Cameleer: a Deductive Verification Tool for OCaml (extended version)*

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Abstract

OCaml is particularly well-fitted for formal verification. On one hand, it is a multi-paradigm language with a well-defined semantics, allowing one to write clean, concise, type-safe, and efficient code. On the other hand, it is a language of choice for the implementation of sensible software, e.g., industrial compilers, proof assistants, and automated solvers. Yet, with the notable exception of some interactive tools, formal verification has been seldom applied to OCaml-written programs. In this paper, we present the ongoing project Cameleer, aiming for the development of a deductive verification tool for OCaml, with a clear focus on proof automation. We leverage on the recently proposed GOSPEL, a Generic OCaml SPECification Language, to attach rigorous, yet readable, behavioral specification to OCaml code. The formally-specified program is fed to our toolchain, which translates it into an equivalent program in WhyML, the programming and specification language of the Why3 verification framework. Finally, Why3 is used to compute verification conditions for the generated program, which can be discharged by off-the-shelf SMT solvers. We present successful applications of the Cameleer tool to prove functional correctness of several significant case studies, like FIFO queues (ephemeral and applicative implementations) and leftist heaps, issued from existing OCaml libraries.

1 Introduction

Over the past decades, we have witnessed a tremendous development in the field of deductive software verification [13]. Interactive proof assistants have evolved from obscure and mysterious tools into de facto standards for proving industrial-size software projects. Notable examples include the SeL4 verified operating system kernel [25], and the verified compilers CompCert [23] and CakeML [35]. On the other end of the spectrum, the so-called SMT revolution and the development of reusable intermediate verification infrastructures contributed decisively to the development of practical automated deductive verifiers. Remarkable applications of automated verification tools include the verified version of the Microsoft’s Hypervisor [4] and, more recently, the use of ghost monitors [9] to analyze installation scenarios of the Debian distribution [3].

Despite all the advances in deductive verification and proof automation, little attention has been given to the family of functional languages [32]. Taking the example of the OCaml language, if it is a language well-fitted for verification (given its well-defined semantics, clear syntax, and state-of-the-art type system), the community still misses an easy to use framework for the specification and verification of OCaml code.

In this paper, we present Cameleer, a tool for the deductive verification of programs directly written in OCaml, with a clear focus on proof automation. Cameleer uses the recently proposed GOSPEL [6], a specification language for the OCaml language. We believe this is one of the strengths of our approach: firstly, GOSPEL makes a certain number of design choices, that turn

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it into a clean and digestible specification language; secondly, GOSPEL terms are written in a subset of the OCaml language. In the scope of this work, we have also extended GOSPEL to include implementation primitives, such as loop invariants and ghost code, evolving the language from an interface specification language into a more mature proof tool.

Cameleer takes as input an OCaml program annotated with GOSPEL specification and translates it into an equivalent counterpart in WhyML, the programming and specification language of the Why3 framework [18]. Why3 is a toolset for the deductive verification of software, clearly oriented towards automated proof. A distinctive feature of Why3 is that it can interface with several different off-the-shelf theorem provers, namely SMT solvers, which greatly increases proof automation. We believe that proof automation is another strong point of Cameleer, on that can ease its adoption by regular OCaml programmers. In this paper, we present some case studies of automatically verified OCaml modules with our tool.

Contributions. To the best of our knowledge, Cameleer is the first deductive verification tool for annotated OCaml programs. It handles a realistic subset of the language, as demonstrated by a comprehensive set of case studies. Another contribution of this paper is our translation of the OCaml module language into WhyML. While sharing many common syntactic constructions, OCaml and WhyML differ more significantly when it comes to their module systems. This poses interesting challenges to our translation scheme.

Paper structure. This paper is organized as follows. Sec. 2 presents a simple example of a verified OCaml program, intended as a smooth introduction to the Cameleer tool and GOSPEL language. Sec. 3 describes the OCaml to WhyML translation mechanism implemented in the core of Cameleer. Sec. 4 reports on relevant case studies verified with Cameleer, including ephemeral and functorial data structures. Finally, we present some related work in Sec. 5 and conclude with future work in Sec. 6. The source code of Cameleer and verified case studies are publicly available online on the GitHub repository of the project.¹

2 Warmup Example

In this section, we present the verified implementation of the Fibonacci function. We first present a purely applicative version of the mathematical definition, and then an efficient implementation using side-effects. This section is intended as a gentle introduction to the Cameleer framework, the GOSPEL specification language, and certain important verification concepts such as ghost code, loop invariants, and function contracts.

