Using Solver-Aided Languages to Build Package Managers

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Abstract

Open-source software is critical for modern development, but most open-source packages require large networks of prerequisite packages, or dependencies, in order to function correctly. Modern software development workflows use package managers to ease this burden. Given a set of constraints, these systems use dependency solving to select compatible versions of dependencies before installing. However, many dependency solvers make ad hoc implementation choices and use heuristics that affect the set of chosen dependencies, and thus affect correctness, code size, and other factors of the final bundled software in ways that are opaque and confusing to programmers.

We present PACSOLVE, a unifying formal semantics of dependency solving. PACSOLVE can compactly represent the key features and differences between NPM, PIP and Cargo, and express a wide variety of alternative semantics for dependency solving. PACSOLVE lends itself to a solver-aided implementation in Rosette, which we use to build a drop-in replacement for NPM called MINPM. MINPM allows the user to customize the dependency solving semantics to choose between different objectives and consistency criteria. We show empirically that PACSOLVE is performant and effective on real-world code. For example, on the top 1000 most downloaded NPM packages, we show that MINPM can shrink the footprint of 20% of packages and produce a newer set of dependencies for 14% of packages. Moreover, MINPM only takes 1.7s longer than NPM on average. We also use MINPM to show that NPM’s tree-solving semantics is only necessary for 3% of these packages.

1 Introduction

Open-source software is now ubiquitous, and a defining feature of contemporary programs is their use of many external open-source packages called dependencies. A program might require several dependencies, each of which, in turn, requires its own set of dependencies. It is not uncommon for a program to transitivity depend on hundreds of packages. Programming language package managers, such as PIP, NPM, and Cargo facilitate this style of programming by allowing package authors to easily publish new packages and new package versions. They also define declarative DSLs that allow programmers to specify dependencies along with constraints on their configuration (versions, features, etc.). Finally, most package managers include a dependency solver, which selects a set of available dependency versions that satisfy all constraints, triggering downloads when necessary.

Choices made by a dependency solver can affect important properties of the program, such as code size, performance, correctness, and security vulnerabilities. For example, in many cases, a program’s dependencies comprise more code than the program itself, and a liberal selection policy can cause the assembled application to be very large. Despite the significance of these choices, the precise semantics of language-specific dependency solvers have been largely overlooked to date.

The semantics of dependency solving varies widely between languages. For example, PIP allows at most one version of a package to be loaded in a single program, whereas NPM allows multiple versions of a package to be loaded at the same time. NPM’s behavior is designed to simplify solving; rather than resolving conflicts, a JavaScript project can simply load two incompatible versions of the same package. PIP and Python refuse to do this, as Python’s module system does not support it. NPM’s choices allow for potentially more surprising errors, when different versions of the same package need to interact [8]. It is worth asking if NPM’s behavior is really necessary. How frequently do programs need to load multiple versions of a package? In this paper, we answer this and other similar questions.

Dependency solvers also employ a variety of different algorithms. NPM uses a tree solver that builds a dependency tree without backtracking. Until recently, PIP also used a greedy algorithm instead of a full backtracking solver [27]. Different dependency solvers also have different objectives. For instance, PIP and Cargo favor versions of packages with larger version numbers, but NPM has a more complex policy
which aims to choose the most recently uploaded versions. These objectives are largely opaque to users.

This paper develops a semantics for dependency solving called PACSOLVE, that captures the essential features and differences between PIP, NPM, and Cargo. To accomplish this, our semantics is parameterized along several key axes, including how version constraints are interpreted, which package versions are co-installable, and the global objectives of dependency solving. This semantics is defined as a predicate over solution graphs, which are directed (possibly cyclic) graphs of packages and their dependencies. This semantics lends itself to an implementation in Rosette [30], which is a solver-aided language that supports program synthesis. We formulate dependency solving as solution graph synthesis, and thus get a highly-customizable dependency solver.

We also present MINNPM, which is a drop-in replacement for NPM that uses PACSOLVE under the hood. From the MINNPM command line, a user can choose different policies for allowing multiple versions of a package to be co-installable, as well as different optimization objectives. We then use MINNPM to perform an empirical evaluation of dependency solving semantics on the NPM package ecosystem. We apply MINNPM in a variety of configurations to the top 1,000 most downloaded JavaScript packages. Our evaluation shows several results, including the following:

- By minimizing dependencies, MINNPM can shrink the footprint of 20% of the top 1,000 packages.
- Only 3% of the top 1,000 NPM packages rely on multiple versions of a package to be co-installable.
- On 14% of the top 1,000 NPM packages, MINNPM finds newer dependencies than NPM on average.
- MINNPM’s solver-based approach is, on average, 1.7s–13.9s slower than NPM.

This slowdown is not an unreasonable cost to pay for predictable semantics. To summarize, our contributions are:

1. **PACsOLVE**: A general semantics of dependency solving, which highlights the essential differences between NPM, PIP, and Cargo; and its implementation in Rosette.
2. **MINNPM**: a drop-in replacement for NPM that uses PACSOLVE and allows the user to customize dependency solving.
3. An empirical evaluation of how choices in dependency solving affect popular NPM packages using MINNPM.

The rest of this paper is organized as follows. Section 2 presents PACSOLVE, our semantics of dependency solving; Section 3 applies PACSOLVE to qualitatively compare and highlight the semantics of PIP, NPM and Cargo; Section 4 presents our approach to synthesizing dependency solutions with PACSOLVE; Section 5 presents MINNPM, a drop-in replacement for NPM based on PACSOLVE; Section 6 presents our evaluation, which compares MINNPM to NPM on the NPM ecosystem; Section 7 presents related work; and Section 8 concludes.

2 A Semantics of Dependency Solving

We begin with an overview of the syntax and semantics of NPM, PIP, and Cargo, to motivate the need for PACSOLVE.

