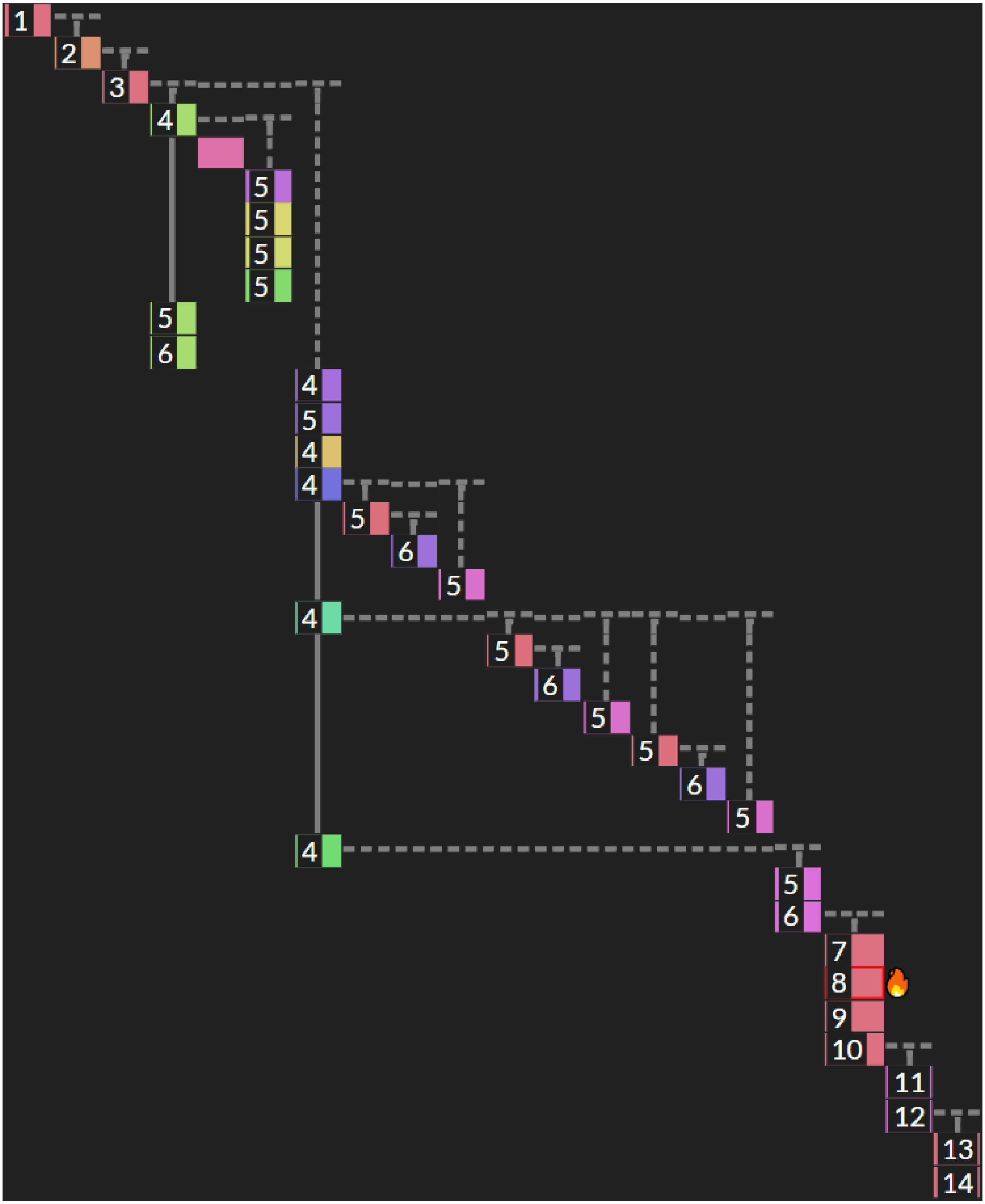


**Figure 13: Hexo**

Figure 14: node-fetch

