Build systems à la carte: Theory and practice

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Abstract
Build systems are awesome, terrifying – and unloved. They are used by every developer around the world, but are rarely the object of study. In this paper, we offer a systematic, and executable, framework for developing and comparing build systems, viewing them as related points in a landscape rather than as isolated phenomena. By teasing apart existing build systems, we can recombine their components, allowing us to prototype new build systems with desired properties.

1 Introduction
Build systems (such as MAKE) are big, complicated, and used by every software developer on the planet. But they are a sadly unloved part of the software ecosystem, very much a means to an end, and seldom the focus of attention. For years MAKE dominated, but more recently the challenges of scale have driven large software firms like Microsoft, Facebook, and Google to develop their own build systems, exploring new points in the design space. These complex build systems use subtle algorithms, but they are often hidden away, and not the object of study.

In this paper, we give a general framework in which to understand and compare build systems, in a way that is both abstract (omitting incidental detail) and yet precise (implemented as Haskell code). Specifically, we make these contributions:

- Build systems vary on many axes, including: static versus dynamic dependencies; local versus cloud; deterministic versus non-deterministic build tasks; early cutoff; self-tracking build systems; and the type of persistently stored build information.

In Section 2, we identify some of these key properties, illustrated by four carefully chosen build systems.
We describe some simple but novel abstractions that crisply encapsulate what a build system is (Section 3), allowing us, for example, to speak about what it means for a build system to be correct.

We identify two key design choices that are typically deeply wired into any build system: the order in which tasks are built (Section 4) and whether or not a task is rebuilt (Section 5). These choices turn out to be orthogonal, which leads us to a new classification of the design space (Section 6).

We show that we can instantiate our abstractions to describe the essence of a variety of different real-life build systems, including MAKE, SHAKE, BAZEL, BUCK, NIX, and EXCEL, each by the composition of the two design choices (Section 6). Doing this modelling in a single setting allows the differences and similarities between these huge systems to be brought out clearly.

Moreover, we can readily remix the ingredients to design new build systems with desired properties, for example, to combine the advantages of SHAKE and BAZEL. Writing this paper gave us the insights to combine dynamic dependencies and cloud build systems in a principled way; we evaluate the result in Section 7.

We use the presented abstractions to more clearly explain details from the original SHAKE paper (Sections 5.2.2 and 7.2) and develop new cloud build features, which are already in use in industry and in the GHC build system (Sections 7.4 and 7.5).

In short, instead of seeing build systems as unrelated points in space, we now see them as locations in a connected landscape, leading to a better understanding of what they do and how they compare, and making it easier to explore other points in the landscape. While we steer clear of many engineering aspects of real build systems, in Section 8, we discuss these aspects in the context of the presented abstractions. The related work is covered in Section 9.

This paper is an extended version of an earlier conference paper (Mokhov et al., 2018). The key changes compared to the earlier version are (i) we added further clarifications and examples to Section 3, and in particular, Section 3.8 is entirely new; (ii) Sections 4 and 5 are based on the material from the conference paper but have been substantially expanded to include further details and examples, as well as completely new material such as Section 5.2.2; (iii) Section 7 is completely new; (iv) Sections 8.1, 8.6, 8.7, 8.8, and 8.9 are almost entirely new, and Section 8.3 has been revised. The new material focuses on our experience and various important practical considerations, hence justifying the “and Practice” part of the paper title.

2 Background

Build systems automate the execution of repeatable tasks, at a scale from individual users up to large organisations. In this section, we explore the design space of build systems, using four examples: MAKE (Feldman, 1979), SHAKE (Mitchell, 2012), BAZEL (Google, 2016), and EXCEL (De Levie, 2004). We have carefully chosen these four to illustrate the various axes on which build systems differ; we discuss many other notable examples of build systems, and their relationships, in Sections 6 and 9.

1 EXCEL appears very different to the others but, seen through the lens of this paper, it is very close.

2 All our models are executable and are available on Hackage as build-1.0.
2.1 The venerable MAKE: Static dependencies and file modification times

MAKE was developed more than 40 years ago to automatically build software libraries and executable programs from source code. It uses makefiles to describe tasks – often referred to as build rules – and their dependencies, in a simple textual form. For example:

```
util.o: util.h util.c
    gcc -c util.c

main.o: util.h main.c
    gcc -c main.c

main.exe: util.o main.o
    gcc util.o main.o -o main.exe
```

The above makefile lists three tasks: (i) compile a utility library comprising files `util.h` and `util.c` into `util.o` by executing\(^4\) the command `gcc -c util.c`, (ii) compile the main source file `main.c` into `main.o`, and (iii) link object files `util.o` and `main.o` into the executable `main.exe`. The makefile contains the complete information about the task dependency graph, which is shown in Figure 1(a).

If the user runs MAKE specifying `main.exe` as the desired output, MAKE will build `util.o` and `main.o`, in any order (or even in parallel) since these tasks are independent, and then `main.exe`. If the user modifies `util.h` and runs MAKE again, it will perform a full rebuild, because all three tasks transitively depend on `util.h`, as illustrated in Figure 1(b). On the other hand, if the user modifies `main.c` then a partial rebuild is sufficient: `util.o` does not need to be rebuilt, since its inputs have not changed, see Figure 1(c). Note that if the dependency graph is acyclic, then each task needs to be executed at most once. Cyclic task dependencies are typically not allowed in build systems, although there are rare exceptions, see Section 8.5.

The fewer tasks are executed in a partial rebuild, the better. To be more specific, consider the following property, which is essential for build systems; indeed, it is their raison d’être:

> There are numerous implementations of MAKE and none comes with a formal specification. In this paper, we use a simple approximation to a real MAKE that you might find on your machine.

> In this example, we pretend `gcc` is a pure function for the sake of simplicity. In reality, there are multiple versions of `gcc`. To account for this, the actual binary for `gcc` is often also listed as a dependency, along with any supporting binaries, or standard libraries (such as `stdio.h`), that are used by `gcc`.
Definition (Minimality). A build system is minimal if it executes tasks at most once per build, and only if they transitively depend on inputs that changed since the previous build.

This property is tightly linked to build system correctness, which we will be ready to define in Section 3.6; for now, we will use minimality as a guiding principle when exploring the design space of build systems.

To achieve minimality, MAKE relies on two main ideas: (i) it uses file modification times to detect which files changed, and (ii) it constructs a task dependency graph from the information contained in the makefile and executes tasks in a topological order. For a more concrete description, see Sections 4.1 and 6.2.

2.2 Excel: Dynamic dependencies at the cost of minimality

Excel is a build system in disguise. Consider the following simple spreadsheet.

A1: 10       B1: A1 + A2
A2: 20

There are two input cells A1 and A2, and a single task that computes the sum of their values, producing the result in cell B1. If either of the inputs change, Excel will recompute B1.

Unlike MAKE, Excel does not need to know all task dependencies upfront. Indeed, some dependencies may change dynamically during computation. For example:

A1: 10       B1: INDIRECT("A" & C1)       C1: 1
A2: 20

The formula in B1 uses the INDIRECT function, which takes a string and returns the value of the cell with that name. The string evaluates to "A1", so B1 evaluates to 10. However, the dependencies of the formula in B1 are determined by the value of C1, so it is impossible to compute the dependency graph before the build starts. In this particular example, the value of C1 is a constant, but it might instead be the result of a long computation chain – so its value will only become available during the build.

To support dynamic dependencies, Excel’s calculation engine (Microsoft, 2011) is significantly different from MAKE. Excel arranges the cells into a linear sequence, called the calc chain. During the build, Excel processes cells in the calc-chain sequence, but if computing a cell C requires the value of a cell D that has not yet been computed, Excel aborts computation of C, moves D before C in the calc chain, and resumes the build starting with D. When a build is complete, the resulting calc chain respects all the dynamic dependencies of the spreadsheet. When an input value or formula is changed, Excel uses the final calc chain from the previous build as its starting point so that, in the common case where changing an input value does not change dependencies, there are no aborts. Notice that build always succeeds regardless of the initial calc chain (barring truly circular dependencies); the calc chain is just an optimisation. We refer to this algorithm as restarting and discuss it in more detail in Sections 4.2 and 6.3.

5 Technically, you can fool MAKE by altering the modification time of a file without changing its content, for example, using the command touch. MAKE is therefore minimal only under the assumption that you do not do that.
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Fig. 2. Dynamic dependencies example: create README and add it to the list of release documents docs.txt.

Dynamic dependencies complicate minimality. In the above example, B1 should only be recomputed if A1 or C1 change, but not if (say) A2 changes; but these facts are not statically apparent. In practice, Excel implements a conservative approximation to minimality: it recomputes a formula if (i) the formula statically mentions a changed cell, or (ii) the formula uses a function like INDIRECT whose dependencies are not statically visible, or (iii) the formula itself has changed.

Item (iii) in the above list highlights another distinguishing feature of Excel: it is self-tracking. Most build systems only track changes of inputs and intermediate results, but Excel also tracks changes in the tasks themselves: if a formula is modified, Excel will recompute it and propagate the changes. Self-tracking is uncommon in software build systems, where one often needs to manually initiate a full rebuild even if just a single task has changed. We discuss self-tracking further in Section 8.8.

2.3 SHAKE: Dynamic dependencies without remorse

Shake was developed to solve the issue of dynamic dependencies (Mitchell, 2012) without sacrificing the minimality requirement.

Building on the Make example from Section 2.1, we add the following files whose dependencies are shown in Figure 2(a):

- LICENSE is an input text file containing the project license.
Fig. 3. An early cutoff example: if a comment is added to `main.c`, the rebuild is stopped after detecting that `main.o` is unchanged, since this indicates that `main.exe` and its dependents do not need to be rebuilt.

- `release.txt` lists all release files. This file is produced by concatenating input text files `bins.txt` and `docs.txt`, which list binary and documentation files of the project.
- `release.tar` is the archive built by executing the command `tar` on the release files.

The dependencies of `release.tar` are not known statically: they are determined by the content of `release.txt`, which might not even exist before the build. Makefiles cannot express such dependencies, requiring workarounds such as `build phases`, which are known to be problematic (Mokhov et al., 2016). In SHAKE, we can express the rule for `release.tar` as:

```
"release.tar" %> \_ --> do
  need ["release.txt"]
  files <- lines <$>
    readFile "release.txt"
  need files
  cmd "tar" "$ [-cf", "release.tar"] ++ files
```

We first declare the static dependency on `release.txt`, then read its content (a list of files) and depend on each listed file, dynamically. Finally, we specify the command to produce the resulting archive. Crucially, the archive will only be rebuilt if one of the dependencies (static or dynamic) has changed. For example, if we create another documentation file `README` and add it to `docs.txt`, SHAKE will appropriately rebuild `release.txt` and `release.tar`, discovering the new dependency, see Figure 2(b).

SHAKE’s implementation is different from both MAKE and EXCEL in two aspects. First, to decide which files need to be rebuilt, it stores the dependency graph that is constructed during the previous build (instead of just file modification times or a linear chain). This idea has a long history, going back to incremental (Demers et al., 1981), adaptive (Acar et al., 2002), and self-adjusting computations – see Acar et al. (2007) and Section 9. Second, instead of aborting and deferring the execution of tasks whose newly discovered dependencies have not yet been built (as EXCEL does), SHAKE suspends their execution until the dependencies are brought up to date. We refer to this task scheduling algorithm as suspending, see a further discussion in Section 4.3 and a concrete implementation in Section 6.4.

SHAKE also supports the early cutoff optimisation, which is illustrated in Figure 3. When it executes a task and the result is unchanged from the previous build, it is unnecessary to execute the dependent tasks, and hence SHAKE can stop a build earlier. Not all build systems support early cutoff: SHAKE and BAZEL (introduced below) do, but MAKE and EXCEL do not; see Section 5.1 for an explanation of why.
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2.4 BAZEL: A cloud build system

When build systems are used by large teams, different team members often end up executing exactly the same tasks on their local machines. A cloud build system can speed up builds dramatically by sharing build results among team members. Furthermore, cloud build systems can support shallow builds that materialise only end build products locally, leaving all intermediates in the cloud.

Consider the example in Figure 4. The user starts by downloading the sources, whose content hashes are (for simplicity) 1, 2, and 3, and requests to build main.exe, see Figure 4(a) and (b). By looking up the global history of all previous builds, the build system finds that someone has already compiled these exact sources before, and the resulting files util.o and main.o had hashes 4 and 5, respectively. Similarly, the build system finds that the hash of the resulting main.exe was 6 and downloads the actual binary from the cloud storage – it must be materialised, because it is the end build product.

In Figure 4(c), the user modifies the source file util.c, thereby changing its hash from 1 to 7. The cloud lookup of the new combination {util.c, util.h} fails, which means that nobody has ever compiled it. The build system must therefore build util.o, materialising it with the new hash 8. The combination of hashes of util.o and main.o has not been encountered before either, thus the build system first downloads main.o from the cloud and then builds main.exe by linking the two object files. When the build is complete, the results can be uploaded to the cloud for future reuse by other team members.

BAZEL is one of the first openly available cloud build systems. As of writing, it is not possible to express dynamic dependencies in user-defined build rules; however, some of the predefined build rules require dynamic dependencies and the internal build engine can cope with them using a restarting task scheduler, which is similar to that of EXCEL but does not use the calc chain. BAZEL is not minimal in the sense that it may restart a task multiple times as new dependencies are discovered and rebuilt, but it supports the early cutoff optimisation. Note that, in practice, the cost of duplicate work due to the use of a restarting scheduler may often be just a small fraction of the overall build cost (Section 4.3).

In practice, old entries are regularly evicted from the cloud storage, as further discussed in Section 8.4.
To support cloud builds, BAZEL maintains (i) a *content-addressable cache* that maps the hash of a file’s content to the actual content of that file; (ii) a memo table that records all executed build commands with their input and output file hashes. The memo table allows the build engine to bypass the execution of a task, by predicting the hash of the result from the hashes of its dependencies; then the content-addressable cache allows the engine to download the result (if needed) based on the result hash. Further details and a concrete implementation will be provided in Sections 5.3 and 6.5.

### 2.5 Summary

We summarise differences between four discussed build systems in Table 1. The column ‘*persistent build information*’ refers to the information that build systems persistently store between builds:

- **MAKE** stores file modification times, or rather, it relies on the file system to do that.
- **EXCEL** stores one dirty bit per cell and the calc chain from the previous build.
- **SHAKE** stores the dependency graph discovered in the previous build, annotated with file content hashes for efficient checking of file changes.
- **BAZEL** stores the content-addressable cache and the history of all previous build commands annotated with file hashes. This information is shared among all users.

In this paper, we elucidate which build system properties are consequences of specific implementation choices (stored metadata and task scheduling algorithm), and how one can obtain new build systems with desired properties by recombining parts of existing implementations. As a compelling example, in Section 6.5, we demonstrate how to combine the advantages of SHAKE and BAZEL.