2.1 The Need for a Semantics

Consider a world with two published packages, $a$ and $b$, where $b$ has three published versions ($1.0.1$, $2.0.1$, and $2.0.2$), and $a$ depends exactly on the latest version of $b$, as shown Figure 1a. A program in JavaScript, Python, or Rust, can use NPM, PIP, or Cargo respectively to specify dependencies. Now suppose that the programmer requests $a$ (at any version), but they request $b$ that is strictly older than $2.0.2$. The programmer may do this because they find that $b$ 2.0.2 contains a new bug which breaks their program. All three package managers allow this request, but it conflicts with $a$’s requirement for $b$ 2.0.2. The three dependency solvers address the situation very differently, as we now explain.

The only way to successfully solve these constraints is to depend on two versions of $b$. PIP does not support this, and it fails. In contrast, NPM lets the program depend on the latest version of $b$ that is consistent (i.e., API compatible) with the constraint ($b$ 2.0.1), while allowing $a$ to depend on $b$ 2.0.2. Cargo’s behavior is more subtle: it does not allow two minor revisions of the same package to co-exist in a context, and the dependency resolves to $b$ 1.0.1 instead.

Arguably, there is no best solution to this problem. Each dependency solver makes a different set of choices on behalf of the programmer. The goal of PACSOLVE is to make these choices more transparent, and to give the programmer more visibility and control over dependency solving.

2.2 Packages, Versions, and Constraints

We now present PACSOLVE, which is a framework for describing dependency solving. For generality, PACSOLVE is parameterized by the syntax and semantics of constraints, the solver objectives, and more. To ground the discussion, this section gives NPM-based examples. But, in Section 3 we show how PACSOLVE can capture the semantics of PIP and Cargo as well.

In PACSOLVE, every package has (1) a package name ($\mathcal{P}$), which is a string; (2) a package version ($\mathcal{V}$), the syntax of which is package-manager dependent; and (3) a set of dependencies ($\mathcal{D}$), which are a list of package names and version constraints ($\mathcal{C}$). Similar to versions, the syntax of version constraints varies between concrete package managers.
Figure 1: Three syntactically similar dependencies for JavaScript (NPM), Rust (Cargo), and Python (PIP). Given the same set of published packages, each dependency solver produces a different result.

(a) Available packages

(b) JavaScript/NPM

(c) Rust/Cargo

(d) Python/PIP

Figure 2: Inputs and outputs in the PACSOLVE Model

(a) Example of $\mathcal{V}$ and $\mathcal{C}$, allowing conjunction, disjunction, and range operators on semver-style versions.

(b) A sat interpretation function for $\mathcal{V}$ and $\mathcal{C}$ defined in Figure 3a.

Figure 3: Example of $\mathcal{V}$, $\mathcal{C}$, and sat
A dependency solver interprets constraints to choose concrete packages from a universe of packages. We model the universe of all (relevant) packages as a set of known nodes \( \mathcal{N} \), which includes a distinguished root that represents the program. Each is a versioned package, and the function \( \text{deps} \) maps each versioned package to its list of dependencies.

As we have seen, every dependency solver interprets constraints and versions in subtly different ways. Thus, \( \text{PAC-SOLVE} \) is parameterized by a satisfaction predicate \( \text{sat} : \mathcal{C} \rightarrow \mathcal{P} \rightarrow \text{Bool} \) that determines if a concrete version satisfies a version constraint.

**Syntax and semantics of NPM** We now show how to encode a fragment of NPM versions and constraints in \( \text{PAC-SOLVE} \). (\( \text{MINNPM} \) is a complete implementation, which we discuss in Section 3.) In NPM, concrete versions are written in a dotted decimal notation \((x.y.z)\), and use semantic versioning (semver): each decimal represents a major, minor, and bugfix version, respectively. Incrementing a major version indicates a break in backward compatibility; incrementing a minor version indicates that features have been added, but none break existing APIs; and patch version differences indicate bugfixes that have no effect on the compatibility of two versions. NPM’s version constraints support a variety of operators, including conjunction, disjunction, upper and lower bounds, and semver compatibility.

In \( \text{PAC-SOLVE} \), we represent a version as a list of three numbers, \((x \ y \ z)\) and write constraints in the parenthesized prefix notation of Racket. Figure 3a shows the syntax of simplified NPM version numbers and constraints. Figure 3b defines the satisfaction predicate as a recursive Racket function, which uses pattern matching to compactly interpret ranges and semver compatibility.

**2.3 Solution Graphs**

We now have enough information to formulate the notion of a dependency solving problem. Given (1) a domain of versions \( \mathcal{V} \), (2) a domain of constraints \( \mathcal{C} \), (3) a satisfaction predicate \( \text{sat} \), and (4) a universe of packages and their dependencies \( (\mathcal{N}, \text{deps}) \), a dependency solver produces a solution graph \( G \). A solution graph is a directed graph with known packages as nodes \( N_R \). Every node has an ordered list of edges \( D_R \) that correspond to a dependency of that node that is selected by the dependency solver.

**Correctness of a solution graph** A solution graph \( G = (N_R, D_R) \) must satisfy six conditions to be correct. First, the solution graph must include the root node, which represents the program itself.

\[
\text{root} \in N_R
\]  

Second, the solution graph must be connected, which ensures that it does not include extraneous packages.

\[
G \text{ is connected}
\]  

Third, for all packages in the solution graph \( (N \in N_R) \), every dependency of the package must be resolved to a concrete package, with no extra resolved packages.

\[
|D_R(N)| = |\text{deps}(N)|
\]  

Fourth, for every edge in the solution graph \(( (p', v) = D_R(N)[n]) \) and the dependency that corresponds to that edge \(( (p, c) = \text{deps}(N)[n]) \), the edge must point to the expected package, and a version that satisfies the dependency constraint:

\[
p = p' \text{ and } \text{sat}(c, v)
\]  

However, dependency correctness still admits solutions that are unacceptable for many package managers. For example, a solution graph with resolved dependencies satisfying all dependency constraints may have several versions of the same package. As we showed in Section 2.1, NPM allows arbitrary versions to be co-installed, Cargo only allows semver-incompatible versions to be co-installed, and PIP only allows exactly one version of a package to be installed at a time. To express this range of behavior, \( \text{PAC-SOLVE} \) requires a consistency predicate \( \text{consistent} : \mathcal{V} \rightarrow \mathcal{V} \rightarrow \text{Bool} \) which determines whether or not two versions of a package may be co-installed.

\[
\forall (p, v), (p, v') \in N_R \cdot \text{consistent}(v, v')
\]  

For NPM, \( \text{consistent} \) is the constant function that produces true.