A logical definition. The classical mathematical definition can be readily translated, in OCaml, into the following recursive function:

```ocaml
let rec fib n =
  if n <= 1 then n else fib (n-1) + fib (n-2)
```

Though very elegant and concise, the above definition presents some pitfalls and raises a number of questions: is this a total function (i.e., it terminates and is defined for every integer argument) and could we avoid repeated computations in recursive calls? We focus now on the former and shall address the latter in a moment.

The Fibonacci function is, traditionally, only defined for a non-negative argument and this is exactly the definition we follow here. Such a constraint on a function arguments is a precondition, i.e., it limits the range of values the function arguments can take. We shall take this opportunity to show a first piece of OCaml code annotated with GOSPEL specification:

¹https://github.com/mariojppereira/cameleer
let rec fib n =  
  if n <= 1 then n else fib (n-1) + fib (n-2)  
(*@ requires n >= 0 *)

A GOSPEL specification is attached to the end of a function definition and is given within special comments of the form (*@ ... *). The requires clause is used to state the precondition of a function. In order to prove that every call to fib halts, we must provide a variant that strictly decreases at each recursive call and has a lower-bound. Here, the value of n decreases at each recursive call and is bounded from below thanks to the precondition. In GOSPEL, we express the variant of a function as follows:

let rec fib n = ...  
(*@ requires n >= 0  
  variant n *)

The given precondition and the variant form what we call the function’s contract. Other than serving as rigorous documentation of the function’s behavior, the interest of providing a contract is to be able to formally prove that the code respects the given specification. This is where the Cameleer toolchain enters the scene.

Assuming function fib is contained in the OCaml file fibonacci.ml, starting a proof is as easy as typing cameleer fibonacci.ml in a terminal. Cameleer translates the input program into an equivalent WhyML counterpart and launches the Why3 graphical integrated development environment. This allows us to visually inspect the verification conditions (VCs) generated by Why3 for the fib function: two of them state the variant decreases and is not a negative value, at each recursive call; the other two state the precondition holds for each recursive call. All of these are easily discharged using SMT solvers, e.g., Alt-Ergo [10], CVC4 [2], or Z3 [12].

The provided fib function is a naive implementation, as it unnecessarily repeats most intermediate computations. Actually, this is not meant to be used as an executable implementation, but rather as a logical description of the Fibonacci definition. This means fib works more as mathematical function than a programming one. In order to instruct Cameleer to consider fib a logical function, we decorate it with the OCaml attribute [@logic], as follows:

let [@logic] rec fib n = ...

Under this setting, the fib function can now be used both inside specification clauses, as well as in regular OCaml code.

A verified efficient implementation. Moving on to an efficient Fibonacci function, a classical approach is to implement it as a loop that goes from 0 to n-1, storing in two auxiliary variables x and y the values for fib n to fib (n + 1) to compute fib (n + 2). The OCaml code and GOSPEL specification are as follows:

let fib_imp n =  
  let y = ref 0 in  
  let x = ref 1 in  
  for i = 0 to n - 1 do  
    let aux = !y in  
    y := !x; x := !x + aux  
  done;  
  !y  
(*@ r = fib_imp n  
  requires n >= 0  
  ensures r = fib n *)
As expected, fib_imp has the same precondition as fib. Here, we name the result of the fibonacci function to mention it in the postcondition, introduced via the ensures clause. This is exactly where we take advantage of the fact that fib can be used as a logical function, since we state the returned value of fib_imp n is equal to fib n.