### 3 Build systems, abstractly

We have introduced a number of components and characteristics of build systems: tasks, dependencies, early cutoff, minimality, etc. It is easy to get confused. To make all this more
concrete, this section presents executable abstractions that can express all the intricacies of build systems discussed in Section 2 and allow us to construct complex build systems from simple primitives. Specifically, we present the task and build abstractions in Sections 3.2 and 3.3, respectively. Sections 4, 5, and 6 scrutinise the abstractions further and provide concrete implementations for several build systems.

### 3.1 Common vocabulary for build systems

**Keys, values, and the store.** The goal of any build system is to bring up to date a store that implements a mapping from keys to values. In software build systems, the store is the file system, the keys are filenames, and the values are file contents. In Excel, the store is the worksheets, the keys are cell names (such as A1), and the values are numbers, strings, etc., displayed as the cell contents. Many build systems use hashes of values as compact summaries with a fast equality check.

**Input, output, and intermediate values.** Some values must be provided by the user as input. For example, main.c can be edited by the user who relies on the build system to compile it into main.o and subsequently main.exe. End build products, such as main.exe, are output values. All other values (in this case main.o) are intermediate; they are not interesting for the user but are produced in the process of turning inputs into outputs.

**Persistent build information.** As well as the key/value mapping, the store also contains information maintained by the build system itself, which persists from one invocation of the build system to the next – its “memory”.

**Task description.** Any build system requires the user to specify how to compute the new value for one key, using the (up-to-date) values of its dependencies. We call this specification the task description. For example, in Excel, the formulae of the spreadsheet constitute the task description; in Make, the rules in the makefile are the task description.

**Build system.** A build system takes a task description, a target key, and a store, and returns a new store in which the target key and all its dependencies have up-to-date values.

We model a build system concretely, as a Haskell program. To that end, Figure 5 provides the type signatures for all key abstractions introduced in the paper. For example, Store i k v is the type of stores, with several associated functions (getValue, etc.). We use k as a type variable ranging over keys, v for values, and i for the persistent build information. Figure 6 lists standard library definitions.

### 3.2 The task abstraction

Our first main abstraction is for task descriptions:

```haskell
newtype Task c k v = Task (forall f. c f => (k -> fv) -> f v)
type Tasks c k v = k -> Maybe (Task c k v)
```

Here c stands for constraint, such as Applicative (Section 3.4 explains why we need it). A Task describes a single build task, while Tasks associates a Task with every non-input key; input keys are associated with Nothing. The highly abstracted type Task describes
how to build a value given a way to build its dependencies and is best explained by an example. Consider this EXCEL spreadsheet:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>10</td>
<td>B1: A1 + A2</td>
</tr>
<tr>
<td>A2</td>
<td>20</td>
<td>B2: B1 * 2</td>
</tr>
</tbody>
</table>

Here, cell A1 contains the value 10, cell B1 contains the formula A1 + A2, etc. We can represent the formulae of this spreadsheet with the following task description:

```haskell
sprsh1 :: Tasks Applicative String Integer
sprsh1 "B1" = Just $ Task $ \fetch -> ((+) <$> fetch "A1"
  <*> fetch "A2")
sprsh1 "B2" = Just $ Task $ \fetch -> ((*) <$> fetch "B1")
sprsh1 _    = Nothing
```

We instantiate keys k with String, and values v with Integer. (Real spreadsheet cells would contain a wider range of values, of course.) The task description sprsh1 embodies all the formulae of the spreadsheet, but not the input values. It pattern-matches on the key to see if it has a task description (in the EXCEL case, a formula) for it. If not, it returns Nothing, indicating that the key is an input. If there is a formula in the cell, it returns the Task to compute the value of the formula. Every task is given a callback fetch to find the value of any keys on which it depends. To run a Task, we simply apply the function it holds to a suitable callback (see the definition of the function run in Figure 5).
The code to “compute the value of a formula” in sprsh1 looks a bit mysterious because it takes place in an Applicative computation (McBride & Paterson, 2008) – the relevant type signatures are given in Figure 6. We will explain why in Section 3.3. For now, we content ourselves with observing that a task description, of type Tasksckv, is completely isolated from the world of compilers, calc chains, file systems, caches, and all other complexities of real build systems. It just computes a single output, using a callback (fetch) to find the values of its dependencies, and limiting side effects to those described by c.

### 3.3 The build abstraction

Next comes our second main abstraction – a build system:

```haskell
type Build c i k v = Tasks c k v -> k -> Store i k v -> Store i k v
```

The signature is very straightforward. Given a task description, a target key, and a store, the build system returns a new store in which the value of the target key is up to date. What exactly does “up to date” mean? We answer that precisely in Section 3.6.
Here is a simple build system:

```haskell
busy :: Eq k => Build Applicative () k v
busy tasks key store = execState (fetch key) store
where
  fetch :: k -> State (Store () k v) v
  fetch k = case tasks k of
    Nothing -> gets (getValue k)
    Just task -> do v <- run task fetch
                   modify (putValue k v)
               return v
```

The `busy` build system defines the callback `fetch` that, when given a key, brings the key up to date in the store and returns its value. The function `fetch` runs in the standard Haskell `State` monad (Figure 6) initialised with the incoming `store` by `execState`. To bring a key `k` up to date, `fetch` asks the task description `tasks` how to compute its value. If `tasks` returns `Nothing` the key is an input, so `fetch` simply reads the result from the store. Otherwise `fetch` runs the obtained `task` to produce a resulting value `v`, records the new key/value mapping in the store, and returns `v`. Notice that `fetch` passes itself to `task` as an argument, so the latter can use `fetch` to recursively find the values of `k`’s dependencies.

Given an acyclic task description, the `busy` build system terminates with a correct result, but it is not a minimal build system (Definition 2.1). Since `busy` has no memory (`i = ()`), it cannot keep track of keys it has already built and will therefore busily recompute the same keys again and again if they have multiple dependents. We will develop much more efficient build systems in Section 6.

Nevertheless, `busy` can easily handle the example task description `sprsh1` from the previous Section 3.2. In the GHCi session below, we initialise the store with `A1` set to 10 and all other cells set to 20.

```
λ> store = initialise () (\key -> if key == "A1" then 10 else 20)
λ> result = busy sprsh1 "B2" store
λ> getValue "B1" result
30
λ> getValue "B2" result
60
```

As we can see, `busy` built both `B2` and its dependency `B1` in the correct order (if it had built `B2` before building `B1`, the result would have been `20 × 2 = 40` instead of `(10 + 20) × 2 = 60`). As an example showing that `busy` is not minimal, imagine that the formula in cell `B2` was `B1 + B1` instead of `B1 × 2`. This would lead to calling `fetch "B1"` twice – once per occurrence of `B1` in the formula – and each call would recompute the formula in `B1`.

To avoid the recomputation, `busy` can keep the set of processed keys in the state monad (in addition to the `store`), treat processed keys as inputs in the `getValue` branch of the `fetch` callback, and include the key `k` into the set of processed keys in the `putValue` branch. This eliminates unnecessary work within a single build, but the next build needs to...
recursively recompute all target’s dependencies again even if no inputs changed. To save work between builds, it is necessary to store some build information persistently.

3.4 The need for polymorphism in task

The previous example illustrates why the Task abstraction is polymorphic in $f$. Recall its definition from Section 3.2:

```haskell
newtype Task c k v = Task (forall f. c f => (k -> fv) -> fv)
```

The busy build system instantiates $f$ to $\text{State}(\text{Store} i k v)$, so that $\text{fetch} :: k -> f v$ can side-effect the Store, thereby allowing successive calls to $\text{fetch}$ to communicate with one another.

We really, really want Task to be polymorphic in $f$. Given one task description $T$, we want to explore many build systems that can build $T$ – and we will do so in Section 6. As we shall see, each build system will use a different $f$, so the task description must not fix $f$.

But the task description cannot possibly work for any $f$ whatsoever; most task descriptions (e.g. sprsh1 in Section 3.2) require that $f$ satisfies certain properties, such as Applicative or Monad. That is why Task has the “$c f =>$” constraint in its type, expressing that $f$ can only be instantiated by types that satisfy the constraint $c$ and, in exchange, the task has access to the operations of class $c$. So the type Task emerges naturally, almost inevitably. But now that it has emerged, we find that constraints $c$ classify task descriptions in a very interesting, and practically useful, way:

- **Task Applicative**: In sprsh1, we needed only Applicative operations, expressing the fact that the dependencies between cells can be determined statically, that is, by looking at the formulae, without “computing” them (see Section 3.7).
- **Task Monad**: As we shall see in Section 3.5, a monadic task allows dynamic dependencies, in which a formula may depend on cell $C$, but which cell $C$ depends on the value of another cell $D$. A simple example of a task with dynamic dependencies is EXCEL formula INDIRECT("A" & C1) from Section 2.2.
- **Task Functor** is somewhat degenerate: a functorial task description cannot even use the application operator $<*>$, which limits dependencies to a linear chain, as for example, in Docker containers (Hykes, 2013) (ignoring the recent multi-stage builds). It is interesting to note that, when run on such a task description, the busy build system will build each key at most once, thus partially fulfilling the minimality requirement 2.1. Alas, it still has no mechanism to decide which input keys changed since the previous build.
- **Task Selective** corresponds to task descriptions with conditional statements, for example, EXCEL formula $\text{IF}(C1=1,B2,A2)$, where it is possible to statically over-approximate the set of task dependencies. Here Selective is a type class of selective applicative functors (Mokhov et al., 2019), which allows us to model build systems like DUNE (Jane Street, 2018) using the presented framework.
- **Task MonadFail** corresponds to monadic tasks that may fail. For example, the formula $A1/A2$ may fail due to division by zero. We will discuss this in Section 8.1.
• Task MonadPlus, Task MonadRandom and their variants can be used for describing tasks with a certain type of non-determinism, as discussed in Section 8.3.
• Task (MonadState i) will be used in Section 6 to describe tasks that have read and write access to the persistently stored build information i.

3.5 Monadic tasks

As explained in Section 2.2, some task descriptions have dynamic dependencies, which are determined by values of intermediate computations. In our framework, such task descriptions correspond to the type Task Monad kv. Consider this spreadsheet example:

A1: 10  B1: IF(C1=1,B2,A2)  C1: 1
A2: 20  B2: IF(C1=1,A1,B1)

Note that B1 and B2 statically form a dependency cycle, so MAKE would not be able to order the tasks topologically, but EXCEL, which uses dynamic dependencies, is perfectly happy. We can express this spreadsheet using our task abstraction as follows:

```haskell
sprsh2 :: Tasks Monad String Integer
sprsh2 "B1" = Just $ Task $ \
fetch -> do
  c1 <- fetch "C1"
  if c1 == 1 then fetch "B2" else fetch "A2"
sprsh2 "B2" = Just $ Task $ \
fetch -> do
  c1 <- fetch "C1"
  if c1 == 1 then fetch "A1" else fetch "B1"
sprsh2 _ = Nothing
```

The big difference compared to sprsh1 is that the computation now takes place in a Monad, which allows us to extract the value of c1 and fetch different keys depending on whether or not c1 == 1. Note that, in this example, one can statically determine the sets of possible dependencies of the formulae IF(C1=1,B2,A2) and IF(C1=1,A1,B1) but this cannot be done in general – recall the spreadsheet with the formula INDIRECT("A" & C1) from Section 2.2, where the argument of the INDIRECT function is a string computed dynamically during the build. Such tasks can also be captured using Tasks Monad:

```haskell
sprsh3 :: Tasks Monad String Integer
sprsh3 "B1" = Just $ Task $ \
fetch -> do
  c1 <- fetch "C1"
  fetch ("A" ++ show c1)
sprsh3 _ = Nothing
```

Since the busy build system introduced in Section 3.3 always rebuilds every dependency it encounters, it is easy for it to handle dynamic dependencies. For minimal build systems, however, dynamic dependencies, and hence monadic tasks, are much more challenging, as we shall see in Section 6.
3.6 Correctness of a build system

We can now say what it means for a build system to be correct, something that is seldom stated formally. Our intuition is this: when the build system completes, the target key, and all its dependencies, should be up to date. What does “up to date” mean? It means that if we recompute the value of the key (using the task description and the final store), we should get exactly the same value as we see in the final store.

To express this formally, we need an auxiliary function compute that computes the value of a key in a given store without attempting to update any dependencies:

\[
\text{compute} :: \text{Task Monad} \ k \ v \to \text{Store} \ i \ k \ v \to \text{v}
\]

\[
\text{compute task store} = \text{runIdentity} \ (\text{run task fetch})
\]

where

\[
\text{fetch} :: k \to \text{Identity} \ v
\]

\[
\text{fetch} \ k = \text{Identity} \ (\text{getValue} \ k \ \text{store})
\]

Here, we do not need any effects in the fetch callback to task, so we can use the standard Haskell Identity monad (Figure 6). This is another use of polymorphism in f, discussed in Section 3.4. The use of Identity just fixes the “impedance mismatch” between the function getValue, which returns a pure value v, and the fetch argument of the task, which must return an f v for some f. To fix the mismatch, we wrap the result of getValue in the Identity monad and pass to the task. The result has type Identity v, which we unwrap with runIdentity.

Definition (Correctness). Suppose build is a build system, tasks is a build task description, key is a target key, store is an initial store, and result is the store produced by running the build system with parameters tasks, key, and store. Or, using the precise language of our abstractions:

\[
\begin{align*}
\text{build} & :: \text{Build} \ c \ i \ k \ v \\
\text{tasks} & :: \text{Tasks} \ c \ k \ v \\
\text{key} & :: k \\
\text{store, result} & :: \text{Store} \ i \ k \ v \\
\text{result} & = \text{build} \ \text{tasks} \ \text{key} \ \text{store}
\end{align*}
\]

The keys that are reachable from the target key via dependencies fall into two classes: input keys and non-input keys, which we will denote by I and O, respectively. Note that key may be in either of these sets, although the case when key is an input is degenerate: we have \(I = \{\text{key}\}\) and \(O = \emptyset\).

The build result is correct if the following two conditions hold:

- result and store agree on inputs, that is, for all input keys \(k \in I\):

  \[\text{getValue} \ k \ \text{result} == \text{getValue} \ k \ \text{store}.\]

In other words, no inputs were corrupted during the build.
The result is consistent with the tasks, that is, for all non-input keys \( k \in O \), the result of recomputing the corresponding task matches the value stored in the result:

\[
\text{getValue } k \text{ result} == \text{compute task result}.
\]

A build system is correct if it produces a correct result for any tasks, key, and store.

It is hard to satisfy the above definition of correctness given a task description with cycles. All build systems discussed in this paper are correct only under the assumption that the given task description is acyclic. This includes the busy build system introduced earlier: it will loop indefinitely given a cyclic tasks. Some build systems provide a limited support for cyclic tasks, see Section 8.5.

The presented definition of correctness needs to be adjusted for build systems that support non-deterministic tasks and shallow cloud builds, as will be discussed in Sections 8.3 and 8.4, respectively.