A final distinction between package managers is whether or not they allow cyclic dependencies. NPM and PIP support them, whereas Cargo does not. Thus \( \text{PAC-SOLVE} \) requires a flag that indicates whether cycles are allowed \( (\text{cycles\_ok}) \).

\[
\neg \text{cycles\_ok} \implies G \text{ is acyclic}
\]  

These six conditions determine whether or not a solution graph is correct with respect to the semantics of a particular dependency solver.

**Optimality of a solution graph** The goal of a dependency solver is to find a solution that is not only correct, but also good by some metric. Some dependency solvers prefer to install versions with larger version numbers, whereas others prefer to install more recently uploaded versions. Other metrics are possible as well, such as total download size or number of dependencies [31] and multiple prioritized objectives [18, 19]. \( \text{PAC-SOLVE} \) supports optimizing an objective function that maps a solution graph to a sequence of numbers that represent a prioritized list of minimization criteria \( (\text{minGoal} : G \rightarrow \mathbb{R}^n) \).
To give a sense of concrete examples of minimization criteria in PacSolve, consider Figure 4, which defines three examples of minimization criteria. The first example (Figure 4a) is the simplest: given a solution graph \( G \), it returns how many nodes are in \( G \), thus minimizing the total number of dependencies.

The second example (Figure 4b) is our interpretation of the common goal that package managers have of trying to choose newer versions of dependencies. In this example, each node in the graph is assigned an \textit{oldness}, which is linear score between 0 (newest) and 1 (oldest) of that version’s rank in the total ordering of versions for that package. These oldness scores are then summed up across the graph. There are two subtleties with this definition. 1) The choice to perform \textit{minimization} rather than \textit{maximization} is important, as a goal of maximizing a newness score, e.g. 1 meaning newest, 0 meaning oldest, would encourage the solver to find very large solution graphs so as to inflate the total newness. 2) The choice to sum rather than average the oldness values likewise discourages the solver from adding in a lot of new nodes so as to inflate the mean oldness.

A third example (Figure 4c) minimizes the co-installation of multiple versions of the same package. The function first counts how many nodes there are in the graph for each package. Then, for each package, we assign a cost of 1 for each extra node, and sum all the costs up.

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**PacSolve Query**  
The addition of the \textit{minGoal} function completes the format of a generalized dependency solving problem. We call this format a PacSolve Query:

\[
\text{PacSolve Query} ::= (V, C, \text{sat}, \text{consistent}, \text{cycles_ok, minGoal, } N, \text{deps})
\]

---

### 3 Comparing Package Managers

Thus far we have presented PacSolve queries by drawing on concrete examples from NPM. We now turn to: (a) examining how PacSolve can be used to model the semantics of both PIP and Cargo, in addition to NPM, and, (b) comparing the formal properties of the dependency solvers of NPM, PIP, and Cargo.

#### 3.1 Modeling a Variety of Semantics

While Figure 3 defined the semantics of a simplified model of NPM, with a bit more work PacSolve can model more complex semantics, which we demonstrate here by fleshing out more details for NPM, as well as sketching models for PIP and Cargo.

**Version Numbers and Constraints**  
The structure of version number data can be chosen so as to include any necessary data to disambiguate configurations of a package. For
example, an accurate structure of version numbers for NPM contains not only three numbers for a semver version, but an additional field for release tags, so for example an element of \( \nu' \) may be (1.2.3 "alpha1"). Python’s PIP package manager uses version specifiers that are fully compatible with semantic versioning, with similar extensions for pre- and post-release versions [11].

Rust’s Cargo package manager presents a more complex situation. In Cargo, packages are allowed to contain named features, which can be used to enable conditional compilation and enable otherwise disabled dependencies. For example, an image processing package may contain the features “png” and “jpeg”. To model this, we might choose elements of \( \nu' \) to have the form \((x,y,z,F)\), where \(F\) is a subset of the listed features for version \(x,y,z\).

Similarly, constraints (\(\epsilon\)) may be enriched to contain necessary data to model the package manager. In Cargo’s case, for example, constraints would be extended to contain both version range constraints similar to Figure 3a and a set of features that are required to be enabled in the dependency.

**Satisfaction Semantics** Based on how the sets of versions and constraints have been chosen, the constraint satisfaction function (\(sat\)) needs to be adapted to model the package manager.

NPM features some tricky semantics when matching prerelease versions: a prerelease version can only satisfy a constraint if a sub-term of the constraint with the same semver version also has a prerelease. For example, the constraint \(1.2.3\text{-alpha.}3\ \&\&\ v1.5.2\text{-alpha.}8\) would be satisfied by \(v1.2.3\text{-alpha.}7\), \(v1.3.4\), and \(v1.5.2\text{-alpha.}6\), but would not be satisfied by \(v1.3.4\text{-alpha.}7\). These semantics can be encoded in \textsc{PacSolve} by having the \textit{sat} function recursively check for constraint terms which contain identical semver versions with prereleases. MINNPM (Section 5) implements these semantics.

The semantics of Cargo’s features requires a node in the solution graph to have enabled all the features which dependents requested, and no extra. Specifically, Cargo implements a unification semantics, where the enabled features of a node \(N\) should be the union of the requested features from all predecessors of \(N\) in the solution graph. These semantics can be encoded in \textsc{PacSolve} by making use of both \textit{sat} and \textit{minGoal}. The \textit{sat} function checks that the enabled features are a subset of the requested features, and the \textit{minGoal} function would minimize at the highest priority the number of enabled features, so that no extras are included.

**Consistency and Cycles** NPM, PIP, and Cargo all make different choices of consistency semantics, at different points along a spectrum of consistency strictness.

PIP is the strictest of these three package managers: it forbids installation of different versions of the same package. This behavior is dictated by two factors. First, Python’s module system identifies modules only by name, and if any two modules with the same name are in Python’s module search path, one will always be found first and shadow the other. Second, at least when installing modules into a single Python installation or virtual environment, two modules with the same name will conflict on the filesystem.