As usual in deductive verification, the presence of the for loop requires us to supply a loop invariant. Here, it boils down to

```ocaml
for i = 0 to n - 1 do
  (*@ invariant !y = fib i && !x = fib (i + 1) *)
```

When fed to Cameleer, four verification conditions are generated for the given fib_impl implementation: a loop invariant initialization, which states the invariant holds before the first iteration; a loop invariant preservation, which states the invariant holds after each iteration; two postcondition, one accounting for the case when the loop does not even execute (n = 0), the other when the loop performs at least one iteration. All of them are automatically discharged. The complete OCaml implementation of the Fibonacci implementation can be found online, at the project’s GitHub repository:\(^2\).  

**The tale of the ghost code.** The fib_imp function is a provably correct implementation of the Fibonacci function. After finishing the proof, the specification has no computational interest and should no be part of compiled code. This includes the fib function which is only useful as a logical definition. This duality between parts of the code that are compiled and other that have only proof interest is a common trait of deductive verification, commonly known as ghost code [16]. Some parts of a program are marked with a special ghost status and should be erased from the regular code after completing the proof effort. In Cameleer, we use the [@ghost] attribute in order to change the status of some functions. For the example of the fib definition, this is as simple as let [@logic] [@ghost] rec fib n. Building a sound mechanism for ghost code erasure is far from a trivial task, especially in the presence of effectful computations [30]. In Sec. 3.3, we discuss several solutions to deal with ghost code that we could put into practice in the scope of the Cameleer project.

## 3 Methodology

This section gives an overview on the core of the Cameleer tool, from the OCaml code annotated with GOSPEL specification to the generation of an equivalent WhyML program. In Sec. 3.1, we describe how we use the GOSPEL toolchain to attach specification to certain nodes in the OCaml AST. In Sec. 3.2 we define our OCaml to WhyML translation as a set of inference rules. Finally, Sec. 3.3 explains how we are currently using Why3 as an intermediate verification framework.

### 3.1 Using GOSPEL toolchain

The Cameleer tool relies on the use of the GOSPEL toolchain\(^3\) to parse and manipulate the OCaml abstract syntax tree. It provides a patched version of the OCaml parser that recognizes GOSPEL special comments and converts them to regular OCaml attributes. For instance, the fib_imp specification from Sec. 2 is translated into the following post-item attribute:

```ocaml
let fib_imp n = ...
[@@gospel "r = fib_main n requires n >= 0 ensures r = fib n"]
```

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\(^2\)https://github.com/mariojppereira/cameleer/tree/master/examples/fibonacci.ml

\(^3\)https://github.com/vocal-project/vocal
The payload of a GOSPEL attribute is, hence, a string that contains the user-supplied specification\(^4\). The GOSPEL attributes are processed by a dedicated parser and type-checker \([6]\), where specifications are attached to nodes of a patched version of the OCaml AST. This custom AST is the entry-point for our OCaml to WhyML translation, which we describe next.

### 3.2 Translation into WhyML

We present our translation from OCaml to WhyML as set of inference rules. All the auxiliary functions and predicates are total definitions. We focus here on a subset of the OCaml and WhyML languages. The complete definitions are depicted in Fig. 1 and Fig. 2, respectively. On the WhyML side, we omit the definition of \(t\) which stands for the logical subset of WhyML. For a comprehensive definition of this part of WhyML, we refer the reader to the Why3 reference manual \([36, \text{Chap. 7}]\). We do not intend to use this section as an heavy formalization of our translation, but rather as a comprehensive presentation of the OCaml subset that Cameleer can handle. Cameleer will report a dedicated error message if a user tries to translate an OCaml program that syntactically falls out of the supported fragment. It is worth noting that our translation is purely syntactic, as we build on the GOSPEL toolchain which is based on a PPX approach. In particular, this means that typing the translated OCaml program is left as a task to Why3. Making our translation type-directed, or at least type-aware, is left as future work.

**Expressions.** Selected OCaml expressions include variables (\(x\) ranges over program variables, while \(f\) is used for function names), the conditional if..then..else, local bindings of (possibly recursive) expressions, function application, records manipulation (for simplicity, we assume every field to be mutable), treatment of exceptions, loop construction, and finally the assert false expression. Values include numerical and Boolean constants, as well as anonymous functions where arguments are annotated with a ghost status. We only consider functions as valid recursive definitions and application is limited to the application of a function name to a list of arguments. The latter is just to ease our presentation; the former is due to recursive definitions in WhyML being limited to functions. Finally, \(A\) notation stands for a (possibly empty) placeholder of OCaml attributes, representing the original place in the expression where GOSPEL elements are introduced. For instance, the first \(A\) in a let..rec expression can contain the [@ghost] and [@logic] attribute, while the second one stands for the function specification. We omit the definition of \(\tau\) and \(t\), respectively from the OCaml and the WhyML sides. The former stands for the grammar of OCaml types, while the latter is the logical subset of WhyML.