### 3.7 Computing dependencies

Earlier, we remarked that a Task Applicative could only have static dependencies. Usually, we would extract such static dependencies by (in the case of EXCEL) looking at the syntax tree of the formula. But a task description has no such syntax tree: as you can see in the definition of Task in Figure 5, a task is just a function, so all we can do is call it. Yet, remarkably, we can use the polymorphism of a Task Applicative to find its dependencies without doing any of the actual work. Here is the code:

```haskell
dependencies :: Task Applicative k v -> [k]
dependencies task = getConst $ run task (\k -> Const [k])
```

Here `Const` is a standard Haskell type defined in Figure 6. We instantiate `f` to `Const [k]`. So a value of type `f v`, or in this case `Const [k] v`, contains no value `v`, but does contain a list of keys of type `[k]` which we use to record dependencies. The `fetch` callback that we pass to `task` records a single dependency; and the standard definition of Applicative for `Const` (which we give in Figure 6) combines the dependencies from different parts of the task. Running the task with `f = Const [k]` will thus accumulate a list of the task’s dependencies – and that is what `dependencies` does:

```haskell
λ> dependencies $ fromJust $ sprsh1 "B1" ["A1","A2"]
λ> dependencies $ fromJust $ sprsh1 "B2" ["B1"]
```

Notice that these calls to `dependencies` do no actual computation (in this case, spreadsheet arithmetic). They cannot: we are not supplying a store or any input numbers. So, through the wonders of polymorphism, we are able to extract the dependencies of the spreadsheet formula, and to do so efficiently, simply by running its code in a different Applicative! This is not new, for example see Capriotti & Kaposi (2014), but it is...
extremely cool. We will see a practical use for dependencies when implementing applicative build systems, see Section 6.2.

So much for applicative tasks. What about monadic tasks with dynamic dependencies? As we have seen in Section 2.3, dynamic dependencies need to be tracked too. This cannot be done statically; notice that we cannot apply the function dependencies to a Task Monad because the Const functor has no Monad instance. We need to run a monadic task on a store with concrete values, which will determine the discovered dependencies. Accordingly, we introduce the function track – a combination of compute and dependencies that computes both the resulting value and the list of its dependencies (key/value pairs) in an arbitrary monadic context m. We need this function to be polymorphic over m, because each build system will execute tasks in its own monad, as we shall see in Section 6.

Here is an implementation of track based on the standard Haskell WriterT monad transformer (Liang et al., 1995), whose main types are listed in Figure 6:

\[
\text{track} :: \text{Monad } m \Rightarrow \text{Task Monad } k v \rightarrow (k \rightarrow m v) \rightarrow m (v, [(k, v)])
\]

\[
\text{track task fetch} = \text{runWriterT } \text{run task trackingFetch}
\]

\[
\text{where}
\]

\[
\text{trackingFetch} :: k \rightarrow \text{WriterT }[(k, v)] m v
\]

\[
\text{trackingFetch } k = \text{do } v \leftarrow \text{lift(fetch } k); \text{tell }[(k, v)]; \text{return } v
\]

This function uses the WriterT transformer for recording additional information – a list of key/value pairs [(k, v)] – when executing a task in an arbitrary monad m. We substitute the given fetch with a trackingFetch that, in addition to fetching a value, tracks the corresponding key/value pair. The task returns a value of type WriterT [(k, v)] m v, which we unwrap with runWriterT. We will use track when implementing monadic build systems with dynamic dependencies, see Section 6.4.

Here we show an example of tracking monadic tasks when m = IO, by defining a corresponding fetchIO of type String -> IO Integer, which allows us to demonstrate the dynamic nature of monadic dependencies in GHCi.

\[
\lambda > \text{fetchIO } k = \text{do putStr } (k ++ ": "); \text{read }\langle\rangle \text{getLine}
\]

\[
\lambda > \text{track (fromJust } \$ \text{sprsh2 } "B1") \text{fetchIO}
\]

\[
\text{C1: 1}
\]

\[
\text{B2: 10}
\]

\[
(10,[("C1",1),("B2",10)])
\]

\[
\lambda > \text{track (fromJust } \$ \text{sprsh2 } "B1") \text{fetchIO}
\]

\[
\text{C1: 2}
\]

\[
\text{A2: 20}
\]

\[
(20,[("C1",2),("A2",20)])
\]

As expected, the dependencies of the cell B1 from sprsh2 (see the spreadsheet in Section 3.5) are determined by the value of C1, which in this case is obtained by reading from the standard input using fetchIO.
3.8 Examples of tasks

In this section, we give examples of tasks whose definitions involve different constraints on the computation context: Functor, Applicative, Monad, and MonadState s. The purpose of these examples is to continue building the intuition behind the Task abstraction and prepare the reader for richer types of tasks that will appear in Sections 6 and 8.

We start with one of the favourite examples for functional programmers – the Fibonacci sequence $F_n = F_{n-1} + F_{n-2}$:

```haskell
fibonacci :: Tasks Applicative Integer Integer
fibonacci n = if n < 2 then Nothing else
  Just $ Task $ \fetch -> (+) <$> fetch (n -1) <*> fetch (n -2)
```

Here the keys $n < 2$ are input parameters, and one can obtain the usual Fibonacci sequence by picking $F_0 = 0$ and $F_1 = 1$, respectively. Any minimal build system will compute the sequence with memoisation, that is, without recomputing the same value twice.

Dependencies of elements of the Fibonacci sequence are known statically, hence we can express it using Tasks Applicative and benefit from static dependency analysis (Section 3.7):

```haskell
λ> dependencies (fromJust $ fibonacci 5)
[4,3]
```

Interestingly, the Ackermann function – a famous example of a function that is not primitive recursive – cannot be expressed as an applicative task, because it needs to perform an intermediate recursive call to determine the value of one of its dependencies $A(m, n - 1)$:

$$A(m, n) = \begin{cases} 
n + 1 & \text{if } m = 0 \\
A(m - 1, 1) & \text{if } m > 0 \text{ and } n = 0 \\
A(m - 1, A(m, n - 1)) & \text{if } m > 0 \text{ and } n > 0
\end{cases}$$

We therefore use Tasks Monad to express this function, binding the dynamic dependency to variable index:

```haskell
ackermann :: Tasks Monad (Integer, Integer) Integer
ackermann (m, n)
| m < 0 || n < 0 = Nothing
| m == 0 = Just $ Task $ const $ pure (n+1)
| n == 0 = Just $ Task $ \fetch -> fetch (m-1, 1)
| otherwise = Just $ Task $ \fetch -> do index <- fetch (m, n-1)
  fetch (m-1, index)
```

Functorial tasks are less common than applicative and monadic, but there is a classic example too – the Collatz sequence, where given an initial value $c_0$, we calculate the next value
$c_n$ from $c_{n-1}$ either by dividing $c_{n-1}$ by 2 (if it is even) or multiplying it by 3 and adding 1 (if it is odd):

\[
\text{collatz} :: \text{Tasks} \quad \text{Functor} \quad \text{Integer} \quad \text{Integer} \\
\text{collatz} \ n \mid n <= 0 = \text{Nothing} \\
\mid \text{otherwise} = \text{Just} \$ \text{Task} \$ \text{\small fetch} -> f <$>$ \text{\small fetch} \ (n - 1)
\]

\[
\text{where} \\
\ f \ k \mid \text{even} \ k = k \ '\text{div}' \ 2 \\
\mid \text{otherwise} = 3 \ * \ k + 1
\]

Functorial tasks correspond to computations with a linear dependency chain. For example, computing the element $c_8$ of the Collatz sequence starting from $c_0 = 6$ leads to the following dependency chain: $c_0 = 6 \rightarrow 3 \rightarrow 10 \rightarrow 5 \rightarrow 16 \rightarrow 8 \rightarrow 4 \rightarrow 2 \rightarrow 1 = c_8$.

Collatz sequence is a good example of the early cutoff optimisation (Section 2.3): if we recompute $c_8$ starting from a different initial value $c_0 = 40$, the resulting computation will have a large overlap with the previous one: $c_0 = 40 \rightarrow 20 \rightarrow 10 \rightarrow 5 \rightarrow 16 \rightarrow 8 \rightarrow 4 \rightarrow 2 \rightarrow 1 = c_8$. We can therefore stop the recomputation after just two steps, since $c_2 = 10$ has not changed.

Note that we can statically extract even more precise dependency information from functorial tasks compared to applicative tasks. Indeed, we statically know that a Task Functor has exactly one dependency:

\[
\text{dependency} :: \text{Task} \quad \text{Functor} \quad k \quad v -> k \\
\text{dependency} \ \text{task} = \text{getConst} \ (\text{run} \ \text{task} \ \text{Const})
\]

The Tasks abstraction allows us to express pure functions in a way that is convenient for their memoisation and incremental recomputation (see Section 9.3 for a discussion on memoisation). If we furthermore need to share computation results via a cloud cache, we can use Tasks (MonadState $s$) that will play an important role in Section 6. Intuitively, by making a shared state of type $s$ available to a task, we give it the abilities to lookup and update cached computation results using the MonadState methods get and modify. For example, below we implement a cloud version of the Ackermann task that uses a Cache of type Map (Integer, Integer) Integer for sharing results of known Ackermann values.

\[
\text{type} \quad \text{Cache} = \text{Map} \ (\text{Integer}, \ \text{Integer}) \ \text{Integer}
\]

\[
\text{cloudAckermann} :: \text{Tasks} \quad (\text{MonadStateCache}) \quad (\text{Integer}, \ \text{Integer}) \quad \text{Integer}
\]

\[
\text{cloudAckermann} \ (m, \ n) \\
\mid m < 0 \ || \ n < 0 = \text{Nothing} \\
\mid m == 0 = \text{Just} \$ \text{Task} \$ \const \$ \text{pure} \ (n+1) \\
\mid n == 0 = \text{Just} \$ \text{Task} \$ \text{\small fetch} -> \text{\small fetch} \ (m-1, \ 1) \\
\mid \text{otherwise} = \text{Just} \$ \text{Task} \$ \text{\small fetch} -> \text{do} \\
\text{cache} <- \text{get} \\
\text{case Map.lookup} \ (m, \ n) \ \text{cache} \ \text{of} \\
\text{Nothing} -> \text{do} \ \text{index} <- \text{\small fetch} \ (m, \ n-1) \\
\text{value} <- \text{\small fetch} \ (m-1, \ \text{index}) \\
\text{modify} \ (\text{Map.insert} \ (m, \ n) \ \text{value}) \\
\text{return} \ \text{value} \\
\text{Just} \ \text{value} -> \text{return} \ \text{value}
\]
The main case \((m > 0 \land n > 0)\) starts by looking up the pair of indices \((m, n)\) in the cache. If the cache has Nothing, we calculate the resulting value as before and modify the cache accordingly; otherwise, if we have a cache hit, we return the obtained value immediately, skipping the actual calculation and thus potentially saving a large amount of work. Indeed, you do not want to recompute \(A(4, 2) = 2^{65,536} - 3\) unnecessarily; all of its 19,729 decimal digits have already been helpfully computed, for example, see Kosara (2008). We will use MonadState tasks in our models of cloud build systems in Section 6.

4 Schedulers

The focus of this paper is on a variety of implementations of Build c i k v, given a user-supplied implementation of Tasks c k v. That is, we are going to take Tasks as given from now on and explore variants of Build: first, abstractly (in this section and in Section 5) and then concretely in Section 6.

As per the definition of minimality (Section 2.1), a minimal build system must rebuild only out-of-date keys and at most once. The only way to achieve the “at most once” requirement while producing a correct build result (Section 3.6) is to build all keys in an order that respects their dependencies.

We have emboldened two different aspects above: the part of the build system responsible for scheduling tasks in the dependency order (a “scheduler”) can be cleanly separated from the part responsible for deciding whether a key needs to be rebuilt (a “rebuilder”). In this section, we discuss schedulers, leaving rebuilders for Section 5.

Section 2 introduced three different task schedulers that decide which tasks to execute and in what order; see the “Scheduler” column of Table 1 in Section 2.5. The following subsections explore the properties of the three schedulers, and possible implementations.

4.1 Topological scheduler

The topological scheduler precomputes a linear order of tasks, which when followed ensures dependencies are satisfied, then executes the required tasks in that order. Computing such a linear order is straightforward – given a task description and a target key, first find the (acyclic) graph of the key’s dependencies, then compute a topological order. Taking the MAKE example from Figure 1, we might compute the following order:

1. main.o
2. util.o
3. main.exe

Given the dependencies, we could have equally chosen to build util.o first, but main.exe must come last.

The advantage of this scheme is simplicity – compute an order, then execute tasks in that order. In addition, any missing keys or dependency cycles can be detected from the graph and reported to the user before any work has commenced.

The downside of this approach is that it requires the dependencies of each task in advance. As we saw in Section 3.7, we can only extract dependencies from an applicative
task, which requires the build system to choose \( c = \text{Applicative} \), ruling out dynamic dependencies.

### 4.2 Restarting scheduler

To handle dynamic dependencies, we cannot precompute a static order – we must interleave running tasks and ordering tasks. One approach is just to build tasks in an arbitrary order, and if a task calls `fetch` on an out-of-date key `dep`, abort the task and build `dep` instead. Returning to the example from Figure 1, we might build the tasks as follows:

1. `main.exe` (abort because it depends on `util.o` which is out of date)
2. `main.o`
3. `util.o`
4. `main.exe` (restart from scratch, completing successfully this time)

We start with `main.exe` (an arbitrary choice), but discover it depends on `main.o`, so instead start building `main.o`. Next, we choose to build `util.o` (again, arbitrarily), before finally returning to `main.exe` that now has all its dependencies available and completes successfully.

This approach works, but has a number of disadvantages. Firstly, it requires a technical mechanism to abort a task, which is easy in our theoretical setting with `Task` (see an implementation in Section 6.3) but leads to engineering concerns in the real world. Secondly, it is not minimal in the sense that a task may start, do some meaningful work, and then abort, repeating that same work when restarted.

As a refinement, to reduce the number of aborts (often to zero), EXCEL records the discovered task order in its `calc chain` and uses it as the starting point for the next build (Section 2.2). BAZEL’s restarting scheduler does not store the discovered order between build runs; instead, it stores the most recent task dependency information from which it can compute a linear order. Since this information may become outdated, BAZEL may also need to abort a task if a newly discovered dependency is out of date.