Neither Rust nor JavaScript have Python’s single version restriction; they allow installation of different versions of the same package. Node is able to support this because packages (JavaScript source files) are laid out in a \texttt{node_modules} directory tree on disk. Any directory in the tree can have its own local version of a dependency. Cargo chooses to restrict this to only allow versions to be co-installed if they are not semver-compatible. Multi-versioning is possible in Rust because Rust binaries are statically linked. They can exploit symbol rewriting to differentiate two instances of the same package. So, under Cargo’s semantics, 1.3.5 and 2.1.4 can be co-installed, but 1.3.5 and 1.4.2 can’t be.

In the most relaxed case, NPM allows any versions whatsoever to be co-installed. All three of these consistency semantics can be encoded in \textsc{PacSolve} as shown in Figure 5.

In addition, the package managers exhibit different semantics with regards to cycles: NPM and PIP allow for cyclic solution graphs, but Cargo forces all solution graphs to be acyclic.

**3.2 Properties of Dependency Solvers**

We have sketched the main differences between PIP, NPM, and Cargo, and shown how these differences can be encoded in \textsc{PacSolve}. We now turn to examining what properties these three dependency solvers appear to provide based on (limited) manual testing we have performed. First, we define the notion of an (abstract) dependency solver, and then walk through three main properties and whether or not they hold for PIP, NPM and Cargo.

A dependency solver \(S\) defined for semantics given by \((\nu', \epsilon, sat, consistent, cycles_{ok}, minGoal)\) is a function producing a solution graph (or error) given as input a set of
known nodes (\(\mathcal{N}\)) and dependency data (deps):

\[ S(\mathcal{N}, \text{deps}) \in G \cup \{\bot\} \]

For the definitions below, we let the parameters for the semantics \((\mathcal{V}, \mathcal{g}, \text{sat}, \text{consistent}, \text{cycles-ok}, \text{minGoal})\) be implicitly fixed to represent the semantics for the respective dependency solver.

**Correctness** A dependency solver \(S\) is **correct** if for all \(\mathcal{N}\) and deps, if \(S(\mathcal{N}, \text{deps}) = G \neq \bot\), then \(G\) is correct (Section 2.3).

In our testing, all three of PIP, NPM and Cargo returned correct solution graphs, for appropriate choices of PacSOLVE semantics as outlined above. Note that this is a stronger property for dependency solvers with strict notions of consistency (PIP, Cargo), and for dependency solvers which disallow cycles (Cargo). Thus, we conjecture that PIP, NPM and Cargo all have correct dependency solvers.

**Completeness** We next examine completeness. We say that a dependency solver \(S\) is **complete** if for all \(\mathcal{N}\) and deps, if there exists a correct solution graph, then \(S(\mathcal{N}, \text{deps}) \neq \bot\).

In our testing, PIP and NPM both always managed to successfully return a solution graph, if a solution graph exists according to their corresponding semantics. The intuitions for how they accomplish this are different however: PIP will backtrack upon finding conflicting nodes, and after enough backtracking will eventually find a solution (if one exists). NPM, on the other hand, does not have conflicts, and thus does not need to perform backtracking. We conjecture that PIP and NPM both have complete dependency solvers.

Cargo also performs backtracking similarly to PIP. However, Cargo also checks that the solution graph is acyclic, and performs this check post-solver, rather than as part of the backtracking phase. We can exploit this to develop a counter-example which demonstrates that Cargo has an incomplete solver. We can construct a package \(A\) with two versions, and a package \(B\) with one version, with dependencies as so: \(A\v_1\theta\theta\) has no dependencies, \(A\v_2\theta\theta\) depends on any version of \(B\), and \(B\v_1\theta\theta\) depends on any version of \(A\). Finally, the root node depends on any version of \(A\).

There exists an acyclic solution to this situation: the root node chooses \(A\v_1\theta\theta\), which then has no further dependencies. However, in this situation Cargo will find a cyclic solution first, such as \(A\v_2\theta\theta\) and \(B\v_1\theta\theta\) which mutually depend on each other, then recognize that it is cyclic, and fail with an error.

**Optimality** The property of optimality depends on the specific choice of minimization criteria (\(\text{minGoal}\)), in addition to the other choices of semantics. A common optimization objective is to prefer newer versions of packages when possible, but NPM, PIP and Cargo do not agree on what “newer” means: PIP and Cargo prefer numerically larger version numbers, while NPM has a more complex strategy of preferring the temporally most recently uploaded version and then falling back to largest version numbers. More generally, a wide range of other optimization criteria are possible, as explained in Section 2.3.

A dependency solver \(S\) is **optimal** for minimization criteria \(\text{minGoal}\) if \(S\) is correct and complete, and if for all \(\mathcal{N}\) and deps, if there exists a correct solution graph, then

\[
\text{minGoal}(S(\mathcal{N}, \text{deps})) = 
\min\{\text{minGoal}(G) \mid G \in \mathcal{G}, G \text{ is correct}\} \tag{7}
\]

NPM, PIP and Cargo all apply their preference for newer versions (for their choice of newer) in a heuristic manner, guided by the order in which they explore solution graphs. All of these package managers are not, in general, optimal for any reasonable encoding of “newness” into minimization criteria.

### 4 Synthesizing Solution Graphs with PacSOLVE

Performing dependency solving in the face of potentially conflicting dependencies is known to be NP-complete [14]. Some package managers use polynomial-time algorithms by giving up on various properties, such as disregarding conflicts (NPM) and eschewing completeness (PIP’s old solver [27]). Since the PacSOLVE model includes a generalized notion of conflicts (consistent), we make use of SMT solvers to implement PacSOLVE efficiently.

We implement PacSOLVE in Rosette [29], which is a **solver-aided language** that facilitates building verification and synthesis tools for DSLs. In the PacSOLVE DSL, the program is a solution graph. We implement a function that consumes (1) a solution graph and (2) the parameters to the correctness criteria (Figure 2), and asserts that the solution graph is correct. Since we use Rosette, with a little effort, we can feed the predicate a solution graph sketch instead of a concrete solution graph. This allows us to use Rosette to perform **angelic execution** [10] to synthesize a solution graph that satisfies the correctness criteria. This section describes the synthesis procedure in more detail, starting with how we build a sketch.