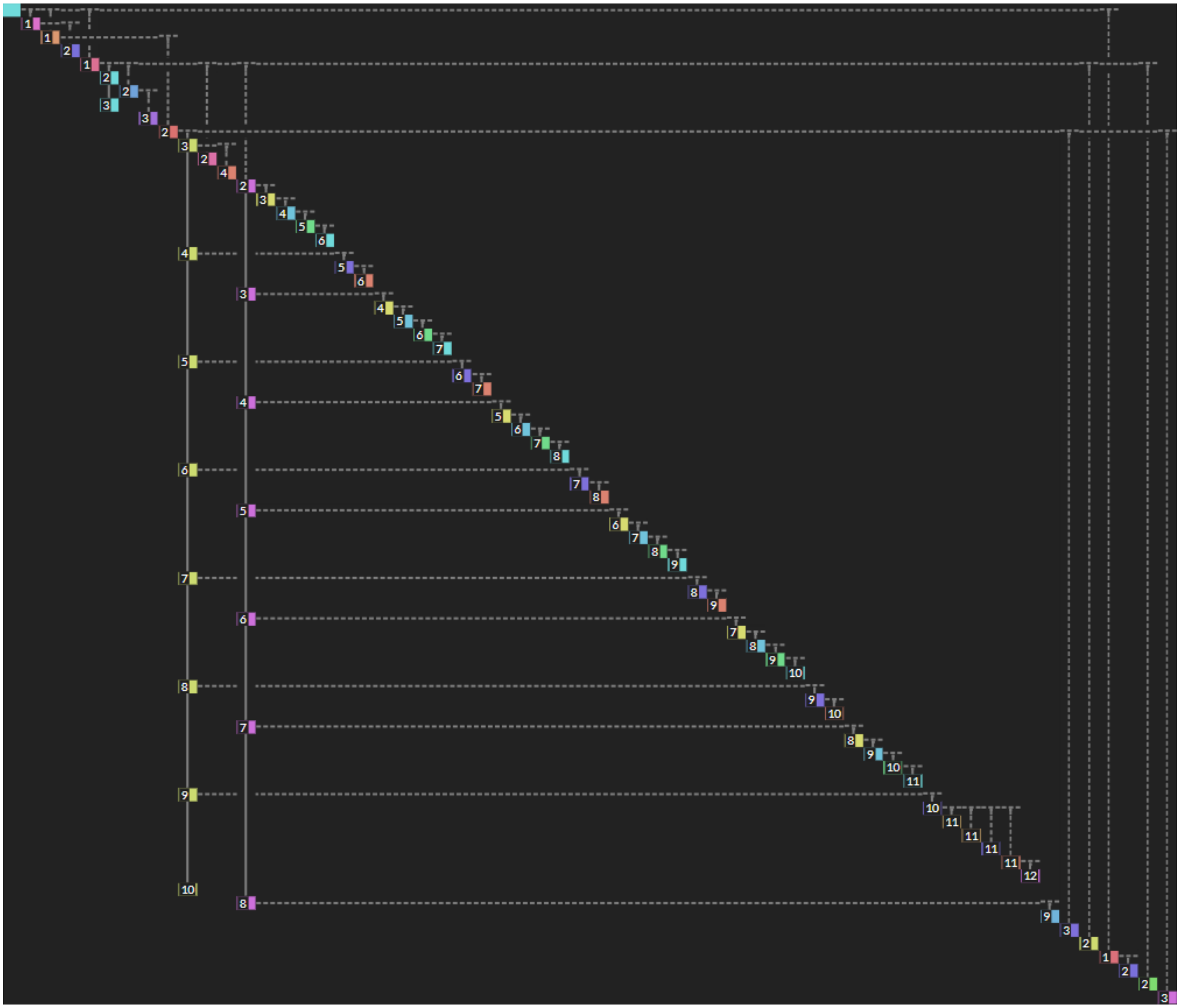

**Figure 15: socket.io**

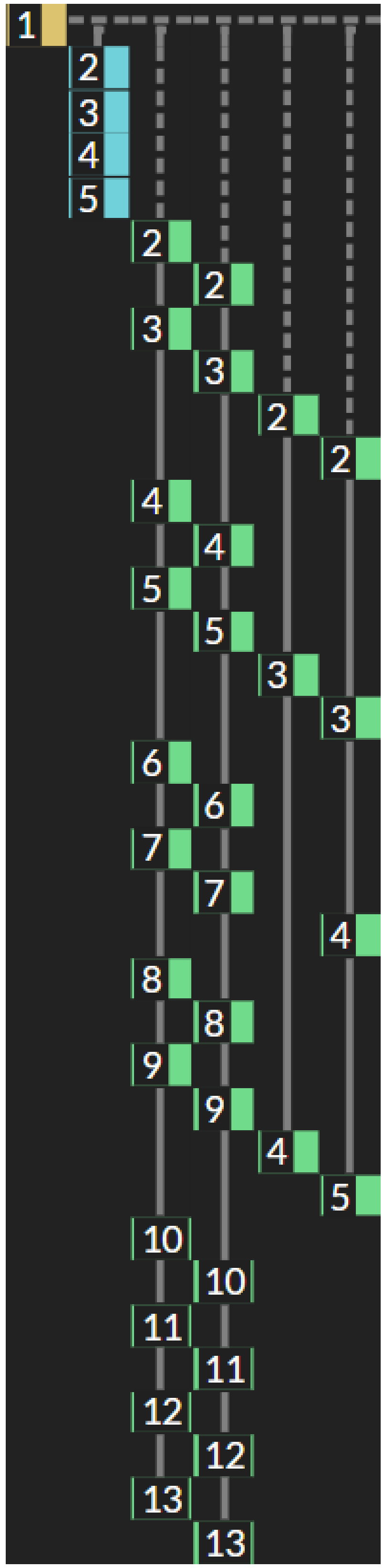