### 4.3 Suspending scheduler

An alternative approach, utilised by the `busy` build system (Section 3.3) and SHAKE, is to simply build dependencies when they are requested, suspending the currently running task when needed. Using the example from Figure 1, we would build

- `main.exe` (suspended)
  \( \leftarrow \) `main.o`
- `main.exe` (resumed then suspended again)
  \( \leftarrow \) `util.o`
- `main.exe` (completed)

We start building `main.exe` first as it is the required target. We soon discover a dependency on `main.o` and suspend the current task `main.exe` to build `main.o`, then resume and suspend again to build `util.o`, and finally complete the target `main.exe`. 
This scheduler (when combined with a suitable rebuilder) provides a minimal build system that supports dynamic dependencies. In our model, a suspending scheduler is easy to write – it makes a function call to compute each dependency. However, a more practical implementation is likely to build multiple dependencies in parallel, which then requires a more explicit task suspension and resumption. To implement suspension, there are two standard approaches:

- Blocking threads or processes: this approach is relatively easy, but can require significant resources, especially if a large number of tasks are suspended. In languages with cheap green threads (e.g. Haskell), the approach is more feasible and it was the original approach taken by SHAKE.
- Continuation-passing style (Claessen, 1999) can allow the remainder of a task to be captured, paused, and resumed later. Continuation passing is efficient, but requires the build script to be architected to allow capturing continuations. SHAKE currently uses this approach.

While a suspending scheduler is theoretically optimal, in practice, it is better than a restarting scheduler only if the cost of avoided duplicate work outweighs the cost of suspending tasks. Note, furthermore, that the cost of duplicate work may often be just a fraction of the overall build cost.

5 Rebuilders

A build system can be split into a scheduler (as defined in Section 4) and a rebuilder. Suppose the scheduler decides that a key should be brought up to date. The next question is: does any work need to be done, or is the key already up to date? Or, in a cloud build system, do we have a cached copy of the value we need?

While Section 2 explicitly listed the schedulers, the rebuilders were introduced more implicitly, primarily by the information they retain to make their decisions. From the examples, we have looked at, we see four fundamental rebuilders, each with a number of tweaks and variations within them.

5.1 A dirty bit

The idea of a dirty bit is to have one piece of persistent information per key, saying whether the key is dirty or clean. After a build, all bits are set to clean. When the next build starts, anything that changed between the two builds is marked dirty. If a key and all its transitive dependencies are clean, the key does not need to be rebuilt. Taking the example from Figure 1(c), if main.c changes then it would be marked dirty, and main.o and main.exe would be rebuilt as they transitively depend on main.c.

EXCEL models the dirty-bit approach most directly, having an actual dirty bit associated with each cell, marking the cell dirty if the user modifies it. It also marks dirty all cells that (transitively) depend on the modified cell. EXCEL does not record dynamic dependencies
of each cell; instead, it computes a static over-approximation – it is safe for it to make more cells dirty than necessary, but not vice versa. The over-approximation is as follows: a cell is marked dirty (i) if its formula statically refers to a dirty cell, or (ii) if the formula calls a volatile function like INDIRECT whose dependencies cannot be guessed from the formula alone. The over-approximation is clear for INDIRECT, but it is also present for IF, where both branches are followed even though dynamically only one is used.

MAKE uses file modification times and compares files to their dependencies, which can be thought of as a dirty bit which is set when a file is older than its dependencies. The interesting property of this dirty bit is that it is not under the control of MAKE; rather it is existing file system information that has been repurposed. Modifying a file automatically clears its dirty bit and automatically sets the dirty bit of the files depending on it (but not recursively). Note that MAKE requires that file timestamps only go forward in time, which can be violated by backup software.

With a dirty bit, it is possible to achieve minimality (Section 2.1). However, to achieve early cutoff (Section 2.3), it would be important to clear the dirty bit after a computation that did not change the value and make sure that keys that depend on it are not rebuilt unnecessarily. For EXCEL, this is difficult because the dependent cells have already been recursively marked dirty. For MAKE, it is impossible to mark a file clean and at the same time not mark the files that depend on it dirty. MAKE can approximate early cutoff by not modifying the result file, and not marking it clean, but then it will be rebuilt in every subsequent build.

A dirty-bit rebuilder is useful to reduce memory consumption, and in the case of MAKE, to integrate with the file system. However, as the examples show, in constrained environments where a dirty bit is chosen, it is often done as part of a series of compromises.

It is possible to implement a dirty-bit rebuilder that is minimal and supports early cutoff. To do so, the build system should start with all inputs that have changed marked dirty, then a key must be rebuilt if any of its direct dependencies are dirty, marking the key dirty only if the result has changed. At the end of the build, all dirty bits must be cleared. This approach only works if all targets are rebuilt each time because clearing dirty bits of keys that are not transitive dependencies of current targets will cause them to incorrectly not rebuild subsequently. To avoid resetting the dirty bit, it is possible to use successive execution numbers, which ultimately leads to an approach we call verifying step traces in Section 5.2.2.

5.2 Verifying traces

An alternative way to determine if a key is dirty is to record the values/hashes of dependencies used last time, and if something has changed, the key is dirty and must be rebuilt – in essence, keeping a trace which we can use to verify existing values. Taking the example from Figure 4(c), we might record that the key util.o (at hash 8) depended on the keys util.c (at hash 7) and util.h (at hash 2). Next time round, if the scheduler decides that it is time for util.o to be rebuilt and all keys still have the same hashes as in the recorded trace, there is nothing to do, and we can skip rebuilding. If any of the hashes is different, we rebuild util.o and record a trace with the new values.
For traces, there are two essential operations – adding a new trace to the trace store and using the trace store to determine if a key needs rebuilding. Assuming a store of verifying traces $VT^k_v$, the operations are:

\[
\text{recordVT} :: k \to \text{Hash } v \to [(k, \text{Hash } v)] \to VT^k_v \to VT^k_v
\]

\[
\text{verifyVT} :: (\text{Monad } m, \text{Eq } k, \text{Eq } v)
\Rightarrow k \to \text{Hash } v \to (k \to m(\text{Hash } v)) \to VT^k_v \to m \text{ Bool}
\]

Rather than storing (large) values $v$, the verifying trace $VT$ can store only hashes of those values, with type $\text{Hash } v$. Since the verifying trace persists from one build to the next – it constitutes the build system’s “memory” – it is helpful for it to be of modest size. After successfully building a key, we call $\text{recordVT}$ to add a record to the current $VT$, passing the key, the hash of its value, and the list of hashes and dependencies.

More interestingly, to verify whether a key needs rebuilding we use $\text{verifyVT}$, supplying the key, the hash of its current value, a function for obtaining the hash of the post-build value of any key (using a scheduling strategy as per Section 4), and the existing trace store $VT$. The result will be a $\text{Bool}$ where $\text{True}$ indicates that the current value is already up to date, and $\text{False}$ indicates that it should be rebuilt.

The most complex argument of $\text{verifyVT}$ is a function $\text{fetchHash} :: k \to m(\text{Hash } v)$ to obtain the hash of the post-build value of any key. With an applicative task, $\text{fetchHash}$ will be called on the statically known task dependencies. However, with a monadic task, the dependencies are not known from the task alone, they are only recorded from previous executions stored in $VT$. If the build system has two traces for a given key $k$, they will both request the same dependency first, since $\text{Task Monad}$ is deterministic. However, based on that first result, they may then request different subsequent dependencies using $\text{fetchHash}$. A curious result is that, for suspending schedulers (Section 4.3) in many cases, the actual build steps are performed as a consequence of checking if a key needs rebuilding!

A verifying trace and other types of traces discussed in this section support dynamic dependencies and minimality; furthermore, all traces except for deep traces (Section 5.4) support the early cutoff optimisation (Section 2.3).

### 5.2.1 Trace representation

One potential implementation would be to record all arguments passed to $\text{recordVT}$ in a list and verify by simply checking if any list item matches the information passed by $\text{verifyVT}$. Concretely, in our implementations from Section 6, traces are recorded as lists of:

\[
\text{data Trace } k \to v \to a = \text{Trace } \{ k, \text{Hash } v, \text{a}
\]

Where $a$ is $\text{Hash } v$ for verifying traces (and $v$ for constructive traces, discussed later in Section 5.3). A real system is highly likely to use a more optimised implementation.
The first optimisation is that any system using Applicative dependencies can omit the dependency keys from the Trace, since they can be recovered from the key field (Section 3.7).

The next optimisation is that there is only very minor benefit from storing more than one Trace per key. Therefore, verifying traces can be stored as \( \text{Map } k \ (\text{Trace } k \ v \ (\text{Hash } v)) \), where the initial \( k \) is the key field of Trace, thus making verifyVT much faster. Note that storing only one Trace per key means that if the dependencies of a key change but the resulting value does not, and then the dependencies change back to what they were before, there will be no valid Trace available and the key will therefore have to be rebuilt, whereas a complete list of all historical traces would allow the rebuilding to be skipped. On the other hand, bounding the number of Trace structures by the number of distinct keys, regardless of how many builds are executed, is a useful property.

5.2.2 Verifying step traces

The SHAKE build system and the associated paper – see Section 2.3.3 in Mitchell (2012) – use a different trace structure, called verifying step traces, which stores less data than verifying traces, and has slightly different early cutoff semantics. Rather than storing the Hash \( v \) for each dependency, it instead stores built time and changed time for each key, and a list of dependency keys (without the hashes). The resulting StepTrace type resembles

\[
\text{data StepTrace } k \ v = \text{StepTrace} \{ \text{key :: k} \ , \ \text{result :: Hash } v \ , \ \text{built :: Time} \ , \ \text{changed :: Time} \ , \ \text{depends :: [k]} \}
\]

The built field is when the key last rebuilt. The changed field is when the result last changed – if the last build changed the value, it will be equal to built, otherwise it will be older. The function recordVT consults the previous step traces to know whether to keep the previous changed value or change it to built. The function verifyVT is a bit more subtle; given a key \( k \) and the hash of its current value \( h \), it performs the following steps:

- Find the latest (with respect to the field built) step trace matching \( k \). If it does not exist, return False: \( k \) was never built before and cannot be verified.
- If \( h \) does not equal the result field of the trace, return False: the current \( k \)’s value was changed externally and thus needs rebuilding.
- For each key \( d \) in depends:
  - Make sure \( d \) is up to date, suspending the current task if needed;
  - If \( d \)’s latest changed time is greater than \( k \)’s built time, return False.
- Return True: the current \( k \)’s value is up to date.

This approach preserves minimality and early cutoff. A variant with only one Time field would lose early cutoff and indeed corresponds quite closely to MAKE. Furthermore, the Time stamp only needs to record which execution of the build is running, so every key built in the same run can share the same Time value – it just needs to be monotonically increasing between runs.
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Fig. 7. An example of verifying step traces. The small rectangles show the changed (left) and built (right) timestamps of each non-input key in the trace store.

This optimisation is useful, at least in the case of SHAKE, to save space. A typical cryptographic hash takes up 32 bytes, while a key (in SHAKE) is an Int taking only 4 bytes. Furthermore, SHAKE permits values to be arbitrarily large and supports a custom value equality (two values can be bit-for-bit unequal but considered equal by SHAKE), hence \( \text{Hash} \ V \) is not a valid encoding. For applicative tasks, \textit{depends} can be omitted, making the size of a \textit{StepTrace} \( O(1) \) instead of \( O(n) \), where \( n \) is the number of dependencies.

While verifying step traces are mostly an optimisation, there are some observable differences from verifying traces, as demonstrated by an example in Figure 7. We first make the full build: all keys get a built and changed of timestamp 1. Next, we change util.c and build util.o; the latter is changed as a result and hence both built and changed are increased to 2. Finally, we change util.c back to what it was originally and build main.exe. With verifying traces, the hashes of the dependencies of main.exe would be equal to the initial build and main.exe would not need rebuilding. With verifying step traces, the changed field of util.o would increase once more and main.exe would therefore be rebuilt. As shown in Figure 7(c), the changed field of main.exe remains 1, since the actual value is unchanged. Other than when building subsets of the targets, we are unaware of any other situation where verifying step traces are less powerful.

5.3 Constructive traces

A verifying trace records only hashes or timestamps, so that it can be small. In contrast, a constructive trace also stores the resulting value. Concretely, it records a list of \textit{Trace} \( k \ V \ v \), where \textit{Trace} is as defined in Section 5.2.1. Once, we are storing the complete result, it makes sense to record many constructive traces per key and to share them with other users, providing cloud build functionality. We can access this additional information with these operations:

\[
\text{recordCT} :: k \rightarrow v \rightarrow [(k, \text{Hash} \ v)] \rightarrow \text{CT} k v \rightarrow \text{CT} k v
\]

\[
\text{constructCT} :: (\text{Monad} \ m, \text{Eq} \ k, \text{Eq} \ v) \\
\rightarrow k \rightarrow (k \rightarrow m (\text{Hash} \ v)) \rightarrow \text{CT} k v \rightarrow m \ [v]
\]

The function \textit{recordCT} is similar to \textit{recordVT} from Section 5.2, but instead of just passing the hash of the resulting value, we pass the actual value. The function \textit{verifyVT} has
been replaced with \texttt{constructCT}, which instead of taking the hash of the current value as \textit{input}, returns a list of possible values as \textit{output} – there may be more than one, because some build tools are non-deterministic, see Section 8.3.

Regardless of the chosen scheduler (Section 4), there are three cases to consider when using a rebuilder based on constructive traces:

\begin{itemize}
  \item If \texttt{constructCT} returns the empty list of possible values, the key must be rebuilt.
  \item If the current value in the store matches one of the possible values, the build system can skip this key. Here, a constructive trace is used for verifying the current value.
  \item If the current value in the store does not match any possible value, we can use any of the possible values \textit{without} doing any work to build it and copy it into the store.
\end{itemize}

Any \textbf{Applicative} build system using constructive traces, for example \textsc{CloudBuild} (Section 6.5), can index directly from the key and the hashes of its dependencies to the resulting value, for example, using a \texttt{Map (k, [Hash v]) v}. Importantly, assuming the traces are stored on a central server, the client can compute the key and the hashes of its dependencies locally and then make a single call to the server to retrieve the result.

In practice, many cloud build systems store hashes of values in the trace store, that is, use \texttt{Trace k v (Hash v)} entries just like verifying traces and have a separate content-addressable cache which associates hashes with their actual contents.

### 5.4 Deep constructive traces

Constructive traces always verify keys by looking at their immediate dependencies, which must have first been brought up to date, meaning that the time to verify a key depends on the number of transitive dependencies. A \textit{deep} constructive trace optimises this process by only looking at the terminal \textit{input keys}, ignoring any intermediate dependencies. The operations capturing this approach are the same as for constructive traces in Section 5.3, but we use the names \texttt{recordDCT} and \texttt{constructDCT}, where the underlying \texttt{DCT} representation need only record information about hashes of inputs, not intermediate dependencies.

Concretely, taking the example from Figure 1, to decide whether \texttt{main.exe} is out of date, a \textit{constructive} trace would look at \texttt{util.o} and \texttt{main.o} (the immediate dependencies), whereas a \textit{deep constructive} trace would look at \texttt{util.c}, \texttt{util.h} and \texttt{main.c}.

An advantage of deep constructive traces is that to decide if \texttt{main.exe} is up to date only requires consulting its inputs, not even considering \texttt{util.o} or \texttt{main.o}. Such a feature is often known as a \textit{shallow build}, as discussed in Section 8.4.