**Sketching solution graphs** Before invoking the Rosette solver, we build a sketch of a solution graph that has a node for every version of every package that is reachable from the set of root dependencies. Every node in a sketch has the following fields: (1) a concrete name and version for the package that it represents (or the distinguished root node); (2) a symbolic boolean included that indicates whether or not the node is included in the solution graph; (3) a symbolic natural number depth which we use to enforce acyclic solutions.
Figure 6: A solution graph sketch corresponding to Figure 1

when desired; (4) a vector of concrete dependency package names; (5) a vector of concrete version constraints for each dependency; and (6) a vector of symbolic resolved versions for each dependency.

Figure 6 illustrates the solution graph sketch corresponding to the dependency solving problem given in Figure 1. The combination of concrete dependency names and symbolic dependency versions can be seen as representing symbolic edges in two parts: a concrete part which does not need to be solved for (solid arrows), and a symbolic part which requires solving (dashed arrows). This representation shrinks the solution space of graphs as outgoing edges can only point to nodes with the correct package name.

Graph Sketch Solving We define three assertion functions that check correctness criteria of a solution graph:

1. check-dependencies consumes a graph and a node, and asserts that if the node is included, then all the dependencies of the node are (1) included in the graph; and (2) consistent with the associated version constraints as judged by the constraint interpretation function (sat). We run this assertion function on all nodes, and additionally assert that the root node is included.

2. globally-consistent? consumes a graph and asserts that for all pairs of nodes that are (a) included in the graph, and (b) have the same package name, their package versions are allowed to be co-installed as given by the consistency function (consistent). We run this assertion function on all nodes, and additionally assert that the root node has depth zero.

3. acyclic? consumes a graph and asserts that the depth of the node is strictly less than the depth of all its dependencies. If an acyclic solution is desired, we run this assertion function on all nodes, and assert that the root node has depth zero.

We also use Rosette to execute the objective function (minGoal) on the graph sketch, yielding a symbolic real-valued formula, and then instruct Rosette to minimize it when concretizing the solution graph sketch. As a final step, to produce a solution graph, we traverse the concretized solution graph sketch from the root node, and produce those nodes that are marked included.

5 MinNPM

We leverage PACSOLVE to implement a new dependency solver for NPM: MinNPM. This allows us to evaluate PACSOLVE to see if it is powerful enough to build a dependency solver for a real-world package manager. Then in Section 6 we evaluate the quality of MinNPM’s solutions compared to standard NPM.

5.1 MinNPM’s User Interface

MinNPM is implemented as a fork of NPM, adding support for a PACSOLVE-based solver which must users must opt-in to. When running a npm install command, users can now write npm install --minnpm to enable the new dependency solver.

MinNPM’s semantics are configurable by the user. The user may choose both the consistency semantics and the minimization objectives. Without customization, MinNPM will by default use standard NPM’s notion of consistency (Figure 5) and minimize at the highest priority the presence of older versions, and at lower priority the total number of resolved dependencies. To change the consistency semantics, the user uses the --consistency <style> option, where <style> is one of npm, pip or cargo. The minimization objectives can be specified by the user providing a comma separated list of prioritized objectives, built from linear combinations of three pre-defined objectives. The pre-defined objectives to choose from are:

- min_oldness: Minimizes the number of installed old versions.
- min_num_deps: Minimizes the number of installed dependencies.
- min_duplicates: Minimizes the number of co-installed different versions of the same package.

The precise meaning of each of the objectives is given in Figure 4. For example, the command:

```
  npm install --minnpm --consistency pip \n  --minimize min_oldness,min_num_deps
```

would force there to be no co-installation of different versions of the same package, while choosing the least old versions possible, and the smallest number of dependencies possible.
5.2 MINNPM’s Implementation

When implementing a package manager’s dependency solver with PACSOLVE, there are two primary steps: 1) Determine how to correctly encode the semantics into the PACSOLVE input language, and 2) determine how to prepare queries consisting of node and dependency data.

The encoding of NPM’s semantics into PACSOLVE has been discussed to some degree in Section 3. To summarize, version numbers (\(V\)) are chosen to be a 4-tuple: 3 components for the standard semver components, and 1 component for prerelease tags. The constraint matching semantics (sat) implement NPM’s subtle prerelease semantics by recursively checking if sub-terms in the constraint syntax have an exact match when checking if a prerelease version is allowed.

Next, MINNPM must decide at runtime what set of packages (\(N\)) to include in the PACSOLVE query. For the solver to be complete and optimal (Section 3.2), MINNPM must include enough nodes in \(N\) such that if there exists a solution, then an optimal solution can be found using only the nodes in \(N\). A sound algorithm for this is a graph traversal starting at the root node, and moving from node \(x\) to node \(y = (p', v)\) if for any \((p, c) \in \text{deps}(x), p = p'\) and sat(c, v) is true. Any potentially useful node for the solve will be visited by the graph traversal. It can easily be seen that any correct and consistent solution graph would be a subgraph of the graph traversal.

6 Evaluation

In this section we evaluate MINNPM in variety of configurations and contrast its performance to NPM.

Dataset We apply MINNPM and NPM to the top 1,000 most downloaded packages from npmjs.com in August 2021. These packages have other dependencies, thus the full set of packages that we build involve more than 1,000 packages.