**Figure 16: todomvc**

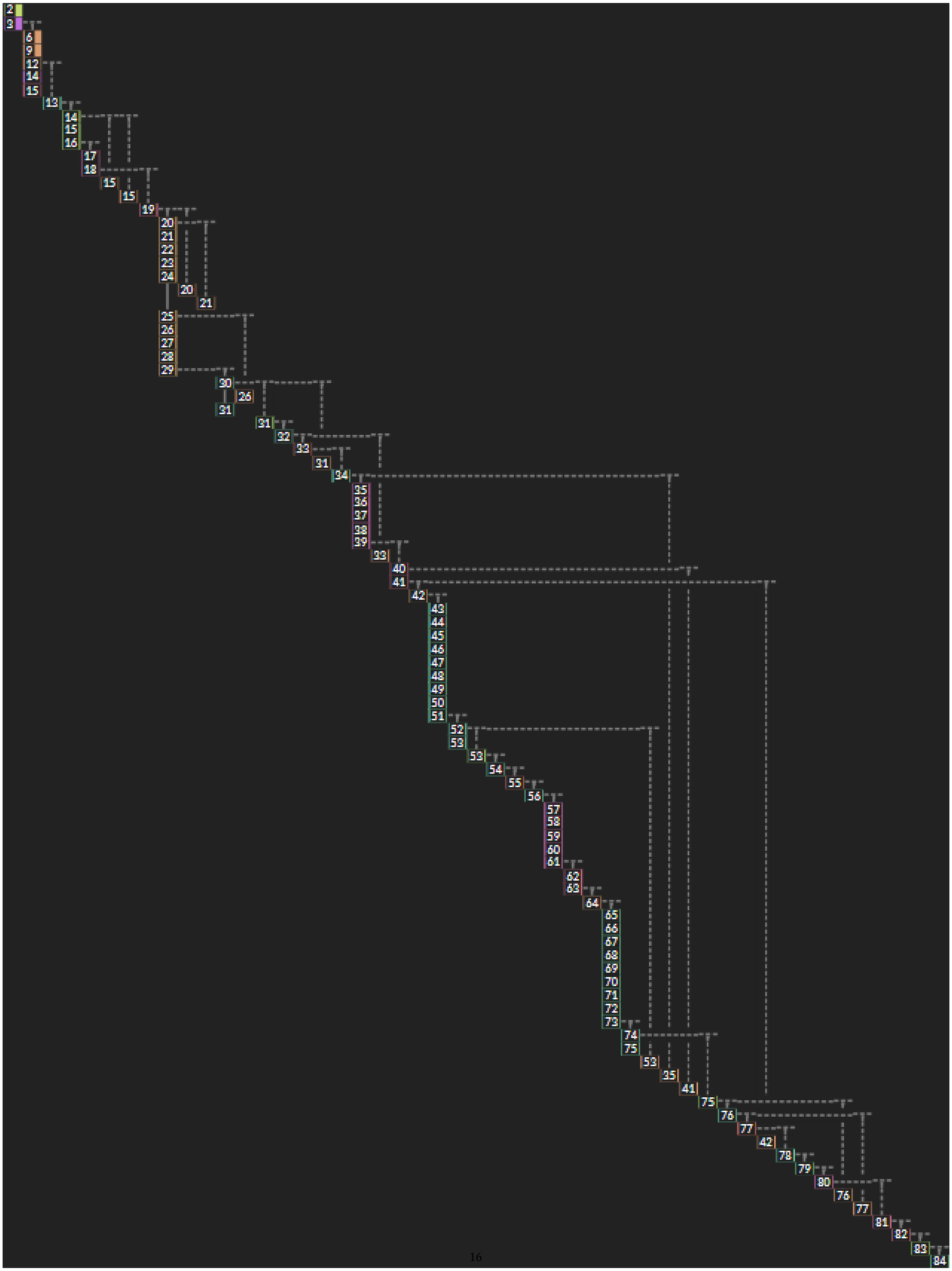


**Figure 17: webpack**