There are two primary disadvantages of deep constructive traces:

\begin{itemize}
  \item \textbf{Tasks must be deterministic}: If the tasks are not \textit{deterministic} then it is possible to violate correctness, as illustrated by the example in Section 8.4, see Figure 12.
  \item \textbf{No early cutoff}: Deep constructive traces cannot support early cutoff (Section 2.3), since the results of intermediate computations are not considered.
\end{itemize}

Current build systems using deep constructive traces always record hashes of terminal input keys, but the technique also works if we skip any number of dependency levels (say $n$ levels). The input-only approach is the special case of $n = \infty$, and constructive traces are
the special case of \( n = 1 \). By picking values of \( n \) in between we would regain some early
cutoff, at the cost of losing such simple shallow builds, while still requiring determinism.

6 Build systems, concretely

In the previous sections, we discussed the types of build systems and how they can be bro-
ken down into two main components: a scheduler (Section 4) and a rebuilder (Section 5).
In this section, we make this abstract distinction concrete by implementing a number of
build systems as a composition of a scheduler and a rebuilder. The result can be sum-
marised in Table 2, which tabulates 12 possible combinations, 8 of which are inhabited by
existing build systems (we discuss these systems in Sections 2 and 9.1). Of the remaining
four spots, all result in workable build systems. The most interesting unfilled spot in the
table corresponds to a suspending scheduler composed with a constructive trace rebuilder.
Such a build system would provide many benefits; we title it CLOUD SHAKE and explore
further in Section 6.5.

6.1 Concrete implementations

We can define schedulers and rebuilders more concretely with the following types
(Figure 5):

\[
\begin{align*}
\text{type} \ & \ Scheduler \ c \ i \ ir \ k \ v = \ Rebuilder \ c \ i \ ir \ k \ v \rightarrow \ Build \ c \ i \ k \ v \\
\text{type} \ & \ Rebuilder \ c \ \ ir \ k \ v = k \rightarrow v \rightarrow \ Task \ c \ k \ v \rightarrow \ Task \ (MonadState \ ir) \ k \ v
\end{align*}
\]

A Scheduler is a function that takes a Rebuilder and uses it to construct a Build system
by choosing which keys to rebuild in which order. The Rebuilder makes use of the per-
sistent build information \( ir \), while the scheduler might augment that with further persistent
information of its own, yielding \( i \).

A Rebuilder takes three arguments: a key, its current value, and a Task that can
(re)compute the value of the key if necessary. It uses the persistent build information \( ir \)
(carryed by the state monad) to decide whether to rebuild the value. If doing so is unnec-
essary, it returns the current value; otherwise, it runs the supplied Task to rebuild it. In
both cases, it can choose to update the persistent build information \( ir \) to reflect what hap-
pened. So, a Rebuilder wraps a Task \( c \ k \ v \), which unconditionally rebuilds the key,
to make a Task (MonadState \( ir \) \) \( k \ v \), which rebuilds the key only if necessary, and
does the necessary book-keeping. Note that the resulting Task is always monadic; static
dependency analysis can be performed on the original Task Applicative if needed.
The scheduler runs the Task returned by the rebuilder passing it a fetch callback that the task uses to find values of its dependencies. The callback returns control to the scheduler, which may in turn call the rebuilder again to bring another key up to date, and so on.

These two abstractions are the key to modularity: we can compose any scheduler with any rebuilder and obtain a correct build system. In this section, we will write a scheduler for each column of Table 2, and a rebuilder for each row; then compose them to obtain the build systems in the table’s body.

6.2 MAKE

An implementation of MAKE using our framework is shown in Figure 8. As promised, its definition is just the application of a Scheduler, topological, to a Rebuilder, modTimeRebuilder. We discuss each component in turn, starting with the rebuilder.

The modTimeRebuilder uses the pair MakeInfo k = (now, modTimes) as persistent build information, carried by a state monad. This MakeInfo comprises the current time now :: Time and the map modTimes :: Map k Time of file modification times. We assume that the external system, which invokes the build system, updates MakeInfo reflecting any file changes between successive builds.

The rebuilder receives three arguments: a key, its current value, and the applicative task that can be used to rebuild the key if necessary. The rebuilder first decides if the key is dirty by consulting modTimes: if the key is not found, that must mean it has never been built before; otherwise, modTimeRebuilder can see if any of the task’s dependencies (computed by dependencies) are out of date. If the key is dirty, we use run task to rebuild it and update the state with the new modification time of the key⁷; otherwise, we can just return the current value.

MAKE’s scheduler, topological, processes keys in a linear order based on a topological sort of the statically known dependency graph (see Section 8.2 for parallel MAKE). Our definition in Figure 8 is polymorphic with respect to the type of build information i and is therefore compatible with any applicative rebuilder. The scheduler calls the supplied rebuilder on every key in the order and runs the obtained newTask to compute the newValue. Note that newTask has access only to the i part of the Store i k v, but the rest of the do block runs in the State (Store i k v) monad; we use the (unremarkable) helper function liftStore to fix the mismatch. The newTask finds values of the key’s dependencies via the fetch callback, which is defined to directly read the store.

The pre-processing stage uses the function dependencies, defined in Section 3.7, to extract static dependencies from the provided applicative task. We compute the linear processing order by constructing the graph of keys reachable from the target via dependencies and performing the topological sort of the result. We omit implementation of textbook graph algorithms reachable and topSort, for example, see Cormen et al. (2001).

Note that the function dependencies can only be applied to applicative tasks, which restricts MAKE to static dependencies, as reflected in the type Build Applicative. Any other build system that uses the topological scheduler will inherit the same restriction.

⁷ The real MAKE relies on the file system to track file modification times, but we prefer to make this explicit in our model.
-- Make build system; stores current time and file modification times

type Time = Integer

type MakeInfo k = (Time, Map k Time)

make :: Ord k => Build Applicative (MakeInfo k) k v
make = topological modTimeRebuilder

-- A task rebuilder based on file modification times
modTimeRebuilder :: Ord k => Rebuilder Applicative (MakeInfo k) k v
modTimeRebuilder key value task = Task $ \fetch -> do
  (now, modTimes) <- get
  let dirty = case Map.lookup key modTimes of
    Nothing -> True
    time -> any (\d -> Map.lookup d modTimes > time) (dependencies task)
  if not dirty then return value else do
    put (now + 1, Map.insert key now modTimes)
    run task fetch

-- A topological task scheduler

topological :: Ord k => Scheduler Applicative i i k v


topological rebuilder tasks target = execState $ mapM_ build order


  where
    build :: k -> State (Store i k v) ()
    build key = case tasks key of
      Nothing -> return ()
      Just task -> do
        store <- get
        let value = getValue key store
            newTask :: Task (MonadState i) k v
                      newTask = rebuilder key value task
        fetch :: k -> State i v
        fetch k = return (getValue k store)
        newValue <- liftStore (run newTask fetch)
        modify $ putValue key newValue
        order = toSort (reachable dep target)
        dep k = case tasks k of { Nothing -> []; Just task -> dependencies task }

-- Standard graph algorithms (implementation omitted)

reachable :: Ord k => (k -> [k]) -> k -> Graph k


topSort :: Ord k => Graph k -> [k] -- Throws error on a cyclic graph

-- Expand the scope of visibility of a stateful computation

liftStore :: State i a -> State (Store i k v) a

liftStore x = do
  (a, newInfo) <- gets (runState x . getInfo)
  modify (putInfo newInfo)

return a

Fig. 8. An implementation of MAKE using our framework.

6.3 EXCEL

Our model of EXCEL uses the restarting scheduler and the dirtyBitRebuilder, see Figure 9. The persistent build information ExcelInfo k is a pair of: (i) a map k -> Bool associating a dirty bit with every key and (ii) a calc chain of type [k] recorded from the previous build (Section 2.2).
Build systems à la carte: Theory and practice

```
-- Excel build system; stores a dirty bit per key and calc chain
type Chain k = [k]
type ExcelInfo k = (k -> Bool, Chain k)

excel :: Ord k => Build Monad (ExcelInfo k) k v
excel = restarting dirtyBitRebuilder

-- A task rebuilder based on dirty bits
dirtyBitRebuilder :: Rebuilder Monad (k -> Bool) k v
dirtyBitRebuilder key value task = Task $ \fetch -> do
  isDirty <- get
  if isDirty key then run task fetch else return value

-- A restarting task scheduler
restarting :: Ord k => Scheduler Monad (ir, Chain k) ir k v
restarting rebuilder tasks target = execState $ do
  chain <- gets (snd . getInfo)
  newChain <- liftChain $ go Set.empty
  $ chain ++ [target | target `notElem` chain]
  modify $ mapInfo $ \(ir, _) -> (ir, newChain)
where
  go :: Set k -> Chain k -> State (Store ir k v) (Chain k)
  go _ [] = return []
  go done (key:keys) = case tasks key of
    Nothing -> (key :) <$> go (Set.insert key done) keys
    Just task -> do
      store <- get
      let newTask :: Task (MonadState ir) k (Either k v)
        newTask = try $ rebuilder key (getValue key store) task
        fetch :: k -> State ir (Either k v)
        fetch k | Set.member k done = return $ Right (getValue k store)
        | otherwise = return $ Left k
      result <- liftStore (run newTask fetch) -- liftStore is in Figure 8
      case result of
        Left dep -> go done $ dep : filter (/= dep) keys ++ [key]
        Right newValue -> do modify $ putValue key newValue
                             (key :) <$> go (Set.insert key done) keys

-- Convert a total task into a task that accepts a partial fetch callback
try :: Task (MonadState i) k v -> Task (MonadState i) k (Either e v)
try task = Task $ \fetch -> runExceptT $ run task (ExceptT . fetch)

-- Expand the scope of visibility of a stateful computation (omitted)
liftChain :: State (Store ir k v) a -> State (Store (ir, Chain [k]) k v) a
```

Fig. 9. An implementation of EXCEL using our framework.

The external system, which invokes EXCEL’s build engine, is required to provide a transitively closed set of dirty bits. That is, if a cell is changed, its dirty bit is set, as well as the dirty bit of any other cell whose value might perhaps change as a result. It is OK to mark too many cells as dirty; but not OK to mark too few.
The dirtyBitRebuilder is very simple: if the key’s dirty bit is set, we run the task to rebuild the key; otherwise, we return the current value as is. Because the dirty cells are transitively closed, unlike MAKE’s modTimeRebuilder, the dirtyBitRebuilder does not need to modify i to trigger rebuilds of dependent keys.

EXCEL’s restarting scheduler processes keys in the order specified by the calc chain. During the build, it constructs a newChain for the next build and maintains a set of keys done that have been processed. For each non-input key, the scheduler tries to rebuild it using a partial fetch callback that returns Either k v instead of v. The callback is defined to fail with Left dep when asked for the value of a dependency dep that has not yet been processed (and hence may potentially be dirty); otherwise, it returns the current value of the dependency by looking it up in the store.

After the newTask is executed (using liftStore), there are two cases to consider:

- The newTask has failed, because one of its dependencies dep has not yet been processed. This indicates that the calculation chain from the previous build is incorrect and needs to be adjusted by moving the dep in front of the key, so that we can restart building the key after the dep is ready.
- The newTask succeeded. The resulting newValue is written to the store, the key is marked as done, and EXCEL continues to build the rest of the chain.

Note that the task returned by the rebuilder expects a total callback function and cannot be executed with the partial callback fetch. We fix the mismatch with the function try that relies on the standard monad transformer ExceptT (Liang et al., 1995). The helper liftChain is analogous to liftStore in Figure 8, so we omit its implementation.

6.4 SHAKE

Our model of SHAKE (Figure 10) stores verifying traces VT k v defined in Section 5.2 as persistent build information and is composed of the suspending scheduler and the vtRebuilder.

The rebuilder performs the verifyVT query to determine if the key is upToDated. If it is, the rebuilder simply returns the key’s current value. Otherwise, it executes the task, obtaining both a newValue and the key’s dynamic dependencies deps (see the definition of track in Section 3.7), which are subsequently recorded in the trace store using recordVT.

The suspending scheduler uses a recursive fetch callback, defined similarly to the busy build system (Section 3.3), that builds a given key, making sure not to duplicate work when called on the same key again in future. To achieve that, it keeps track of keys that have already been built in a set done :: Set k. Given a non-input key that has not yet been built, we use the supplied rebuilder to embed the build information i into the task. We then execute the obtained newTask by passing it the fetch function as a callback for building dependencies: the newTask will therefore be suspended while its dependencies are being brought up to date. The newValue obtained by running the newTask is stored, and the key is added to the set done.

The fetch computation runs in the State (Store i k v, Set k) monad. To make MonadState i access the i inside the Store, we use the helper function liftRun (which uses a newtype to provide a MonadState instance that sees through into the Store).
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As discussed in Section 5.2.2, SHAKE actually uses verifying step traces, but here we choose to focus on the more explicit verifying traces. We have implemented verifying step traces in our framework, and they compose with schedulers as you would hope.

**6.5 Cloud build systems: Bazel, CloudBuild, Cloud Shake, Buck and Nix**

Figure 11 shows our models of several cloud build systems. BAZEL, CloudBUILD, and CLOUD SHAKE are based on constructive traces (Section 5.3), whereas BUCK and NIX use deep constructive traces (Section 5.4).

The implementation of `ctRebuilder` is analogous to that of `vtRebuilder` in Figure 10, but the `verifyVT` query is replaced with a more powerful query to `constructCT` that returns a list of suitable `cachedValues` by looking them up the cloud cache. If the current `value` is in the list, we can use it as is. Otherwise, if the list is non-empty, we can use an arbitrary `cachedValue`. Finally, if the cache has no suitable values, we fall back to
executing the \texttt{task}. The obtained \texttt{newValue} and the \texttt{task}'s dependencies are recorded as a new constructive trace for future use.

The \textsc{Bazel} build system uses a restarting scheduler whose implementation we omit. It is similar to \textsc{Excel}’s \texttt{restarting} scheduler defined in \texttt{Figure 9}, but instead of building keys in the order specified by the persistently stored calc chain, \textsc{Bazel} uses a \textit{build queue}. The build starts with the queue containing all dirty keys. Similarly to \textsc{Excel}, the rebuilding of a key extracted from the queue may fail because one of its dynamic dependencies is dirty. In this case, the key is marked as \texttt{blocked} and its rebuilding is deferred. Whenever a key is successfully rebuilt, all keys that were previously blocked on it are added back to the queue and their build is eventually restarted.
Note that although both our model and BAZEL’s actual implementation supports dynamic dependencies, it is currently not possible to define new monadic build rules in the language available to users. Instead, users have to rely on a collection of predefined built-in rules, which cover many common instances of dynamic dependencies.

By switching to the topological scheduler, we obtain a model of Microsoft’s CLOUDBUILD – an applicative build system that combines conventional scheduling of statically known directed acyclic graphs with constructive traces (Esfahani et al., 2016). We convert a monadic ctRebuilder into an applicative one by applying an adapter adaptRebuilder, which unwraps a given Task Applicative and wraps it into Task Monad.