Experimental setup Our performance benchmarks are reported on Linux, with a 16-Core AMD EPYC 7282 CPU and 64 GB RAM. We use NPM 7.20.1. MINNPM uses Racket 8.2, Rosette 4.0, and Z3 4.8.8. NPM and MINNPM cache packages locally, and we warm the cache before measuring running times. We also configure NPM to not run post-install scripts, not install optional features, and not perform audits.1

We ask several questions in this section:

1. How frequently does dependency solving fail with NPM and MINNPM, and why? On our dataset of 1,000 packages we observe 38 with NPM, and 42—45 failures with MINNPM (depending on how it is configured).
2. Is NPM’s tree solver necessary for solves to succeed? NPM allows multiple versions of the same package to be co-installed with no restrictions whatsoever. This makes dependency solving less likely to fail, but can produce bloated dependencies. We configure MINNPM to disallow duplicate packages, and find that only 3% of packages fail.
3. Can MINNPM produce newer packages? We configure MINNPM with newness as a global objective, and find that it produces newer dependencies on 14% of packages.
4. Can MINNPM successfully reduce the number of dependencies? This is a straightforward objective for MINNPM, and we find that it can reduce the number of dependencies for 20% of packages.
5. How much slower is MINNPM than NPM? NPM uses a non-backtracking tree solver, partly to improve performance. MINNPM times out on 16–18 packages (depending on how it is configured). In other cases, MINNPM takes an addition 1.7s on average.

The rest of this section presents these results in more depth, and highlights several illustrative examples.

6.1 Failures in NPM and MINNPM

On the top 1,000 packages, Table 1 shows the number of packages on which NPM and MINNPM fail. Overall, NPM itself fails to solve dependencies for 38 packages, whereas MINNPM with NPM-style consistency fails on 42—45 packages. (We discuss failures with PIP-style consistency in Section 6.2.)

It may come as a surprise that NPM itself fails to solve dependencies on a few packages. Many of these failures occur because NPM attempts to solve for broken peer-dependencies (a type of optional conflicting dependency in NPM). In contrast, MINNPM succeeds because these broken dependencies are optional.2 Overall, there are 29 cases where MINNPM fails but NPM succeeds. In all cases, the failure is either due to a crash in PACSOLVE, or a crash or timeout in the Z3 solver.

6.2 The Need for Tree Solving

NPM uses a tree solver (Section 3), which ensures that dependency solving cannot fail when two dependencies have conflicting constraints. When such a scenario occurs, NPM happily loads two versions of the same dependency to avoid the conflict. However, this approach has its shortcomings. It is obvious that it can lead to code bloat. But, more subtle errors can occur when two versions of the same dependency need to

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1We use --no-audit, --prefer-offline, --ignore-scripts, --omit dev, --omit peer, --omit optional as flags for NPM.

2They are peerDependencies that aren’t necessary to build the project. However, NPM attempts to solve for them, even when --omit-peer is specified.
communicate or share state. We can configure \textsc{MinNPM} to either 1) use NPM-style consistency, or 2) a strictly PIP-style consistency model, which disallows multiple versions of the same dependency. In the latter mode, an additional 32 packages fail (Table 1). Whether or not 32 more failures out of 1,000 packages is too many or negligible could be argued either way. Instead, let’s examine a package that succeeds with NPM-style consistency, but fails with PIP-style consistency.

### Fixing a failure

The package \texttt{terser@5.9.0} is a widely used JavaScript parser that fails with PIP-style consistency. The package directly depends on version 0 of \texttt{source-map} and version 0.5.y of \texttt{source-map-support}. However, \texttt{source-map-support} depends on version 0.6.z of \texttt{source-map}. This forces \texttt{terser} to include two versions of \texttt{source-map}: 0.7.x and 0.6.z. The ideal fix is to upgrade \texttt{source-map-support} to support 0.7.x of \texttt{source-map}, which will allow \texttt{terser} to include only one version of \texttt{source-map}.

#### 6.3 Minimization Criteria

NPM uses a greedy algorithm that prefers newer versions of a dependency. In contrast, \textsc{MinNPM} is configurable with a variety of objectives, including minimizing the total oldness of dependencies, and the total number of dependencies. We now compare NPM to \textsc{MinNPM} with these two objectives, in this order.

**Minimizing Oldness** We define the oldness of a package version \(\text{old}(p, v)\) as a function that assigns the newest version the value 0, the oldest version the value 1, and other versions on a linear scale in between. Given a solution graph we calculate its mean oldness:

\[
\bar{\text{old}}((N_R, D_R)) = \{ \text{old}(n_{src}) | n_{src} \in N_R, n_{dst} \in D_R(n_{src}) \} \tag{8}
\]

The metric is slightly different from the oldness minimization objective in \textsc{MinNPM} in two ways: this metric counts multiple uses of the same package version, and takes the mean rather than sum. This metric is more natural to interpret, as it gives the average oldness of code that is loaded by import statements.

Figure 7a shows a point for every package, with its mean oldness for NPM and \textsc{MinNPM} as the \(x\) and \(y\) coordinates. Points along the main diagonal \((y = x)\) are packages whose dependencies are just as old with both NPM and \textsc{MinNPM}. 14% of points are below the diagonal and 3% are above the diagonal, which indicates that \textsc{MinNPM} produces newer dependencies on average.

**Minimizing the number of dependencies** Another objective function in \textsc{MinNPM} minimizes the total number of dependencies. However, this objective must be used with care: older versions of a package can have fewer dependencies. So, asking for the minimum number of dependencies can have the undesirable effect of choosing ancient dependencies! It is best to combine this objective with another. We compare NPM’s behavior with \textsc{MinNPM} minimizing total number of dependencies and total oldness.

Figure 7b shows an empirical CDF, where the \(x\)-axis shows the fraction of dependencies with \textsc{MinNPM} instead of NPM. Thus for about 20% of packages, \textsc{MinNPM} is able to reduce the number of dependencies. For the same set of packages, the total space required shrinks significantly (Figure 8). Half the packages require 40% less disk space with \textsc{MinNPM}.

#### 6.4 Performance of \textsc{MinNPM}

Note that \textsc{MinNPM} exhibits a solver crash or times out after 10 minutes on up to 27 packages (Table 1). On the remaining packages, we compare its performance to NPM. Figure 7c is an empirical CDF of the amount of additional time (in seconds) that \textsc{MinNPM} takes to solve dependencies on these packages. \textsc{MinNPM} takes up to 13.9s extra time, but only 1.7s more on average than NPM.

