

Improving Agda's module system*

Ivar de Bruin
Bohdan Liesnikov
Jesper Cockx
TU Delft
Delft, Netherlands

ABSTRACT

Agda is a dependently typed programming language and proof assistant. It has a module system that provides namespacing, module parameters and module aliases, which can be used to write shorter and cleaner programs and proofs. However, the current implementation of the module system has several issues, including an exponential slowdown in the desugaring of module aliases. This paper shows how the module system can be changed to address these issues. Instead of desugaring modules during type checking, we handle module parameters and aliases directly during name lookup in the scope checker, simplifying the implementation and eliminating the exponential behavior. Thus we allow users to make full use of the module system where doing so was previously too costly. Furthermore, our changes to the module system also pave the way to fix other issues in Agda's implementation of pretty-printing, records and open public statements.

ACM Reference Format:

Ivar de Bruin, Bohdan Liesnikov, and Jesper Cockx. 2023. Improving Agda's module system. In *Proceedings of ACM Conference (Conference'17)*. ACM, New York, NY, USA, 9 pages. <https://doi.org/10.1145/nnnnnnn.nnnnnnn>

1 INTRODUCTION

Throughout programming history, programmers have struggled with bugs. This is especially true in security-related programs where bugs can have big consequences. One possible solution is to verify the correctness of the program using a proof assistant such as Coq, Lean, or Agda. This has notably seen use in, for example, the creation of a C compiler [30].

To create such proofs, programmers work in proof assistants [9]. Many of these proof assistants are programming languages with strong type systems and termination checkers that enable writing proofs as programs through the Curry-Howard correspondence. This paper focuses on Agda [4], a proof assistant that uses a syntax similar to Haskell, allowing users to write programs in Agda, prove them correct, then transform them to Haskell code using the Haskell back-end. This workflow produces code that is optimised

for performance while maintaining the guarantee that the proven properties hold.

Agda is also used to prove various mathematical properties or even formalize entire mathematical fields [11, 35]. To help programmers structure larger proofs, Agda provides a module system. Modules allow for easy namespacing and grouping of proofs. In addition, there are two interesting features that can be of great help when writing proofs: module parameters and module aliases.

Module parameters are declared once and are then in scope for all declarations in that module, while module aliases introduce new names for a module that instantiate these parameters with specific values. As an example, consider the module `CatProofs` that contains a variety of proofs generalised over a `Category c`, and a module alias `GroupCatProofs` specializing these proofs to the category of groups `groupCategory`.

```
module CatProofs (c : Category) where
```

```
-- ...
```

```
module GroupCatProofs = CatProofs groupCategory
```

Structuring proofs this way increases the usability as well as the readability and ease of writing proofs. Unfortunately, the current version of Agda (version 2.6.4) does not perform well when many aliases are used. The problem is caused by how Agda desugars each module alias to a set of specialized functions, which is similar to how other compilers such as the Rust compiler deal with parametrized functions [6].

While this technique makes sense for a compiler, it is not necessarily a good idea for a proof assistant, as we do not care for the speed of the type checked code, but about the speed of the type checker. Furthermore, removing aliases makes the implementation of the type checker more complex and bug-prone due to the increase in transformations needed. Finally, any information about module aliases is not available to the back-end as they have been removed by the type checker, making back-end features more difficult to implement.

In this paper we analyse different possible implementations of Agda's module system with the goal of removing this performance bottleneck while preserving the module features during type checking. Concretely, we make the following contributions:

- We analyse the issues on the Agda GitHub issue tracker to **identify the main problems with Agda's module system**: the lack of structure, the performance problems with nested module aliases, and a variety of issues related to pretty-printing (Section 3).
- We introduce the concept of **term-qualified names** and demonstrate how these can be used to remove the need to desugar modules and module aliases during type checking, simplifying the implementation (Section 4).

*This is a shortened version of my Master thesis with the same title [17]. All code and results used in this paper can be found at: <https://github.com/ivardb/AgdaModuleImprovement>

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Conference'17, July 2017, Washington, DC, USA
© 2023 Association for Computing Machinery.
ACM ISBN 978-x-xxxx-xxxx-x/YY/MM...\$15.00
<https://doi.org/10.1145/nnnnnnn.nnnnnnn>

- We analyse different implementations of a type checker for a **minimal version of Agda with parametrized modules and module aliases** on randomly generated files, which shows that keeping aliases intact has far superior performance, with barely any downsides. We also verify the validity of our experiments by comparing the performance of our baseline implementation to the actual Agda implementation (Section 5).
- Based on our results as well as other factors such as the difficulty of refactoring Agda, we provide **advice for the future evolution of Agda's module system**, arguing that it should switch to an approach that preserves module aliases (Section 6).

2 AGDA'S MODULE SYSTEM

This section will cover the required background information on Agda's module system. It is assumed that readers are already familiar with dependent typing [24] and its associated concepts such as weak head normal form (WHNF) [29] and telescopes [16]. A full description of Agda's module system can be found in Norell's thesis [34].