Our models of BUCK (Facebook, 2013) and NIX (Dolstra et al., 2004) use the rebuilder based on deep constructive traces (Section 5.4), called dctRebuilder, whose implementation we omit since it is very similar to that of ctRebuilder. BUCK uses the topological scheduler and is an applicative build system, whereas NIX uses the suspending scheduler and is therefore monadic.

Using the abstractions built thus far, we have shown how to compose schedulers with rebuilders to reproduce existing build systems. To us, the most interesting build system as yet unavailable would compose a suspending scheduler with constructive traces – providing a cloud-capable build system that is minimal and supports both early cutoff and monadic dependencies. Using our framework, it is possible to define and test such a system, which we call CLOUD SHAKE. All we need to do is compose suspending with ctRebuilder, as shown in Figure 11.

7 Experience

We have presented a framework that can describe, and indeed execute in prototype form, a wide spectrum of build systems. But our ultimate goal is a practical one: to use these insights to develop better build systems. Our earlier work on SHAKE (Mitchell, 2012), and applying SHAKE to building Glasgow Haskell Compiler (GHC) (Mokhov et al., 2016), makes progress in that direction.

Based on the theory developed in this paper, we have extended SHAKE to become CLOUD SHAKE, the first cloud-capable build system to support both early cutoff and monadic dependencies (Section 6.5), and used it to implement GHC’s (very substantial) build system, HADRIAN (Mokhov et al., 2016). In this section, we reflect on our experience of turning theory into practice.

7.1 Haskell as a design language

Build systems are surprisingly tricky. It is easy to waffle and remarkably hard to be precise. As this paper exemplifies, it is possible to use Haskell as a design language, to express quite abstract ideas in a precise form – indeed, precise enough to be executed.

Moreover, doing so is extremely beneficial. The discipline of writing executable prototypes in Haskell had a profound effect on our thinking. It forced misconceptions to surface early. It required us to be explicit about side effects. It gave us a huge incentive to design abstractions that had simple types and an explicable purpose.
Consider, for example, our Task type:

```haskell
newtype Task c k v = Task (forall f. c f => (k -> fv) -> fv)
```

We started off with a much more concrete type and explored multiple variants. During those iterations, this single line of code gave us a tangible, concrete basis for productive conversations, much more so than general debate about “tasks”.

It is also worth noting that we needed a rather expressive language to faithfully express the abstractions that seem natural in this setting. In the case of Task, we needed a data constructor with a polymorphic field; a higher-kindred type variable `f :: * -> *`; an even more abstracted kind for `c :: (* -> *) -> Constraint`; and, of course, type classes. Our models have since been translated to Rust (Gandhi, 2018) and Kotlin (Estevez & Shetty, 2019), and in both cases there was a loss of precision due to language-specific limitations.

When thinking about the type constructors over which `f` might usefully range, it turned out that we could adopt the existing abstractions of Functor, Applicative, Monad, and so on. That in turn led us to a new taxonomy of build systems – see Section 3.4. In the other direction, trying to express an existing build system DUNE in our models led us to finding a new abstraction – the Selective type class (Mokhov et al., 2019), which turned out to be useful outside the build systems domain.

The effect of using a concrete design language went well beyond merely expressing our ideas: it directly influenced our thinking. For example, here are definitions for a scheduler and rebuilder, from Section 6.1:

```haskell
type Scheduler c i ir k v = Rebuilder c i ir k v -> Build c i k v

type Rebuilder c i ir k v = k -> v -> Task c k v -> Task (MonadState ir) k v
```

These powerful and modular abstractions, which ultimately formed part of the conceptual structure of the paper, emerged fairly late in the project as we repeatedly reviewed, redesigned, and refactored our executable prototypes. It is hard to believe that we could have developed them without the support of Haskell as a design language.

### 7.2 Experience from SHAKE

The original design of SHAKE has not changed since the initial paper, but the implementation has continued to mature – there have been roughly 5,000 subsequent commits to the SHAKE project. These commits added concepts like resources (for handling situations when two build tasks contend on a single external resource), rewriting serialisation to be faster, documentation including a website, and add a lot of tests. The biggest change in that time period was an implementation change: moving from blocking threads to continuations for the suspending scheduler. But otherwise, almost all external and internal details remain the same. We consider the lack of change suggestive that SHAKE is based on fundamental principles – principles we can now name and describe as a consequence of this paper.

---

8 See [https://github.com/ndmitchell/shake](https://github.com/ndmitchell/shake).
9 See [https://shakebuild.com](https://shakebuild.com).
10 The most visible change is purely notational: switching from `*->` to `%->` for defining rules, because a conflicting `*->` operator was added to the Haskell Prelude.
There are two main aspects to the original SHAKE paper (Mitchell, 2012) that are described more clearly in this paper. Firstly, the rebuilder can now be described using verifying step traces Section 5.2.2, with a much clearer relationship to the unoptimised verifying traces of Section 5.2. Secondly, in the original paper, the tasks (there called “actions”) were described in continuation-passing style using the following data type\footnote{The original paper uses concrete types Key and Value. Here we generalise these types to \( k \) and \( v \), and also add \( a \) so that \( \text{Action} \ k \ v \ a \) can be an instance of \( \text{Monad} \ ).}:

\[
\text{data \ Action} \ k \ v \ a = \text{Finished} \ a \\
| \text{Depends} \ k \ (v \ \rightarrow \ \text{Action} \ k \ v \ a)
\]

In this paper, we describe tasks more directly, in a monadic (or applicative or functorial) style. But in fact the two are equivalent: \( \text{Task Monad} \ k \ v \) is isomorphic to \( \text{Action} \ k \ v \ v \). To be concrete, the functions \( \text{toAction} \) and \( \text{fromAction} \) defined below witness the isomorphism in both directions.

\[
\begin{align*}
\text{instance Monad (Action} \ k \ v \) \ where \\
\text{return} &= \text{Finished} \\
\text{Finished} \ x &= f = f \ x \\
\text{Depends} \ ds \ op &= f = \text{Depends} \ ds \ (\lambda v \rightarrow \ op \ v) \ (\rightarrow = f)
\end{align*}
\]

\[
\begin{align*}
\text{toAction} :: \text{Task Monad} \ k \ v \rightarrow \text{Action} \ k \ v \ v \\
\text{toAction} \ (\text{Task} \ \text{run}) &= \text{run} \ (\lambda k \rightarrow \text{Depends} \ k \ \text{Finished})
\end{align*}
\]

\[
\begin{align*}
\text{fromAction} :: \text{Action} \ k \ v \ v \rightarrow \text{Task Monad} \ k \ v \\
\text{fromAction} \ x &= \text{Task} \ (\lambda \text{fetch} \rightarrow \ f \ \text{fetch} \ x) \\
\text{where} \\
\ f &= (\text{Finished} \ v) = \text{return} \ v \\
\ f \ \text{fetch} \ (\text{Depends} \ d \ op) &= \text{fetch} \ d \ (\rightarrow = f \ \text{fetch} \ . \ op)
\end{align*}
\]

Similarly, in the original paper, MAKE tasks were described as:

\[
\begin{align*}
\text{data Rule} \ k \ v \ a = \text{Rule} \ (\{ \text{depends} :: [k], \text{action} :: [v] \rightarrow a \})
\end{align*}
\]

Assuming the lengths of the lists \([k]\) and \([v]\) always match, the data type \( \text{Rule} \ k \ v \ v \) is isomorphic to \( \text{Task Applicative} \ k \ v \), and we can define a similar \text{Applicative} instance and conversion functions.

By expressing these types using \text{Task}, we are able to describe the differences more concisely (\text{Monad} versus \text{Applicative}), use existing literature to determine what is and is not possible, and explore other constraints beyond just \text{Monad} and \text{Applicative}. These and other isomorphisms for second-order functionals, that is, functions of the form

\[
\forall f. \ c \ f \Rightarrow (k \rightarrow f \ v) \rightarrow f \ a
\]

for various choices of \( c \) are studied in depth by Jaskelioff and O’Connor (2015).

11 The original paper uses concrete types Key and Value. Here we generalise these types to \( k \) and \( v \), and also add \( a \) so that \( \text{Action} \ k \ v \ a \) can be an instance of \( \text{Monad} \ ).
7.3 Experience from Cloud Shake

Converting Shake into Cloud Shake was not a difficult process once armed with the road map in this paper. The key was the introduction of two new functions:

\[
\begin{align*}
\text{addCloud} &: \ k \to \text{Ver} \to \text{Ver} \to \left[\left(\text{k, Hash v}\right)\right] \to v \to \left[k\right] \to \text{IO } () \\
\text{lookupCloud} &: \ (k \to m \left(\text{Maybe (Hash v)}\right)) \to k \to \text{Ver} \to \text{Ver} \\
&\quad \to m \left(\text{Maybe (v, [[k]], IO ()})\right)
\end{align*}
\]

These functions are suspiciously like recordCT and constructCT from Section 5.3, with their differences perhaps the most illustrative of the changes required.\(^\text{12}\)

- Two Ver arguments are passed to each function. These are the versions of the build script and the rule for this particular key. If either version changes, then it is as though the key has changed and nothing will match. These versions are important to avoid using stale build products from previous versions of the build script.
- The list of dependencies to addCloud is a list of lists, rather than a simple list. The reason is that Shake allows a list of dependencies to be specified simultaneously, so they can all be built in parallel.
- The addCloud function also takes a list of keys [k], being the files that this rule produces. These produced files include those which are output keys from a rule and those declared with the function produces.
- The lookupCloud function allows an explicit Nothing when looking up a dependent key, since some keys are not buildable.
- The lookupCloud function returns at most one result, rather than a list. This change was made for simplicity.

To integrate these functions into Shake, we found the most expedient route was to leave Shake with verifying traces, but if the verifying trace does not match, we consult the constructive trace. By bolting constructive traces onto the side of Shake, we avoid re-engineering of the central database. We have not found any significant downsides from the bolt-on approach thus far, so it may be a sensible route to go even if developing from scratch – allowing an optimised verified trace implementation in many cases and falling back to a more complex implementation (requiring consulting remote servers) only rarely.

The one thing we have not yet completed on the engineering side is a move to hosting caches over HTTP. At the moment all caches are on shared file systems. This approach can use mounted drives to mirror HTTP connections onto file systems, and reuse tools for managing file systems, share caches with rsync, and is simple. Unfortunately, on certain operating systems (e.g. Windows) mounting an HTTP endpoint as a file system requires administrator privileges, so an HTTP cache is still desirable.

\(^{12}\) We have made some minor changes from actual Shake, like replacing Key for k, to reduce irrelevant differences.
7.4 Experience from using CLOUD SHAKE

While we expected the GHC build system to be the first to take advantage of CLOUD SHAKE, we were actually beaten to it by Standard Chartered who reported

*Thanks for the symlinks release, we just finished upgrading this build system to use --share. ... Building from scratch with a warm cache takes around 5 s, saving us up to 2 h. Not bad!*

Converting to a build suitable for sharing is not overly onerous, but nor is it trivial. In particular, a cloud build is less forgiving about untracked operations – things that are wrong but usually harmless in local builds often cause serious problems in a cloud setting. Some things that require attention in moving to a cloud build:

- **Irrelevant differences**: A common problem is that you do not get shared caching when you want it. As one example, imagine two users install gcc on different paths (say /usr/bin/gcc and /usr/local/bin/gcc). If these paths are recorded by the build system, the users will not share cache entries. As another example, consider a compiler that embeds the current time in the output: any users who build that file locally will not get any shared caching of subsequent outputs. Possible solutions include using relative paths; depending only on version numbers for system binaries (e.g. gcc); controlling the environment closely (e.g. using Nix); and extra flags to encourage compilers to be more deterministic.

- **Insufficient produced files**: A build rule must declare all files it produces, so these can be included in the cache. As an example using Haskell, compilation of Foo.hs produces Foo.hi and Foo.o. If you declare the rule as producing Foo.hi, and other rules depend on Foo.hi, but also use Foo.o after depending on Foo.hi, a local build will probably work (although treating Foo.o as a proper dependency would definitely be preferable). However, if Foo.hi is downloaded from a remote cache, Foo.o will not be present and subsequent commands may fail (e.g. linking). In practice, most issues encountered during the move to cloud builds for GHC were caused by failing to declare produced files.

- **Missing dependencies**: While missing dependencies are always a problem, the move to a cloud build makes them more serious. With local builds, outputs will be built at least once per user, but with a cloud build they might only be built *once ever*.

To help with the final two issues – insufficient dependencies and produced files – we have further enhanced the SHAKE lint modes, coupling them to a utility called FSATrace, which detects which files are read/written by a command line execution. Such information has been very helpful in making the GHC build cloud ready (Eichmann, 2019).

7.5 Experience from building GHC with SHAKE

HADRIAN is a build system for the Glasgow Haskell Compiler (The GHC Team, 2019). It was developed to replace a MAKE-based build system and solve multiple scalability and

---

13 [https://groups.google.com/d/msg/shake-build-system/NbB5kMFS34I/mZ9L4TgkBwAJ](https://groups.google.com/d/msg/shake-build-system/NbB5kMFS34I/mZ9L4TgkBwAJ)
maintainability challenges. As discussed in detail by Mokhov et al. (2016), most of these challenges were consequences of two key shortcomings of MAKE: (i) poor abstraction facilities of makefiles, notably the need to program in a single namespace of mutable string variables and (ii) the lack of dynamic dependencies (Section 2.3). HADRIAN benefits both from SHAKE’s features and from the host language Haskell, making the new GHC build system easier to understand and maintain.

Interestingly, although SHAKE is not a self-tracking build system (Section 8.8), HADRIAN implements a little domain-specific language for constructing build command lines and then tracks command lines by treating them as a type of values – an example of partial self-tracking made possible by SHAKE’s support for key-dependent value types (Section 8.6).

The development of CLOUD SHAKE allows GHC developers to benefit from caching build results between builds. Building GHC 8.8 from scratch takes \( \sim 1 \) hour on Windows using HADRIAN or the original MAKE-based build system. This time includes building the compiler itself, 29 bundled libraries, such as base (each in vanilla and profiled way), and 6 bundled executables, such as Haddock. One would hope that the build cache would be particularly useful for GHC’s continuous integration system that builds and tests every commit but our experience has been mixed. In an ideal case, when a commit does not affect the resulting GHC binaries, for example, only modifies tests, HADRIAN can build GHC from scratch in just 3 minutes, by simply creating symbolic links to the previously built results stored in the cache. However, if a commit modifies the “Stage 1 GHC” executable – an intermediate compiler built as part of the GHC bootstrapping – any further cache hits become unlikely, thus limiting benefits of the build cache to Stage 1 only (Eichmann, 2019).

A small number of GHC build rules cannot be cached. These rules register libraries in the package database, and rather than producing files, they mutate a shared file. CLOUD SHAKE provides a way to manually label such build rules to exclude them from caching.