A significant portion of these two seconds is the time it takes to serialize the input from \textsc{MinNPM} for \textsc{PacSolve} (JavaScript), start \textsc{PacSolve} (Racket), and communicate with the solver (Z3). Rosette relies on Racket, and allows us to prototype \textsc{PacSolve}, but this step could be eliminated in a re-implementation that is focused on performance.

| Solver | Consistency | Minimization | Unsat | Timeout | Other |
|--------|-------------|--------------|-------|---------|-------|
| NPM    | npm         | min_oldness,min_num_deps | 0     | 0       | 38    |
| MinNPM | npm         | min_num_deps,min_oldness | 0     | 17      | 26    |
| MinNPM | npm         | min_duplicates,min_oldness | 0     | 16      | 26    |
| MinNPM | npm         | min_oldness,min_duplicates | 0     | 18      | 27    |
| MinNPM | pip         | min_oldness,min_num_deps | 9     | 18      | 50    |
| MinNPM | pip         | min_num_deps,min_oldness | 9     | 18      | 50    |

Table 1: Failures that occur on top 1000 downloaded Node packages
Oldness with NPM
Oldness with MinNPM
(a) Packages may have newer dependencies.
(b) Packages may have fewer dependencies.
(c) MinNPM takes a few more seconds.

Figure 7: Comparing NPM to MinNPM. These plots ignore failures in both solvers and have MinNPM configured to use NPM-style consistency. In Figure 7a, MinNPM is configured to minimize oldness and the number of dependencies (in that order). Each point represents a package, and those below the line have newer dependencies, by the metric in Equation (8). In Figure 7b, MinNPM is configured to minimize the number of dependencies and oldness (in that order). MinNPM reduces dependencies in about 20% of packages. In Figure 7c, MinNPM is configured to minimize oldness and the number of dependencies. On average, MinNPM takes 1.7s more time than NPM.

Figure 8: MinNPM can reduce space required.

7 Related Work

Van der Hoek et al. first discussed the idea of “software release management” [32] for large numbers of independent packages in 1997, and the first package managers for Linux distributions emerged at around the same time [16, 22]. The version selection problem was first shown to be NP-complete and encoded as a SAT and Constraint Programming (CP) problem by Di Cosmo et al. [14, 25] in 2005. This early work led to the Mancoosi project, which developed the idea of a modular package manager with customizable solvers [5, 6]. This work centers around the Common Upgradeability Description Format (CUDF), an input format that can be generated by package manager front-ends to describe a given upgradeability scenario to a back-end solver.

CUDF facilitated the development of solver implementations using Mixed-Integer Linear Programming, Boolean Optimization, and Answer Set Programming [7, 20, 26], and many modern Linux distributions have adopted CUDF-like approaches [4]. OPIUM [31] examined the use of ILP with weights to minimize the number of bytes downloaded or the total number of packages installed.

While package managers have their roots in Linux distributions, they have evolved considerably since the early days. Modern language ecosystems have evolved their own package managers [2, 9, 28, 33], with solver requirements distinct from those of a traditional Linux distribution. Distribution package managers typically manage only a single, global installation of each package, while language package managers are geared more towards programmers and allow multiple installations of the same software package.

For the most part, language ecosystems have avoided using complete solvers. There are a number of reasons for this. Solvers are complex, and they have a steep learning curve. Even on the Linux distribution side, so-called functional Linux distributions [12, 15] eschew solving altogether, opting instead to focus on reproducible configurations maintained by humans. Most programmers do not know how to use solvers effectively, and fast, high-quality solver implementations do not exist for new and especially interpreted languages. Moreover, package managers are now fundamental to software ecosystems, and most language communities prefer to write and maintain their core tooling in their own language.

Despite this, developers are starting to realize the need for
completeness and well defined dependency resolution semantics [4]. The Python community, plagued by inconsistencies in resolutions done by PIP has recently switched to a new resolver with a proper solver [27]. Dart now uses a custom CDCL SAT solver called PubGrub [33], and Rust’s Cargo [2] package manager is moving towards this approach [3].

Solvers themselves are becoming more accessible through tools like Rosette [29], which makes features of the Z3 [13] SMT solver accessible within regular Racket [17] code. Stack [19] makes complex constraints available in a Python DSL, and implements their semantics using Answer Set Programming [18, 21]. APT is moving towards using Z3 to implement more sophisticated dependency semantics [23].

The goal of our work is to further separate concerns away from package manager developers. PACSOLVE focuses on consistency criteria and formalizes the guarantees that can be offered by package solvers. NPM [28]’s tree-based solver avoids the use of an NP-complete solver by allowing multiple, potentially inconsistent versions of the same package in a tree. Tools like Yarn [1] attempt to improve on this with post-hoc techniques like hoisting [24] that deduplicate the dependency graph after solving. However, they still do not guarantee consistent semantics. PACSOLVE provides the best of all these worlds. It combines the flexibility of multi-version resolution algorithms with the guarantees of complete package solvers, and it guarantees a minimal dependency graph.

8 Conclusion

We present PACSOLVE, a semantics of dependency solving that we use to highlight the essential features and differences between NPM, PIP, and Cargo. We use PACSOLVE to implement MinNPM, a drop-in replacement for NPM that allows the user to customize dependency solving with a variety of global objectives and consistency criteria. We use MinNPM to conduct an empirical evaluation of dependency solving for the top 1,000 packages in the NPM ecosystem. We find that MinNPM produces solutions with fewer dependencies and newer dependencies for many packages. For future work, we hope to use PACSOLVE to build new dependency solvers for other package managers as well.