Agda's module system. In addition to standard namespacing, modules in Agda can be nested and have parameters:

```
module M (x : Bool) where
  module M1 (y : Bool) where
    f : Bool
    f = x
  module M2 (z : Bool) where
    g : Bool
    g = M1.f true
```

In the function call `M1.f true`, there is no need to provide a value for the parameter `x` as it is still in scope. However, when a declaration is used outside of its module, the module parameters have to be supplied just like normal function parameters, so we do need to provide an argument corresponding to the parameter `y`.

When you often make use of the same module with the same module arguments, it can be useful to make use of a module alias instead:

```
module N (X : Type) where
  id : X → X
  id x = x
module NBool = N Bool
```

Module aliases create a copy of the module that instantiates zero or more of the parameters. Module aliases and parameters can be extremely useful when writing a set of proofs that all depend on a number, a category, or some other value.

Desugaring parametrized modules. The desugaring of parametrized modules happens in three steps. First, Agda replaces each name by its fully qualified version. Next, it lifts all declarations to the top level, turning module parameters into regular function parameters. Third, each function call is given additional arguments corresponding to the module parameters that are in scope for both the

function call and the definition. For example, the module `M` above is desugared into the following:

```
M.M1.f : Bool -> Bool -> Bool
M.M1.f = \x y . x
M.M2.g : Bool -> Bool -> Bool
M.M2.g = \x z . M.M1.f x True
```

The call to `M.M1.f` needs to be explicitly passed the `x` argument as it is no longer automatically in scope.

Desugaring module aliases. To desugar a module alias, new definitions are introduced: for each definition in the original module, we need a definition in the new module that redirects to the old definition, passing the appropriate arguments. For example, the module `N` above is desugared into:

```
N.id : (X : Type) → X → X
N.id x x = x

NBool.id : Bool -> Bool
NBool.id = N.id Bool
```

This means that any arguments passed to an aliased module will be copied once for each declaration.

There are several problems with this way of type-checking and section 3 will explain what these problems are in more detail.

Interface files. In order to avoid having to re-check a file that has already been checked, Agda stores information about the type-checked code in an *interface file*. These files are then used whenever a file needs to be imported to prevent it from having to be type-checked every time it is used.

Such an interface file consists of two parts: the sections and the declarations. Each section corresponds to a module with its full set of parameters, but without any declarations. This information is needed to type-check module aliases. For example, the interface file generated from the module `M` above will contain the following sections:

```
section M (x : Bool)
section M1 (x : Bool) (y : Bool)
section M2 (x : Bool) (z : Bool)
```

After the sections, the declarations are the functions and data-types together with their given or inferred type signatures. The declarations are all using fully qualified names and are lifted to the top level.

3 PROBLEM DESCRIPTION

The implementation of Agda's module system has several problems, many of which are reported as issues on GitHub¹. But first we describe a more general problem: the loss of information caused by the desugaring of modules and module aliases.

Agda allows for the implementation of custom back-ends which can be used to compile Agda to different languages. However, by the time the program is given to the back-end, its modules are already removed and the module parameters are moved to the declaration level. This means that the back-end is not able to decide itself how to handle these features. This rules out certain kinds of

¹<https://github.com/agda/agda/issues?q=label%3Amodules+sort%3Aupdated-desc+>

back-ends, for example a back-end that applies a transformation and then returns valid Agda code.

Apart from this conceptual problem, there are a number of issues related to the module system that have been reported on the Agda issue tracker on GitHub. We divide these issues into three major groups:

(1) **Lack of module structure in the typing environment:**

The first class of issues is caused by the lifting of declarations from (parametrized) modules to the top level. In the past, there have been bugs in this lifting due to wrong renaming [15] or parameters missing from function arguments [21, 27, 2]. While these bugs have been fixed, others are still open. One such issue is issue #6359, which is caused by a declaration that should only exist locally being added to the global scope, thereby breaking the tracking of specific data and ultimately resulting in an illegal function call being accepted [33]. These issues show that the current approach of Agda is both complex and restrictive.

(2) **Performance problems:** The second and more serious class of issues is caused by the desugaring of module aliases. This desugaring causes poor performance either by inserting large numbers of module parameters [26] or more often by the large numbers of declarations that are generated by the desugaring of module aliases [1, 10]. The current behavior of the open public statement is also considered to be unintuitive by many users [19, 14] due to its behavior being different depending on whether module parameters are provided or not. However, making the behavior consistent would require every open public statement to be handled as a module alias, which is considered to be too big of a performance sacrifice with the current implementation [20].

(3) **Pretty-Printing problems:** The final class of problems is related to the pretty-printing of calls to functions that come from a (parametrized) module. Either Agda forgets from which module alias a definition originated [23, 3] or it loses track of module parameters, making infix operators especially confusing to read [22, 12].

4 A STRUCTURED MODULE SYSTEM

Making changes to the actual Agda code base is not a quick process. To be able to prototype a number of different approaches we introduce a simplified version of Agda, called Simple Agda (Section 4.1). To handle parametrized modules, Simple Agda has two important components: it uses term-qualified names in the syntax (Section 4.2) and a structured signature that preserves both modules and module aliases (section 4.3). Finally, we define the signature lookup operation that is required to look up term-qualified names in the structured signature (section 4.4).