One of the benefits of using SHAKE is that we have access to high-quality build profiling information, allowing us to compute critical paths and other metrics; see Mitchell (2019) for an overview of SHAKE’s profiling features. This information has shown us, for example, that more CPUs would not help (on unlimited CPUs the speed up would be less than 10%), and that a handful of build tasks (two anomalously slow Haskell compilations and calls to slow single-threaded configure) take up a significant fraction of build time (at least 15%).

8 Engineering aspects

In the previous sections, we have modelled the most critical subset of various build systems. However, like all real-world systems, there are many corners that obscure the essence. In this section, we discuss some of those details what would need to be done to capture them in our model and what the impact would be.
8.1 Partial stores and exceptions

Our model assumes a world where the store is fully defined, every \( k \) is associated with a \( v \), and every compute successfully completes returning a valid value. In the real world, build systems frequently deal with errors, for example, “file not found” or “compilation failed”. There are many ways of modelling errors, and in this section we give three simple examples.

One simple approach is to include failures into the type of values \( v \), for example, to model a partial store we can use an algebraic data type isomorphic to \( \text{Maybe} \):

\[
data \text{ Value } = \text{ FileNotFound } \mid \text{ FileContents String}
\]

This is convenient if tasks are aware of failures. For example, a task may be able to cope with missing files, for example, if \( \text{fetch } \text{"username.txt" } \) returns \( \text{ FileNotFound } \), the task could use the literal string \( \text{"User" } \) as a default value. In this case, the task will depend on the fact that the file \( \text{username.txt } \) is missing and will need to be rebuilt if the user later creates this file. In general, we can use values of type \( \text{Either e v } \) when dealing with failures of type \( e \). To automatically convert a “failure-free” task into an equivalent task operating with values of type \( \text{Either e v } \), we can use the following function:

\[
\text{liftEither :: Task Monad k v } \rightarrow \text{ Task Monad k (Either e v)}
\]

\[
\text{liftEither task = Task } \$ \backslash \text{fetch } \rightarrow
\]

\[
\text{runExceptT } \$ \text{run task (ExceptT . fetch)}
\]

Here, \( \text{liftEither } \) wraps the result of the given \( \text{fetch :: k } \rightarrow \text{ Either e v } \) into \( \text{ExceptT } \) and then runs the task in the \( \text{ExceptT } \) monad transformer (Liang et al., 1995).

Another approach is to include failures into the computation context \( f \). Recall from Section 3.4 that we require tasks to be polymorphic in \( f \) and can therefore choose to execute a Task in an \( f \) with failures, the simplest example being \( f = \text{Maybe} \). Below we define a callback that returns Just value for keys A1 and A2 but fails with Nothing on all other keys:

\[
\text{fetchA1A2 :: String } \rightarrow \text{ Maybe Integer}
\]

\[
\text{fetchA1A2 k } = \text{Map.lookup k (Map.fromList } \{(\text{"A1"}, 10), (\text{"A2"}, 20)\})
\]

We can directly run any Task with this callback. For example, the task \( B1 = A1 + A2 \) from sprsh1 in Section 3.2 returns Just 30, whereas the task \( B2 = B1 * 2 \) returns Nothing because \( \text{fetchA1A2 } \) fails on \( B1 \).

This approach is convenient if tasks are not aware of failures, for example, we can model EXCEL formulae as pure arithmetic functions and introduce failures “for free” if/when needed by instantiating Tasks with an appropriate \( f \). In a real system, this \( f \) would be more complex than just \( \text{Maybe} \), for example \( \text{MaybeT (State Spreadsheet)} \), thus allowing us to combine failures with access to EXCEL’s spreadsheet state using the \( \text{MaybeT } \) monad transformer (Liang et al., 1995).

Finally, the task itself might not want to encode failures into the type of values \( v \), but instead demand that \( f \) has a built-in notion of failures. This can be done by choosing a
suitable constraint \( c \), such as `Alternative`, `MonadPlus` or even better something specific to failures, such as `MonadFail`. Then both the callback and the task can reuse the same failure mechanism as shown below:

```haskell
class Monad m => MonadFail m where
  fail :: String -> m a

sprsh4 :: Tasks MonadFail String Integer
sprsh4 "B1" = Just $ Task $ \fetch -> do
  a1 <- fetch "A1"
  a2 <- fetch "A2"
  if a2 == 0 then fail "division by 0" else return (a1 `div` a2)
sprsh4 _ = Nothing
```

With this approach, we can implement a build system that accepts `Tasks MonadFail k v` and handles errors by aborting the build early and returning `Either String (Store ikv)` instead of just `Store ikv` as in our `Build` abstraction Section 3.3. One possible implementation of such a failure-handling build system is based on adding an extra `Either String` layer into the monad stack, for example, augmenting the monad `State (Store ikv)` used by the schedulers in Section 6 with exceptions. We omit the actual implementation: while fairly direct, it is also tedious due to additional wrapping and unwrapping.

### 8.2 Parallelism

We have given simple implementations assuming a single thread of execution, but all the build systems we address can actually build independent keys in parallel. While it complicates the model, the complications are restricted to the scheduler:

1. The **topological** scheduler can build the full dependency graph, and whenever all dependencies of a task are complete, the task itself can be started.
2. The **restarting** scheduler can be made parallel in a few ways, but the most direct is to have \( n \) threads reading keys from the build queue. As before, if a key requires a dependency not yet built, it is moved to the end – the difference is that sometimes keys will be moved to the back of the queue not because they are out of date but because of races with earlier tasks that had not yet finished. As a consequence, if the build order is persisted over successive runs (as in `EXCEL`), potentially racey dependencies will be separated, giving better parallelism over time.
3. The **suspending** scheduler can be made parallel by starting multiple dependencies in parallel. One approach is to make the request for dependencies take a list of keys, as implemented by `SHAKE`. Another approach is to treat the `Applicative` dependencies of a `Task Monad` in parallel, as described by Marlow et al. (2014).

Once sufficient parallelism is available, the next challenge is preventing excess parallelism and machine resource starvation, which is usually achieved with a thread pool/limit.

The actual implementation of the parallel schedulers is not overly onerous, but neither it is beautiful or informative, so we omit it.
8.3 Impure computations

In our model, we define `Task` as a function – when given the same inputs it will always produce the same output. Alas, the real world is not so obliging. Some examples of impure tasks include:

- **Untracked dependencies**: Some tasks depend on untracked values – for example, C compilation will explicitly list the `source.c` file as a dependency, but it may not record that the version of `gcc` is also a dependency.
- **Non-determinism**: Some tasks are non-deterministic, producing any result from a possible set. As an example, GHC programs compiled using parallelism can change the order in which unique variables are obtained from the name supply, producing different but semantically identical results.
- **Volatility**: Some tasks are defined to change in every build, for example, EXCEL provides a “function” `RANDBETWEEN` producing a fresh random number in a specified range on each recalculation. Similarly, build systems like MAKE and SHAKE provide volatile phony rules. The main difference from non-deterministic tasks is that volatile tasks cannot be cached. They are readily modelled as depending on a special key `RealWorld` whose value is changed in every build.

There is significant interplay between all three sources of impurity. Systems like BAZEL use various sandboxing techniques to guard against missing dependencies, but none are likely to capture all dependencies right down to the CPU model and microcode version. Tasks with untracked dependencies can be marked volatile, a technique EXCEL takes with the `INDIRECT` function, fixing the untracked dependency at the cost of minimality.

Most of the implementations in Section 6 can deal with non-determinism, apart from BUCK, which uses the assumption of task determinism to reduce the number of cloud lookups: if all tasks are deterministic, one needs just a single cloud lookup for obtaining the value of the target key from the hash of its terminal inputs. This is highly desirable not only for shallow builds, but for non-shallow builds too, because under the assumption of task determinism all intermediate values are fully determined by the terminal inputs, and can therefore be requested in a single batch query to the server.

One way of modelling non-determinism is to demand that `f` has a built-in source of non-determinism, for example, by enriching `Tasks Monad` to `Tasks MonadRandom` that has access to an additional method `getRandom :: (Integer, Integer) -> m Integer`, that is, a source of random numbers in a specified range. Here is a task description corresponding to a spreadsheet with the formula `B1 = A1 + RANDBETWEEN(1,2)`:  

```haskell
sprsh5 :: Tasks MonadRandom String Integer
sprsh5 "B1" = Just $ Task $ \fetch -> do a1 <- fetch "A1"
       r <- getRandom (1,2)
       return (a1 + r)

sprsh5 _ = Nothing
```

Such tasks can be modelled in our framework by adjusting the correctness definition (Section 3.6): instead of requiring that the produced value equals the result of recomputing the task, we now require that produced value belongs to the set of possible results of recomputing the task, for example, the set `{A1 + 1, A1 + 2}` in the above example.
Interestingly, Task Monad Random is powerful enough to express dependency-level non-determinism, for example, \texttt{INDIRECT("A" & \texttt{RANDBETWEEN}(1,2))}, whereas most build tasks in real-life build systems only experience a value-level non-determinism. Excel handles this example simply by marking the cell volatile – an approach that can be readily adopted by any of our implementations.

### 8.4 Cloud implementation

Our model of cloud builds provides a basic framework to discuss and reason about them, but lacks a number of important engineering corners:

- **Communication**: When traces or contents are stored in the cloud, communication can become a bottleneck, so it is important to send only the minimum amount of information, optimising with respect to build system invariants. For example, incremental data processing systems in the cloud, such as Reflow (GRAIL, 2017), need to efficiently orchestrate terabytes of data.

- **Offloading**: Once the cloud is storing build products and traces, it is possible for the cloud to also contain dedicated workers that can execute tasks remotely – offloading some of the computation and potentially running vastly more commands in parallel.

- **Eviction**: The cloud storage, as modelled in Section 5.3, grows indefinitely, but often resource constraints require evicting old items from the store. When evicting an old value \( v \), one can also evict all traces mentioning the now-defunct \( \text{hash } v \). However, for shallow builds (see below), it is beneficial to keep these traces, allowing builds to “pass-through” hashes whose underlying values are not known, recreating them only when they must be materialised.

- **Shallow builds**: Building the end target, for example, an installer package, often involves many intermediate tasks. The values produced by these intermediate tasks may be large, so some cloud build systems are designed to build end targets without materialising any intermediate values, producing a so-called shallow build – see an example in Section 2.4. Some build systems go even further, integrating with the file system to only materialise the file when the user accesses it (Microsoft, 2017).

Shallow builds have a slightly weaker correctness property than in the Definition 3.6. Instead of demanding that all keys reachable from the target match, we only require matches for the target itself and the input keys reachable from the target.

As described in Section 7.4, non-determinism (Section 8.3) is harmful for cloud builds, reducing the number of cache hits. However, for deep constructive traces (Section 5.4) it is much worse, even leading to incorrect results. Figure 12 shows a Frankenbuild Esfahani et al. (2016) example, where the target \texttt{report.txt}, which is downloaded from the cloud, is inconsistent with its immediate dependency \texttt{main.prof}. This inconsistency is caused by two factors: (i) inherent non-determinism of profiling – running a profiling tool on the very same \texttt{main.exe} will produce different \texttt{main.prof} results every time; and (ii) relying on deep constructive traces that cache build results based on the hashes of terminal task inputs (in this case \texttt{main.exe}). The result violates all three definitions of correctness: the main definition (Section 3.6), the variant for non-deterministic tasks (Section 8.3), and the variant for shallow builds (this section).
8.5 Iterative computations

Some computations are best described not by a chain of acyclic dependencies, but by a loop. For example, LATEX requires repeated rebuilding until it reaches a fixed point, which can be directly expressed in build systems, such as PLUTO (Erdweg et al., 2015). Another example is EXCEL, where a cell can depend on itself, for example, \( A1 = A1 + 1 \). In such cases, EXCEL will normally not execute anything, but if the “Iterative Calculations” feature is enabled EXCEL will execute the formula for a specified maximum number \( N \) of times per calculation (where \( N \) is a setting that defaults to 100).

For example like LATEX, we consider the proper encoding to not be circular tasks, but a series of iterative steps, as described by Mitchell (2013). It is important that the number of executions is bounded, otherwise the build system may not terminate (a legitimate concern with LATEX, which can be put into a situation where it is bistable or diverging over multiple executions). The examples in EXCEL tend to encode either mutable state or recurrence relations. The former is only required because EXCEL inherently lacks the ability to write mutable state and the latter is probably better solved using explicit recurrence formulae.

We choose not to deal with cyclic dependencies – a choice that most build systems also follow. There are computation frameworks that support dependency cycles under the assumption that tasks are monotonic in a certain sense (Pottier, 2009; Radul, 2009).

8.6 Key-dependent value types

Key-dependent value types allow a build system to work with multiple different types of values, where the type of any particular value is determined by the key. As an example of why this might be useful, consider a build system where keys can be files (whose contents are strings) or system executables (represented by their version number) – using a single type for both values reduces type safety. SHAKE permits such key-dependent value types,
for example, see the oracle rule in Mitchell (2012), and users have remarked that this additional type safety provides a much easier expression of concepts (Mokhov et al., 2016).

We can encode key-dependent value types using generalised algebraic data types or GADTs (Peyton Jones et al., 2006). The idea is to replace the callback \( \text{fetch} : : k \to f v \) by its more polymorphic equivalent \( \text{fetch} : : k v \to f v \), where \( k v \) is a GADT representing keys tagged by the type \( v \) of corresponding values. The variable \( k \) has changed from kind \( * \) (a type), to \( * \to * \) (a type function), permitting the key to constrain the type of the value. The idea is best explained by way of an example:

```haskell
data Version = Version { major :: Int, minor :: Int }
deriving (Eq, Ord)

data Key a where
  File :: FilePath -> Key String
  Program :: String -> Key Version

Here, we extend the usual mapping from file paths to file contents with an additional key type Program which maps the name of a program to its installed Version. The task abstraction needs to be adjusted to cope with such keys (the suffix T stands for “typed”):

```haskell
type Fetch k f = forall v. k v -> f v

newtype TaskT c k v = TaskT (forall f. c f => Fetch k f -> f v)

type TasksT c k = forall v. k v -> Maybe (TaskT c k v)

The changes compared to the definition in Section 3.2 are minimal: (i) the TaskT now uses a typed Fetch callback (we define a separate type synonym only for readability) and (ii) the type of TasksT is now polymorphic in \( v \) instead of being parameterised by a concrete \( v \).
The example below demonstrates how fetch can be used to retrieve dependencies of different types: the rule release.txt concatenates the contents of two Files, while the rule main.o uses the numeric Program "gcc" to determine how the source file should be compiled.

```haskell
example :: TasksT Monad Key
example (File "release.txt") = Just $ TaskT $ \fetch -> do
  readme <- fetch (File "README")
  license <- fetch (File "LICENSE")
  return (readme ++ license)

example (File "main.o") = Just $ TaskT $ \fetch -> do
  let source = "main.c"
  version <- fetch (Program "gcc")
  if version >= Version 8 0 then compileNew source
     else compileOld source

example _ = Nothing
```
Note that like all key-dependent tasks, this example could be expressed without key dependence, at the cost of some type safety. As we will see in Sections 8.7 and 8.8, using key-dependent value types can make it easier to work with more complicated tasks.