The OCaml and WhyML languages are very similar, hence our translation of expressions is mostly an isomorphism. We give the complete set of rules in Appendix A and explain here only the more subtle aspects of this translation. Let us begin with the translation of an OCaml expression of the form let..rec..in into its WhyML counterpart. The corresponding translation rule is the following:

\[
\begin{align*}
(\text{EREc}) & \\
& \frac{e_0 \xrightarrow{\text{function}} \overbrace{\beta x, e'_0}^\text{\beta x}}{\text{let } A_0 \text{ rec } f_0 = e_0 \text{ in } e_1 \xrightarrow{\text{expression}} e'_1} \\
& \quad \quad \frac{\neg \text{is_ghost}(A_0) \quad \text{kind}(A_0) = \mathcal{K} \quad A_1 \xrightarrow{\text{function spec}} S_1}{\text{rec } \mathcal{K} f(\beta x) S_1 = e'_0 \text{ in } e'_1}
\end{align*}
\]

For the sake of presentation, we use here only a single recursive function and omit any mutually recursive definition. In fact, translating a set of mutual definitions simply amounts to a recursive

\(^4\)In fact, GOSPEL elements can be directly provided using attributes in the source code.
call to our expressions translation procedure, as depicted in Appendix A. Let us consider the following generic expression as a running example to explain the \((\text{ERec})\) rule:

\[
\text{let rec } \text{foo} (x \text{[@ghost]}) y = \text{e0} \quad \text{(*@ r }= \text{foo x }y \text{ requires ... variant ... ensures ... *)}
\]

\[
\text{in } \text{e1}
\]

The second premise of the rule translates expression \(\text{e1}\) and it simply amounts to a recursive call to the translation scheme. The first premise is a bit more evolving, hence we explain it in more detail. The definition of \(\text{foo}\) is desugared by the OCaml parser into the following Curried expression:

\[
\text{let rec } \text{foo} = \text{fun (x \text{[@ghost]}) -> fun y -> e}
\]

When translating into WhyML, we revert such an operation: we traverse the body of \(\text{foo}\), building a list of ghost-annotated arguments from the argument of each \text{fun} construction. The body of the translated function is the body of the last \text{fun}. This is done in the first premise of the rule, using the \text{function} operation. This conversion into multi-argument functions is justified by the limits of Why3 when it comes to higher-order and anonymous functions. In WhyML, one can only define pure anonymous functions, \textit{i.e.}, free of any side effects. Hence,
directly translating the Curried definition of `foo` would yield a syntactically correct WhyML expression, however this would be rejected by the language type-and-effect system. The other three premises deal with specification elements. The first uses the `is_ghost` operation to test whether the `[@ghost]` attribute is provided in $\mathcal{A}_0$. If that is the case (rule (ERecGhost) in Appendix A), the function body is translated into `ghost e`. The kind of a function is either `reg` (only usable as a program function) or `logic` (also usable inside specification). We introduce the `kind(\cdot)` operation, which also retrieves the function kind from $\mathcal{A}_0$ (in case of a regular function, the attribute can be omitted). The last premise translates the supplied GOSPEL preconditions, variants, and postconditions into the WhyML specification language. We omit the definition of `function spec` since this is a trivial (syntactic) transformation.