4.1 Simple Agda

Simple Agda supports dependent function types, a single universe `Type` with `Type : Type`, and primitive types `Unit` and `Bool`. The full syntax of Simple Agda can be found in Grammar 1. It does not have support for implicit arguments, universe levels, or inductive

$$\begin{array}{c}
 \frac{}{\Sigma \vdash (\lambda x. u) v \longrightarrow u[x := v]} \quad \frac{\Sigma \vdash u \longrightarrow u'}{\Sigma \vdash u v \longrightarrow u' v} \\
 \\
 \frac{}{\Sigma \vdash \text{if true then } v \text{ else } w \longrightarrow v} \\
 \\
 \frac{}{\Sigma \vdash \text{if false then } v \text{ else } w \longrightarrow w} \\
 \\
 \frac{\Sigma \vdash u \longrightarrow u'}{\Sigma \vdash \text{if } u \text{ then } v \text{ else } w \longrightarrow \text{if } u' \text{ then } v \text{ else } w}
 \end{array}$$

Figure 1: Small-step evaluation of Simple Agda terms

data types, as these do not impact the module system, only the complexity of the implementation.

A, B, u, v	$::=$	x	Variable
		<code>Type</code>	Universe
		<code>Unit</code> <code>Bool</code>	Built-in types
		<code>1</code> <code>true</code> <code>false</code>	Basic values
		<code>if u then v else w</code>	if expressions
		$(x : A) \rightarrow B$	Dependent function types
		$\lambda x. u$	Lambda
		$u v$	Application
Δ, Γ	$::=$	ϵ $(x : A)\Delta$	Contexts

Grammar 1: Simple Agda grammar, without modules

As Simple Agda is dependently typed, we need to be able to evaluate terms to WHNF. The evaluation rules can be found in figure 1. The typing rules of Simple Agda are standard. and can be found in figure 2.

So far Simple Agda has no way to introduce new functions or modules. This is our focus for the rest of this section.

4.2 Term-qualified names

Looking back at the desugaring of the module `M` in section 2, the inserted parameters are always exactly those belonging to the modules whose names are added to create fully qualified names. So instead of transforming module parameters into function arguments, we introduce *term-qualified names* to the syntax in grammar 2.

A, B, u, v	$::=$	\dots
		$\alpha.f$ <i>Term-qualified name</i>
α, β	$::=$	ι <i>No qualifier</i>
		$(M \bar{u}).\alpha$ <i>Module qualifier</i>

Grammar 2: Term-qualified names

Term-qualified names extend the syntax of qualified names to allow passing arguments directly to the module. For example, this allows us to write `(M x).M1.f true` instead of `M.M1.f x true`, keeping module arguments next to the module they belong to.

Since the scope checker already replaces each name with its fully qualified version, it is easy to add the appropriate module arguments at the same time. The type checker now no longer needs

$\frac{x : A \in \Gamma}{\Sigma; \Gamma \vdash x : A}$	$\Sigma; \Gamma \vdash \text{Type} : \text{Type}$
$\Sigma; \Gamma \vdash \text{Bool} : \text{Type}$	$\Sigma; \Gamma \vdash \text{Unit} : \text{Type}$
$\Sigma; \Gamma \vdash \text{true} : \text{Bool}$	$\Sigma; \Gamma \vdash \text{false} : \text{Bool}$
$\Sigma; \Gamma \vdash 1 : \text{Unit}$	
$\Sigma; \Gamma \vdash u : \text{Bool}$	$\Sigma; \Gamma \vdash v : A$
$\Sigma; \Gamma \vdash w : A$	
$\Sigma; \Gamma \vdash \text{if } u \text{ then } v \text{ else } w : A$	
$\Sigma; \Gamma \vdash A : \text{Type}$	$\Sigma; \Gamma, x : A \vdash B : \text{Type}$
$\Sigma; \Gamma \vdash (x : A) \rightarrow B : \text{Type}$	$\Sigma; \Gamma, x : A \vdash u : B$
$\Sigma; \Gamma \vdash \lambda x. u : A \rightarrow B$	
$\Sigma; \Gamma \vdash u : A$	$\Sigma \vdash A \longrightarrow^* (b : B) \rightarrow C$
$\Sigma; \Gamma \vdash v : B$	
$\Sigma; \Gamma \vdash u v : C[b := v]$	
$\Sigma; \Gamma \vdash u : A$	$\Sigma \vdash A \longrightarrow^* C$
$\Sigma \vdash B \longrightarrow^* C$	
$\Sigma; \Gamma \vdash u : B$	

Figure 2: Typing rules for terms

$\frac{\Sigma; \Gamma \vdash A : \text{Type}}{\Sigma; \Gamma \vdash f : A}$	$\frac{\Sigma; \Gamma \vdash u : A}{\Sigma; \Gamma \vdash f = u}$
$\frac{\Sigma; \Gamma \vdash \Delta \quad \Sigma; \Gamma \Delta \vdash \Sigma'}{\Sigma; \Gamma \vdash \text{module } M \Delta \text{ where } \Sigma'}$	$\frac{\Sigma; \Gamma \vdash \Delta \quad \Sigma; \Gamma \Delta \vdash \Sigma? \alpha}{\Sigma; \Gamma \vdash \text{module } M \Delta = \alpha}$

Figure 3: Typing rules for declarations in Simple Agda

to deal with the moving around and insertion of module parameters.