8.7 Multiple output build tasks

Some build tasks produce multiple output keys, for example, \texttt{ghc A.hs} produces both \texttt{A.hi} and \texttt{A.o}. This pattern can be encoded by having a key \texttt{A.hi+A.o} which produces both results, then each of \texttt{A.hi} and \texttt{A.o} can extract the relevant result from \texttt{A.hi+A.o}. We can express this pattern more clearly with the extra type safety from Section 8.6:

\begin{verbatim}
data Key a where
  File :: FilePath -> Key String
  Files :: [FilePath] -> Key [String]

task :: TasksT Monad Key

  task (File "A.hi") = Just $ TaskT $ \fetch ->
    [hi,o] <- fetch (Files ["A.hi","A.o"])
    return hi

  task (File "A.o") = Just $ TaskT $ \fetch ->
    [hi,o] <- fetch (Files ["A.hi","A.o"])
    return o

  task (Files ["A.hi","A.o"]) = Just $ TaskT $ \fetch ->
    compileWithGHC "A.hs"

One awkward aspect is that both \texttt{A.hi} and \texttt{A.o} must ask for exactly the same \texttt{Files} key. If one \texttt{File} key swapped the order of the list to \texttt{Files}, then it would likely run GHC twice. To help construct a well-formed multiple output build task, it is convenient to partition the set of keys into elementary subsets. We can encode such a partition with a function from any key to all the members of its subset (in a consistent order).

\begin{verbatim}
type Partition k = k -> [k]

In our example, the partition function on either of the output names "A.hi" or "A.o" would return ["A.hi","A.o"].

With a suitable \texttt{Partition}, it is possible to create a mapping that resolves \texttt{File} keys automatically into the correct \texttt{Files} key.

\begin{verbatim}
task :: Partition FilePath -> TasksT Monad Key

  task partition (File k) = Just $ TaskT $ \fetch ->
    let ks = partition k
    let Just i = elemIndex k ks
    vs <- fetch (Files ks)
    return (vs !! i)

  task (Files ["A.hi","A.o"]) = Just $ TaskT $ \fetch ->
    compileWithGHC "A.hs"

... -- more tasks for elementary subsets as required
\end{verbatim}
In the above function, we compute the elementary subset $k_\text{s}$ of the given key $k$, find the index of $k$ within the subset (using `elemIndex`), run the `fetch` to build every key in the subset, then extract out the value corresponding to $k$ (using the indexing operation `!!`).

### 8.8 Self-tracking

Some build systems, for example Excel and Ninja, are capable of recomputing a task if either its dependencies change, or the task itself changes. For example:

$$A_1 = 20 \quad B_1 = A_1 + A_2 \quad A_2 = 10$$

In Excel, the user can alter the value produced by $B_1$ by either editing the inputs of $A_1$ or $A_2$, or editing the formula in $B_1$, for example, to $A_1 \times A_2$. This pattern can be captured by describing the rule producing $B_1$ as also depending on the value $B_1$-formula. The implementation can be given very directly in a Tasks Monad — concretely, first look up the formula, then interpret it:

```haskell
sprsh6 "B1" = Just $ Task $ \fetch -> do
  formula <- fetch "B1-formula"
  evalFormula fetch formula
```

The build systems that have precise self-tracking are all ones which use a non-embedded domain-specific language to describe build tasks, that is, a task is described by a data structure (or syntax tree), and tasks can be compared for equality by comparing those data structures. Build systems that use a full programming language, for example, Shake, are faced with the challenge of implementing equality on arbitrary tasks — and a task is just a function. For such build systems, the only safe approach is to assume (pessimistically) that any change to the build system potentially changes any build task — the classic example being build tasks depending on the makefile itself.

Below we show how to implement self-tracking in a build system that allows users to describe build tasks by scripts written in a non-embedded domain-specific language. We will denote the type of scripts by $\text{s}$ and will assume that scripts are indexed by keys $k$ just like all other values $v$. More specifically, we use the following GADT to tag keys $k$ with corresponding result types: $\text{s}$ for scripts and $v$ for other values.

```haskell
data Key kvsa where
  Script :: k -> Key kvss -- Keys for build scripts
  Value :: k -> Key kvsv -- Keys for all other values
```

The function `selfTracking` defined below is a generalisation of the approach explained in the above Excel example `sprsh6`. The function takes a parser for scripts, of type $\text{s} \rightarrow \text{Task Monad} \ k \ v$, and a description of how to build all scripts, of type $\text{Tasks Monad} \ k \ s$. For `sprsh6`, the latter would simply fetch $B_1$-formula when given the key $B_1$ and return `Nothing` otherwise, but the presented approach can cope with much more sophisticated scenarios where scripts themselves are derived from “script sources”, for example, all C compilation scripts can be obtained from a single pattern rule, such as...
gcc -c [source] -o [object]. The resulting typed task description \(\text{TasksT Monad (Key k v s)}\) tracks both values and scripts that compute them and is therefore self-tracking.

\[
\text{selfTracking} :: (s \rightarrow \text{Task Monad} \ k \ v) \rightarrow \text{Tasks Monad} \ k \ s \\
\rightarrow \text{TasksT Monad (Key k v s)}
\]

\[
\text{selfTracking} \ 	ext{parse tasks key} = \text{case key of}
\]
\[
\begin{align*}
\text{Script} \ k & \rightarrow \text{getScript} \ <?> \ \text{tasks k} \\
\text{Value} \ k & \rightarrow \text{runScript} \ <?> \ \text{tasks k}
\end{align*}
\]

where

-- Build the script and return it
\[
\text{getScript} :: \text{Task Monad} \ k \ s \rightarrow \text{TaskT Monad (Key k v s) s}
\]

\[
\text{getScript} \ \text{task} = \text{TaskT} \ \$ \ \text{fetch} \rightarrow \text{run task (fetch . Script)}
\]

-- Build the script, parse it, and then run the obtained task
\[
\text{runScript} :: \text{Task Monad} \ k \ s \rightarrow \text{TaskT Monad (Key k v s) s}
\]
\[
\text{runScript} \ \text{task} = \text{TaskT} \ \$ \ \text{fetch} \rightarrow \text{do}
\]
\[
\begin{align*}
\text{script} & \leftarrow \text{run task (fetch . Script)} \\
\text{run (parse script) (fetch . Value)}
\end{align*}
\]

It is possible to implement \text{selfTracking} without relying on GADTs and typed tasks presented in Section 8.6, at the cost of using partial functions.

### 8.9 File watching versus polling

Most build systems use files for their inputs. When running a build, to check if a file is up to date, one option is to take the modification time or compute the content hash of each input file. However, for the largest projects, the mere act of checking the modification time for all the input files can become prohibitive. To overcome that problem, build systems targeted at large scale, for example, BAZEL and BUCK, rely on file watching API’s to detect when a file has changed. Using that information, the build can avoid performing many file accesses.

File-watching build systems face new engineering challenges. Firstly, a running task may become obsolete due to a concurrent modification of its direct or transitive dependencies. To minimise the amount of unnecessary work, a scheduler can cancel the obsolete task and restart it once its dependencies are up to date. Note that topological schedulers (Section 4.1) cannot be easily adapted to support such situations, since a new topological sort may be required when file dependencies change. A further complication is that spurious dependency cycles may form during a series of file modifications, and a file-watching build system integrated with an IDE should be able to cope with such spurious cycles gracefully instead of terminating with an error.

Build systems that run continuously are also more likely to encounter errors caused by concurrent modification of build outputs. For example, if an output file is checked into the source repository, then downloading a new version of the file can interfere with the build task producing it, resulting in a corrupted output that the build system will be unable
to detect. This problem can be solved by ensuring that tasks have an \textit{exclusive access} to their outputs, for example, by sandboxing the tasks whose outputs can be modified externally.

\section{Related work}

While there is research on individual build systems, there has been little research to date comparing different build systems. In Section 2, we covered several important build systems – in this section, we relate a few other build systems to our abstractions and discuss other work where similar abstractions arise.

\subsection{Other build systems}

Most build systems, when viewed at the level we talk, can be captured with minor variations on the code presented in Section 6. Below, we list some notable examples:

- \textbf{DUNE} (Jane Street, 2018) is a build system designed for OCaml/Reason projects. Its original implementation used \textit{arrows} (Hughes, 2000) rather than monads to model dynamic dependencies, which simplified static dependency approximation. DUNE was later redesigned to use a flavour of selective functors (Mokhov \textit{et al.}, 2019), making it a closer fit to our abstractions.

- \textbf{NINJA} (Martin, 2017) combines the \textit{topological} scheduler of MAKE with the verifying traces of SHAKE – our associated implementation provides such a combination. NINJA is also capable of modelling build rules that produce multiple results, a limited form of multiple value types Section 8.6.

- \textbf{NIX} (Dolstra \textit{et al.}, 2004) has coarse-grained dependencies, with precise hashing of dependencies and downloading of precomputed build products. We provided a model of NIX in Section 6.5, although it is worth noting that NIX is not primarily intended as a build system and the coarse-grained nature (packages, not individual files) makes it targeted to a different purpose.

- \textbf{PLUTO} (Erdweg \textit{et al.}, 2015) is based on a similar model to SHAKE, but additionally allows cyclic build rules combined with a user-specific resolution strategy. Often such a strategy can be unfolded into the user rules without loss of precision, but a fully general resolution handler extends the Task abstraction with new features.

- \textbf{REDO} (Bernstein, 2003; Grosskurth, 2007; Pennarun, 2012) almost exactly matches SHAKE at the level of detail given here, differing only in aspects like rules producing multiple files Section 8.6. While REDO predates SHAKE, they were developed independently; we use SHAKE as a prototypical example of a monadic build system because its implementation presents a closer mapping to our Task abstraction.

- \textbf{TUP} (Shal, 2009) functions much like MAKE, but with a refined dirty-bit implementation that watches the file system for changes and can thus avoid rechecking the entire graph. TUP also automatically deletes stale results.
The one build system we are aware of that cannot be modelled in our framework is FABRICATE by Hoyt et al. (2009). In FABRICATE, a build system is a script that is run in order, in the spirit of:

```
gcc -c util.c
gcc -c main.c
gcc util.o main.o -o main.exe
```

To achieve minimality, each separate command is traced at the OS level, allowing FABRICATE to record a trace entry stating that `gcc -c util.c` reads from `util.c`. In future runs, FABRICATE runs the script from start to finish, skipping any commands where no inputs have changed. The main difference from our Tasks abstraction is that instead of supplying a mapping from keys to tasks, a FABRICATE script supplies a list of build statements, in a user-scheduled order, without declaring what each statement reads or writes.

Taking our abstraction, it is possible to encode FABRICATE assuming that commands like `gcc -c util.c` are keys, there is a linear dependency between each successive key, and that the OS-level tracing can be lifted back as a monadic Task function. However, in our pure model, the mapping is not perfect as `gcc` writes to arbitrary files whose locations are not known in advance. One way of capturing arbitrary writes in our model is to switch from one callback `fetch` to two callbacks, say `read` and `write`, allowing us to track both reads and writes separately.

### 9.2 Self-adjusting computation

While not typically considered build systems, self-adjusting computation is a well-studied area, and in particular, the contrast between different formulations has been thoroughly investigated, for example, see Acar et al. (2007). Self-adjusting computations can automatically adjust to an external change to their inputs. A classic example is a self-adjusting sorting algorithm, which can efficiently (in $O(\log n)$ time where $n$ is the length of the input) recalculate the result given an incremental change of the input. While very close to build systems in spirit, self-adjusting computations are mostly used for in-memory computation and rely on the ability to dynamically allocate new keys in the store for sharing intermediate computations – an intriguing feature rarely seen in build systems (SHAKE’s oracles Section 8.6 can be used to model this feature to a limited degree). Another important optimisation that self-adjusting computation engines often support is the incremental processing of deltas, where instead of marking a value as “changed to 8”, one can mark it as “changed by +1”, assuming it was equal to 7 before. When a delta is small, it can often be propagated to the output more efficiently than by recomputing the output value from scratch.

A lot of research has been dedicated to finding efficient data structures and algorithms for self-adjusting computations, with a few open-source implementations, for example, INCREMENTAL by Jane Street (2015). We plan to investigate how these insights can be utilised by build systems as future work.

---

14 SHAKE provides support for FABRICATE-like build systems – see Development.Shake.Forward.
9.3 Memoisation

Memoisation is a classic optimisation technique for storing values of a function instead of recomputing them each time the function is called. Minimal build systems (Section 2.1) certainly perform memoisation: they store values instead of recomputing them each time. Memoisation can, therefore, be reduced to a minimal build system (as we demonstrate below), but not vice versa, since minimal build systems solve a more complex optimisation problem.

As a simple example of using a build system for memoisation, we solve a textbook dynamic programming problem – Levenshtein’s edit distance (Levenshtein, 1966): given two input strings $a$ and $b$, find the shortest series of edit operations that transforms $a$ to $b$. The edit operations are typically inserting, deleting, or replacing a symbol. The dynamic programming solution of this problem is so widely known, for example, see Cormen et al. (2001), that we provide its encoding in our Tasks abstraction without further explanation. We address elements of strings $a_i$ and $b_i$ by keys $A$ and $B$ $i$, respectively, while the cost of a subproblem $c_{ij}$ is identified by $C$ $i$ $j$.

```haskell
data Key = A Int | B Int | C Int Int deriving Eq

editDistance :: Tasks Monad Key Int
editDistance (C i 0) = Just $ Task $ const $ pure i
editDistance (C 0 j) = Just $ Task $ const $ pure j
editDistance (C i j) = Just $ Task $ \fetch -> do
  ai <- fetch (A i)
  bj <- fetch (B j)
  if ai == bj
    then fetch (C (i -1 ) (j -1 ))
    else do
      insert <- fetch (C i (j -1 ))
      delete <- fetch (C (i -1 ) j )
      replace <- fetch (C (i -1 ) (j -1 ))
      return (1 + minimum [insert, delete, replace])
editDistance _ = Nothing
```

When asked to build $C n m$, a minimal build system will calculate the result using memoisation. Furthermore, when an input $a_i$ is changed, only necessary, incremental recomputation will be performed – an optimisation that cannot be achieved just with memoisation.

Self-adjusting computation, memoisation, and build systems are inherently related topics, which poses the question of whether there is an underlying common abstraction waiting to be discovered.

10 Conclusions

We have investigated multiple build systems, showing how their properties are consequences of two implementation choices: what order you build in and how you decide whether to rebuild. By first decomposing the pieces, we show how to recompose the pieces
to find new points in the design space. In particular, a simple recombination leads to a
design for a monadic suspending cloud build system, which we have implemented and use
in our day-to-day development.

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Conflicts of Interest

None

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