References

[1] Yarn: Yet Another Resource Negotiator (javascript package manager). https://github.com/yarnpkg/yarn.
[2] Cargo: The Rust package manager. Online, March 2014. https://github.com/rust-lang/cargo.
[3] PubGrub version solving algorithm implemented in Rust. Online. 2020. https://github.com/pubgrub-rs/pubgrub.
[4] P. Abate, R. Di Cosmo, G. Gousios, and S. Zacchirolli. Dependency solving is still hard, but we are getting better at it. In 2020 IEEE 27th International Conference on Software Analysis, Evolution and Reengineering (SANER), pages 547–551. IEEE, 2020.
[5] P. Abate, R. Di Cosmo, R. Treinen, and S. Zacchirolli. Dependency solving: a separate concern in component evolution management. Journal of Systems and Software, 85(10):2228–2240, 2012.
[6] P. Abate, R. Di Cosmo, R. Treinen, and S. Zacchirolli. A modular package manager architecture. Information and Software Technology, 55(2):459 – 474, 2013. Special Section: Component-Based Software Engineering (CBSE), 2011.
[7] J. Argelich, D. Le Berre, I. Lynce, J. P. M. Silva, and P. Raphelaud. Solving linux upgradeability problems using boolean optimization. In I. Lynce and R. Treinen, editors, Proceedings First International Workshop on Logics for Component Configuration, LoCoCo 2010, Edinburgh, UK, 10th July 2010, volume 29 of EPTCS, pages 11–22, 2010.
[8] A. Behel. Github issue: React 17 support, October 26 2020. https://github.com/atlassian/react-beautiful-dnd/issues/1993.
[9] I. Bicking. pip: Package Install tool for Python, April 2011. https://github.com/pypa/pip.
[10] M. Broy and M. Wirsing. On the algebraic specification of nondeterministic programming languages. In Colloquium on Trees in Algebra and Programming, pages 162–179. Springer, 1981.
[11] N. Coghlan. PEP 440 – Version Identification and Dependency Specification. Online, March 18 2013. https://www.python.org/dev/peps/pep-0440.
[12] L. Courtès and R. Wurmus. Reproducible and User-Controlled Software Environments in HPC with Guix. In 2nd International Workshop on Reproducibility in Parallel Computing (RepPar), Vienne, Austria, Aug. 2015.
[13] L. De Moura and N. Björner. Z3: An efficient smt solver. In International conference on Tools and Algorithms for the Construction and Analysis of Systems, pages 337–340. Springer, 2008.
[14] R. Di Cosmo. EDOS deliverable WP2-D2.1: Report on Formal Management of Software Dependencies. Technical report, INRIA, May 15 2005. hal-00697463.
[15] E. Dolstra, M. de Jonge, and E. Visser. Nix: A Safe and Policy-Free System for Software Deployment. In Proceedings of the 18th Large Installation System Administration Conference (LISA XVIII), LISA ’04, pages 79–92, Berkeley, CA, USA, 2004. USENIX Association.
[16] M. Ewing and E. Troan. RPM Timeline. Online, 1995. https://rpm.org/timeline.html.
[17] M. Felleisen, R. B. Findler, M. Flatt, S. Krishnamurthi, E. Barzilay, J. McCarthy, and S. Tobin-Hochstadt. The racket manifesto. In Proceedings First International Workshop on Logics for Component Configuration, LoCoCo 2010, Edinburgh, UK, 10th July 2010, volume 29 of EPTCS, pages 11–22, 2010.
[18] T. Gamblin. Spack’s new Concretizer: Dependency solving is more than just SAT! In Free and Open source Software Developers’ European Meeting (FOSDEM’20), Brussels, Belgium, February 1 2020.
[19] T. Gamblin, M. P. LeGendre, M. R. Collette, G. L. Lee, A. Moody, B. R. de Supinski, and W. S. Futral. The Spack Package Manager: Bringing order to HPC software chaos. In Supercomputing 2015 (SC’15), Austin, Texas, November 15-20 2015. LLNL-CONF-669890.
[20] M. Gebser, R. Kaminski, and T. Schaub. aspcud: A linux package configuration tool based on answer set programming. Electronic Proceddings in Theoretical Computer Science, 65:12–25, Aug 2011.
[21] M. Gebser, B. Kaufmann, R. Kaminski, M. Ostrowski, T. Schaub, and M. Schneider. Potassco: The potassco answer set solving collection. AI Communications, 24(2):107–124, 2011.
[22] J. Gunthorpe. APT User’s Guide. Online, 1998. https://www.debian.org/doc/manuals/apt-guide/.
[23] J. A. Klode. APT Z3 Solver Basics. Online, November 21 2021. https://blog.jak-linux.org/2021/11/21/apt-z3-solver-basics/.
[24] T. Maier. A guide to understanding how Yarn hoists dependencies and handles conflicting packages. Online, November 27 2021. https://maier.tech/posts/a-guide-to-understanding-how-yarn-hoists-dependencies-and-handles-conflicting-packages.

[25] F. Mancinelli, J. Boender, R. di Cosmo, J. Vouillon, B. Durak, X. Leroy, and R. Treinen. Managing the complexity of large free and open source package-based software distributions. In 21st IEEE/ACM International Conference on Automated Software Engineering (ASE’06), pages 199–208, 2006.

[26] C. Michel and M. Rueher. Handling software upgradeability problems with MILP solvers. In I. Lynce and R. Treinen, editors, Proceedings First International Workshop on Logics for Component Configuration, LoCoCo 2010. Edinburgh, UK, 10th July 2010, volume 29 of EPTCS, pages 1–10, 2010.

[27] Python Software Foundation. New pip resolver to roll out this year. Online, March 23 2020. https://pyfound.blogspot.com/2020/03/new-pip-resolver-to-roll-out-this-year.html.

[28] I. Z. Schlueter. NPM. Online, September 2009. https://github.com/npm/npm.

[29] E. Torlak and R. Bodik. Growing solver-aided languages with rosette. In Proceedings of the 2013 ACM International Symposium on New Ideas, New Paradigms, and Reflections on Programming & Software, Onward! 2013, page 135–152, New York, NY, USA, 2013. Association for Computing Machinery.

[30] E. Torlak and R. Bodik. A lightweight symbolic virtual machine for solver-aided host languages. 2014.

[31] C. Tucker, D. Shuffelton, R. Jhala, and S. Lerner. Opium: Optimal package install/uninstall manager. In Proceedings of the 29th International Conference on Software Engineering, ICSE ’07, pages 178–188, USA, 2007. IEEE Computer Society.

[32] A. Van Der Hoek, R. S. Hall, D. Heimbigner, and A. L. Wolf. Software release management. ACM SIGSOFT Software Engineering Notes, 22(6):159–175, 1997.

[33] N. Weizenbaum. PubGrub: Next-Generation Version Solving. https://medium.com/@nex3/pubgrub-2f6470504f, April 2 2018.