4.3 A structured signature

To facilitate working with term-qualified names, we switch to using a *structured signature* that preserves modules and their parameters. The syntax for structured signatures is given in grammar 3.

$\text{decl} ::= f : A$	Type declarations
$\quad \mid f = u$	Function definition
$\quad \mid \text{module } M \Delta \text{ where } \Sigma$	Module definition
$\quad \mid \text{module } M \Delta = \alpha$	Module alias
$\Sigma ::= \epsilon \mid \text{decl}, \Sigma$	Declaration signature

Grammar 3: Structured signature

We define the typing rules for declarations in Simple Agda in figure 3. Checking a type declaration or a function definition amounts to checking that respectively the type or the body is well-typed. There is no check that each symbol is only declared and defined once or that its declaration and definition are consistent, but such a check can easily be added. For typing a module, we check that the telescope is well-formed and that the declarations in it are valid. For module aliases, we also first check the telescope and then use

$\frac{\text{module } M \Delta = \Sigma' \in \Sigma \quad (\Delta_1, \Delta_2) = \text{split}(\Delta, \bar{a}) \quad \Sigma_0 \vdash \Sigma'[\Delta_1 := \bar{a}]! \alpha \rightsquigarrow (\Delta', \Sigma'')}{\Sigma_0 \vdash \Sigma!(M \bar{a}).\alpha \rightsquigarrow (\Delta_2 \Delta', \Sigma'')}$
$\frac{\text{module } M \Delta = \beta \in \Sigma \quad (\Delta_1, \Delta_2) = \text{split}(\Delta, \bar{a}) \quad \Sigma_0 \vdash \Sigma_0! \beta \rightsquigarrow (\Delta', \Sigma') \quad \Sigma_0 \vdash \Sigma'[\Delta_1 := \bar{a}]! \alpha \rightsquigarrow (\Delta'', \Sigma'')}{\Sigma_0 \vdash \Sigma!(M \bar{a}).\alpha \rightsquigarrow (\Delta_2 \Delta' \Delta'', \Sigma'')}$
$\frac{}{\Sigma_0 \vdash \Sigma! \iota \rightsquigarrow (\epsilon, \Sigma)}$

Figure 4: Signature lookup

$\frac{\Sigma \vdash \Sigma! \alpha \rightsquigarrow (\Delta, \Sigma') \quad f = u \in \Sigma'}{\Sigma \vdash \alpha.f \rightarrow \lambda \Delta. u}$
--

Figure 5: Evaluation of term-qualified names

the typing rules for qualifier from figure 7 to check that the alias is well-formed (see section 4.4).

In contrast to the current specification of Agda's module system [34], these typing rules do not need to insert any parameters, nor do we need to create or modify any declarations for dealing with module aliases.

4.4 Signature lookup

Term-qualified names need to be handled properly during evaluation of expressions. For example, the term `(M false).(M2 false).g` evaluates in one step to `(M false).(M1 true).f`, which evaluates further to `false`.

Signature lookup is the process of finding the declaration corresponding to a given (term-qualified) name. To formally define signature lookup, we use the syntax $\Sigma_0 \vdash \Sigma! \alpha \rightsquigarrow (\Delta, \Sigma')$ to say that we are looking for the signature belonging to the module α relative to Σ and that this results in the signature Σ' . Here the telescope Δ represents the remaining module parameters in case any module in α is underapplied, and the signature Σ_0 represents the root signature that is used for looking up module aliases.

The definition of signature lookup can be found in figure 4. In the case where we encounter a module application, we split the module telescope into two (potentially empty) parts: the part of the parameter telescope for which arguments are provided, and the remaining part. Next, we substitute the arguments into the module's signature and look up the remaining qualifier in it. In an actual implementation the substitution on the signature would be implemented lazily as there is no need to perform it on the whole signature. When we encounter a module alias during lookup, we need to find the signature belonging to the aliased module. This lookup is relative to the root signature instead of relative to the current signature, as we use fully qualified names which are relative to the root. We also split the telescope of the module being aliased, as it is not required to provide an argument for each of the parameters in an alias. The final remaining telescope consists of the unused

$$\begin{array}{c}
\text{module } M \Delta = \Sigma' \in \Sigma \quad (\Delta_1, \Delta_2) = \text{split}(\Delta, \bar{a}) \\
\Sigma_0; \Gamma \vdash \bar{a} : \Delta_1 \quad \Delta_2 = \epsilon \text{ OR } \text{noArgs}(\alpha) \\
\Sigma_0; \Gamma \vdash \Sigma'[\Delta_1 := \bar{a}]? \alpha \\
\hline
\Sigma_0; \Gamma \vdash \Sigma?(M \bar{a}).\alpha \\
\\
\text{module } M \Delta = \beta \in \Sigma \quad (\Delta_1, \Delta_2) = \text{split}(\Delta, \bar{a}) \\
\Sigma_0; \Gamma \vdash \bar{a} : \Delta_1 \quad \Delta_2 = \epsilon \text{ OR } \text{noArgs}(\alpha) \\
\Sigma_0 \vdash \Sigma_0! \beta \rightsquigarrow (\Delta', \Sigma') \quad \Sigma_0 \vdash \Sigma'[\Delta := \bar{a}]? \alpha \\
\hline
\Sigma_0; \Gamma \vdash \Sigma?(M \bar{a}).\alpha \qquad \Sigma_0; \Gamma \vdash \Sigma?l
\end{array}$$

Figure 6: Typing rules for qualifiers

$$\frac{\Sigma; \Gamma \vdash \Sigma? \alpha \quad \Sigma! \alpha \rightsquigarrow \Sigma' \quad f : A \in \Sigma'}{\Sigma; \Gamma \vdash \alpha.f : \Delta \rightarrow A}$$

Figure 7: Typing of term-qualified names

parameters of the module alias (Δ_2), the unused parameters of the aliased qualifier (Δ'), and the unused parameters of the remaining qualifier (Δ'').

Signature lookup is used for evaluation of term-qualified names, as shown in figure 5. The unused parameters Δ become additional arguments to the function by introducing an iterated lambda $\lambda \Delta$.

When evaluating a term we can typically assume that the term is well-typed. However, when type checking a qualified name $\alpha.f$, we should also check that all the terms embedded in the qualifier α are well-typed as arguments to their respective modules. This is done through the auxiliary judgement $\Sigma_0; \Gamma \vdash \Sigma? \alpha$ as defined in figure 6. If we encounter an underapplied module (i.e. Δ_2 is not empty), we forbid any further module parameters from appearing in the rest of the qualifier with the side condition $\text{noArgs}(\alpha)$. This is because the types of these parameters could depend on the missing parameters, which would be problematic. Since the current implementation of Agda requires parameters to be given sequentially, this is not removing any expressivity from the language.

Finally, the typing rule for term-qualified names is given in figure 7. The unused parameters Δ now become an iterated function type $\Delta \rightarrow$.

5 EXPERIMENTAL EVALUATION

This section will cover the experiments used to measure the performance improvement of our proposed changes to the implementation of Agda's module system. The experiments were executed for our implementations of Simple Agda as well as on Agda itself to verify the accuracy of our baseline. We will only cover four of our experiments in this paper, the remaining experiments can be found in chapter 7 of the full thesis [17].

5.1 The implemented type checkers

For the experimental evaluation, we implement three versions of a type checker for Simple Agda, differing only in how they handle modules:

- **Version 0** uses the approach Agda takes and lifts all declarations to the top level at the same time, removing all module features. This version will serve as the baseline of our experiments.
- **Version 1** makes use of term-qualified names and uses a structured signature, preserving modules and module parameters. Module aliases will create new declarations, similar to version 0, except these declarations will now be a part of modules with module parameters.
- **Version 2** makes use of term-qualified names and a structured signature supporting module aliases. This version therefore no longer has to make any changes during type-checking, completely preserving the original source syntax.

In addition to the three versions, we implemented a **version 3** that also enables term-qualified syntax for programmers. This does not change the performance, but does allow us to fix the pretty-printing issues with infix and mixfix operators [22]. An analysis of how other pretty-printing issues related to the module system could be addressed in future work is discussed in section 5.3 of the full thesis [17].

5.2 Experiment setup

For our evaluation we need to be able to isolate the impact of specific aspects of the module system on the performance, and we need to make sure that our test files do not use Agda features that are not supported in Simple Agda. Hence we create a generator that can generate files according to some parameters, such as the size of the arguments provided to a module alias. Using this generator, we generate 15 files for each of our experiment configurations. These files are then converted from Simple Agda to Agda to allow them to be run by Agda as well.

The Simple Agda experiments were timed using the timestats library for Haskell [18], while the Agda experiments made use of the Agda-2.6.2.2 executable and its built-in benchmarking features [4].

The experiments were all executed on a 6-core Intel i7-8750H running at 2.20 GHz with 16 GB of RAM and each experiment was repeated 50 times, after which all times were averaged. The run-times for the different files were also averaged to create a single set of timing data per experiment configuration.

5.3 Performance comparison

The first experiment to look at is an experiment using only declarations with no module parameters or aliases. This experiment, found in figure 8, shows that the later type checkers perform slightly better, but that all implementations behave roughly the same. This makes sense as there are no large differences between the implementations in this case. However, it is useful to observe that the simplification of the code in the later versions has performance benefits, even in cases where the complexity is not necessary. This also explains why Agda needs multiple seconds to type-check the files: it is a much more complex language and thus the type checker will always be slower.

The second experiment, shown in figure 9, shows the first clear difference between the implementations. In this experiment, we have created a module of 40 declarations and aliased it. We then increase the size of the argument provided to the module. Both

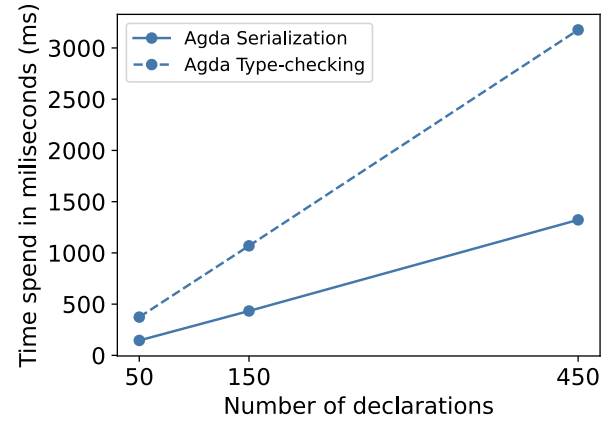
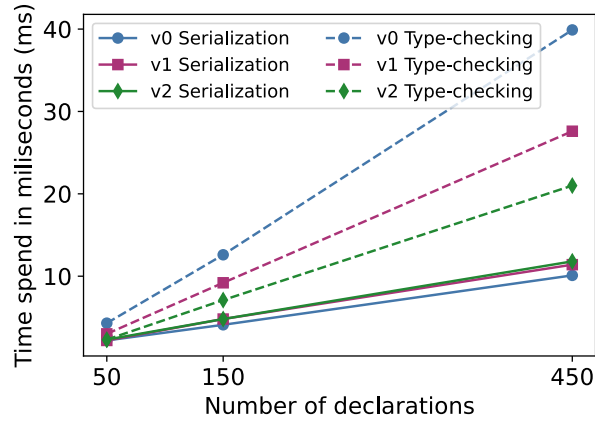


Figure 8: Experiment 1: Only declarations

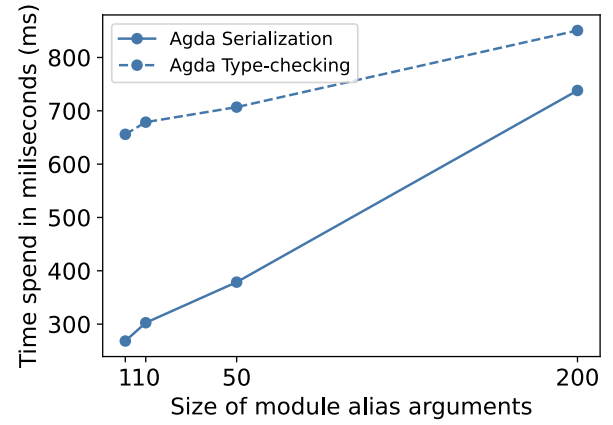
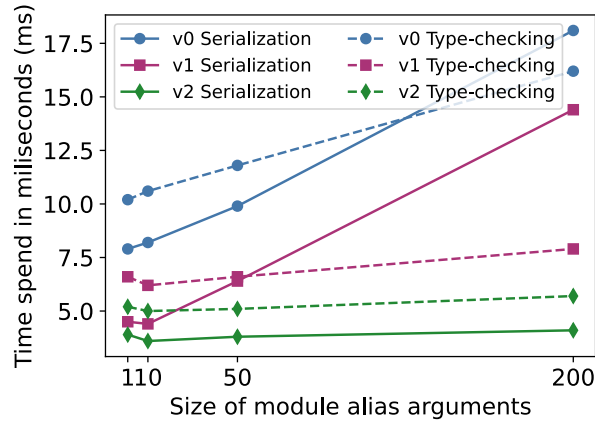


Figure 9: Experiment 2: Module argument size

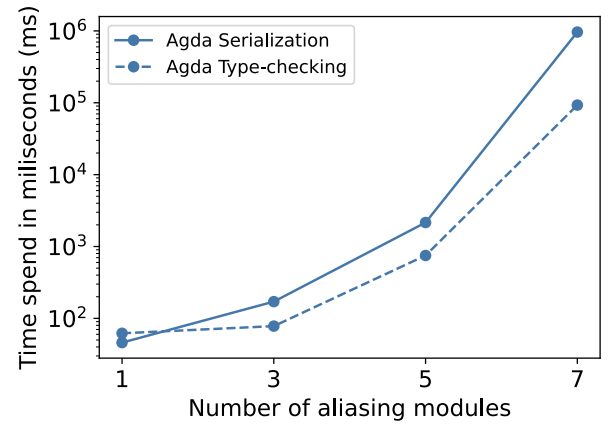
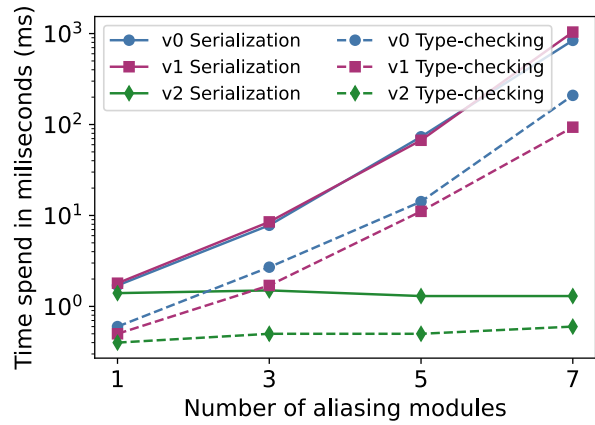


Figure 10: Experiment 3: Nested module aliases

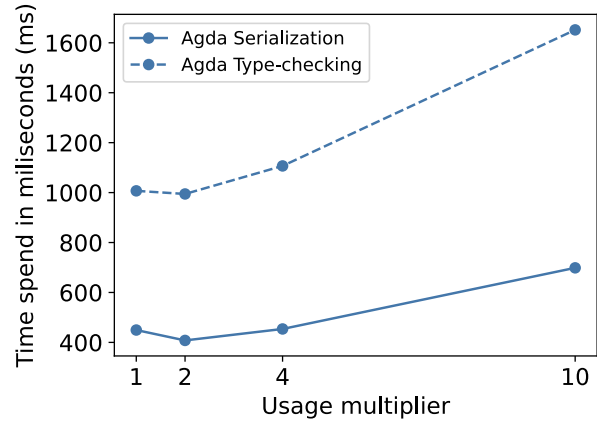
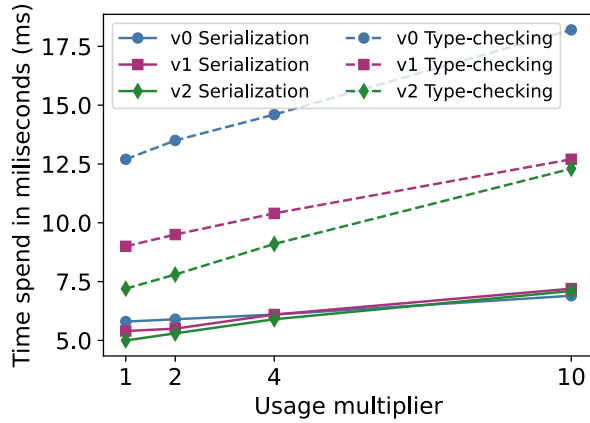


Figure 11: Experiment 4: Increased usage of module aliases

versions 0 and 1, as well as Agda itself, see a significant increase in serialization time. This makes sense as they are all copying the module argument once for each declaration in the module. Version 2 is barely affected by the increasing size as it does not create these copies. Furthermore, we can see that both Agda and version 0 are also affected in their type-checking performance. The reasons for this are not as obvious, but this is likely related to the increased amount of parameter manipulations.

The third experiment, shown in figure 10, shows the clearest difference between the approaches. For this experiment, we have a base module `M0` with 5 declarations and a single module parameter. We then add an increasing number of modules that look like this:

```

module M0 (x : Bool) where -- ...

module M1 (x : Bool) where
  module P = M0
  module Q = P (f1 x)
  module R = P (f2 x)

module M2 (x : Bool) where
  module P = M1
  module Q = P (f1 x)
  module R = P (f2 x)

-- ...

```

This creates a number of nested aliases which produces an exponential number of declarations when aliases are expanded. This is the case in all implementations except for version 2, which we can see from the graph is the only version that does not show an exponential increase in both serialization and type-checking time.

Not generating the new declarations does have some disadvantages. When a declaration is used multiple times, the type will have to be generated multiple times as well, while if you generate all declarations immediately, they will only be generated once. This experiment, shown in figure 11, will increasingly make use of aliased declarations, in the most extreme case generating expressions such as:

```
M'.d70 (M'.d59 (M'.d87 (M'.d91 (M'.d75 ((\x258.
```

```

M'.d29 (M'.d40 (M'.d51 (M'.d60 (M'.d45 (M'.d85
(M'.d5 (M'.d68 (M'.d85 (M'.d55 (M'.d98 (M'.d75
(M.d5 (if d191 then x258 else True)
(if True then d146 else False))))))))))
(if False then d120 else d212))))))

```

From the results, we can see that this does close the gap between version 1 and version 2 a bit, but even in the worst case version 2 is still faster.

6 DISCUSSION

From the results in the previous section, it should be clear that version 2 is a massive improvement compared to version 0. It has no exponential growth in code size and even in its worst case it is still faster than the other versions. Furthermore, the comparison to Agda shows that version 0 behaves the same or better as Agda in the experiments. This means that if we implement the module system of version 2 for Agda, it should also lead to significant improvements.

The performance argument is not the only reason to switch to the new implementation. The system is much simpler to implement and preserves more information to be used by the pretty-printer or eventual compilers. This increase in information allows us to improve the pretty-printing as the display form system can be enhanced [17] and it also allows us to resolve an interesting problem with pretty-printing infix operators. At the moment, Agda does not know which parameters are module parameters and which parameters are normal parameters, leading it to pretty-print incorrect terms:

```

module If (A : Type) where
  if_then_else_ : Bool → A → A → A
  if true then x else y = x
  if false then x else y = y
  if-lemma : (b : Bool) →
    If.if_then_else_ Bool b true false ≡ b
  if-lemma b = {! }
  -- Goal : (If.if Bool then b else false) true ≡ b

```

Agda prints the module parameter as if it is the first argument provided to the `if` statement. With more knowledge about which arguments are module parameters, this bug could be prevented. By using term-qualified names, as implemented in version 3, we can even fix it completely by printing the goal as

```
(If Bool).if b then false else true .
```

Finally, implementing the changed module system is not very difficult. It will be time-consuming, but for the most part, we are removing complexity in the type checker rather than adding it. However, there are a lot of side-effects on the Agda codebase, which will take time to implement. Qualified names were always considered to be a simple value, while now they will contain terms. This will require refactoring the representation of names used internally, but it should have no performance effects as those parameters used to be present as function arguments.

Similar sorts of refactors are required for many other parts of the Agda type checker that assume that all declarations are global, while now there is a local state as well. This is better, as it allows us to fix a number of bugs, but refactoring all the different systems is time-consuming.

Given these reasons, We believe it is absolutely worth it to switch the module system of Agda to the implementation proposed by version 2. It has large performance benefits with few disadvantages and the hardest part about the refactoring process is finding someone that has the time to do it, not actually doing it.

7 RELATED WORK

In this section, we go over a few implementations of other module systems and explain how their problems and solutions differ from the ones in Agda.

ML modules. While modules in Agda are parametrized over values, *functors* in ML and ML-like languages are modules that are parametrized over other modules [31, 32]. There have been attempts to unify the module and term-level languages [36], which would also allow modules parametrized by terms as in Agda. Compared to ML, Agda modules themselves are not first-class, but ML-style functors can be simulated by using records [5]. When there have been problems with exponential growth in code size in ML [38, 37], this has been caused by the compiler actually duplicating full definitions. Agda does not have this problem, as it only ever generates aliases to existing definitions, which can be quickly generated on-the-fly when needed, as demonstrated by our implementation.

Rust generics. Generic functions in Rust [28, 6] and other languages are also specialized to concrete types during compilation. This specialization requires some extra work and produces larger code, but this is an acceptable trade-off as long as it has benefits during the execution of the compiled code. In contrast, in a type checker like Agda we are more concerned with the speed of the type checking itself, and we can leave optimization of the code to the back-end compiler.

Lean namespaces and sections. The Lean proof assistant has support for nested, hierarchical namespaces as well as sections parametrized over variables [40]. Together these can simulate Agda modules, but not module instantiations. Since there is no way to specialize a section to specific values, there is also no risk of code size explosion.

Coq modules. The Coq proof assistant has an extensive module system including module types, nested modules, higher-order functors and module subtyping [39, 13]. The module structure is preserved in the kernel of Coq so there is no code generation and hence no risk of exponential code explosion. There is no way to directly parametrize a module by a term-level variable, so arguments to functors are typically smaller than module arguments in Agda.

Isabelle locales. Locales are Isabelle's approach for dealing with parametric theories [8, 7]. They provide a way to define a shared set of parameters and assumptions about those parameters. Each locale can then be *extended* with definitions and theorems. This can happen at any point in the program, making locales more flexible than Agda modules at the cost of making name lookup more complicated. A locale can also extend another locale by *importing* it, which corresponds to a nested module in Agda. Finally, a locale can be *interpreted* by instantiating its parameters, which creates qualified copies of each definition of the locale. Ballarín describes how locales are implemented by means of a *development graph* [25], which serve a similar role to the structured signature we introduced in our implementation. However, since Isabelle uses classical logic and does not by default produce proof terms, there are no issues with exponential growth.

8 CONCLUSION AND FUTURE WORK

The main goal of this work was to improve the performance of Agda's module system. We have created a simpler language called Simple Agda to evaluate the performance of three different approaches: Agda's current approach, keeping modules and module parameters intact and keeping modules and module aliases both intact. We have introduced the concept of term-qualified names, which allows us to implement these later versions with ease, by realising that much of the difficulty of Agda's module system can be resolved by the scope checker.

We have evaluated these approaches in a variety of scenarios using randomly generated files. These experiments showed that the best approach is to keep modules and module aliases intact during type-checking. This will perform better in all evaluated scenarios and completely eliminates the exponential complexity of Agda's current system when aliases are nested.

Furthermore, we have seen that this change will allow for several other problems to be addressed as well. The improved module system makes use of term-qualified names internally: `(M true).f`. Allowing this syntax to be used when programming in Agda will remove a significant number of pretty-printing problems. The improved performance of module aliases also means that open public statements can be changed to a more intuitive implementation. This was not yet possible due to the performance bottleneck.

The performance benefits combined with the other benefits mean that making the proposed changes to Agda will massively improve the user experience and eliminate some long-standing open issues. The performance problems especially have hampered the development of, for example, category theory proofs as these benefit massively from module aliases, which so far, could not be used extensively.

There are two major areas related to Agda's module system that should be looked at in future work: pretty-printing and records. For

pretty-printing, it will need to be decided how we want to qualify terms. Do we keep the alias qualifier when evaluating, akin to a sort of dynamic dispatch, or do we reduce it to the aliased term and start fully reducing terms? Now that we maintain aliases after type-checking, such questions and many others can start to be analyzed in much more detail.

The second major area for future work are Agda's records. Agda's record functionality has been extended multiple times in the past few years but this often occurred in an isolated manner. This means that it is unclear what the various interactions between the record features are. Furthermore, there is also a lack of consensus on how records should interact with the module system. Now that the module system has been cleared up more, it is time to do the same for the record system and see how it should interact with itself and with modules.

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