We highlight two more interesting cases of expressions translation: the `assert false` construction and local non-recursive bindings. Contrarily to any other `assert` expression, `assert false` is used in OCaml to indicate unreachable points in the code and “is treated in a special way by the OCaml type-checker”\(^5\). WhyML features the `absurd` construction which has the exact same semantics, which greatly simplifies our translation effort (rule (EAbsurd) in Appendix A). Finally, when translating a `let..in` expression, we need to account for both the

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\(^5\)To quote a comment from the OCaml compiler source code itself.
introduction of a local function, as well as the binding of a non-functional value. The translation rule for the latter is as follows:

\[
\frac{\neg \text{is\_ghost}(A) \quad \neg \text{is\_functional}(e_0) \quad e_0 \, \text{expression} \quad e'_0 \quad e_1 \, \text{expression} \quad e'_1}{\text{let}\ A = e_0 A' \text{ in } e_1 \, \text{expression} \quad \text{let reg } x = e'_0 \text{ in } e'_1}
\]

This rule stands for the sub-case where the bound variable is regular, hence the use of the \text{reg} kind. Any \text{GOSPEL} specification possibly contained in \( A' \) is ignored. Finally, the use of the auxiliary predicate \text{is\_functional}(\cdot) is what allows us to distinguish between locally-bound variables and functions. This predicate decides whether \( e_0 \) is a \text{fun} \( x \rightarrow \ldots \) expression, in which case we introduce a \text{WhyML} local function (rule (ELetFun) in Appendix A). This approach does not take partial applications into account, which are directly translated into its \text{WhyML} counterpart. If a partial application introduces an effectful computation, this will be rejected by the \text{Why3} type system.

**Top-level declarations.** Selected top-level declarations include exceptions and type declaration, (mutually-recursive) function definition, and introduction of sub-modules. An exception takes a list of \( \pi \) values, types annotated with a ghost status, to account for the possibility of ghost arguments. In \text{Why3} vocabulary, this is the \text{mask} of an exception [30, Chap. 3.1]. The complete set of translation rules for top-level declarations and type definitions is given in Appendix B. We highlight here the cases of record type definition and sub-modules.

The attribute \( A \) after a record type definition is used to express in \text{GOSPEL} a type invariant, i.e., a predicate that every inhabitant of such type must satisfy. Type invariants are readily supported by \text{Why3}, as depicted in rule \text{(TDRecord)} in Fig. 5, Appendix B. Each field of the record type is also annotated with a ghost status. This is a common practice in deductive verification: some fields act as logical models of the record value; these can be explored within the proof to reason about the represented data structure. It is worth noting that in \text{WhyML}, contrarily to \text{OCaml}, type arguments are introduced on the right-hand side of the type name.

Finally, translation of a sub-module definition is guided by the following rule:

\[
\frac{m \, \text{module} \ d}{\text{module } M = m \, \text{declaration} \quad \text{scope } M \ d \ \text{end}}
\]

We translate the module expression \( m \) into a list of \text{WhyML} declarations. \text{WhyML} does not feature the notion of sub-module, hence we encapsulate the translated declarations into a \text{scope}, the \text{WhyML} unit for namespaces management. In what follows, we provide a more detailed account of the \text{WhyML} module system and its differences with respect to that of \text{OCaml}.

**Modules.** The most interesting cases in our translation is how we deal with the modules language from the \text{OCaml} side. A \text{WhyML} program is a list of modules, a module is a list of top-level declarations, and declarations can be organized within scopes.

The first module expression we take into account is the \text{struct..end} construction. This is translated into a \text{WhyML} declarations, as depicted in rule \text{(MStruct)} (Appendix C). We note this does not change the structure and code organization of the original program, since a \text{struct..end} expression follows a \text{module} declaration. Hence, a declaration of the form \text{module } \( M \ d \ \text{end} \) is translated into \text{scope } \( M \ d \ \text{end} \).

Functors are a central notion when programming in \text{OCaml}, so it is out of question to develop a verification tool for \text{OCaml} without a (at least minimal) support for functors. \text{WhyML} does...
not feature a syntactic construction for functors; instead, these are represented as modules
containing only abstract symbols [19]. Thus, we propose the following translation rule:

\[
\begin{align*}
\text{(MFUNCTOR)} & \\
& \frac{\text{module type } \overline{d} \quad \text{module } \overline{d}'}{\text{functor}(\mathcal{X} : \overline{m}) \rightarrow \text{module scope } \mathcal{X} \overline{d} \text{ end } \overline{d}'}
\end{align*}
\]

Each functor expression is translated into a WhyML scope followed by a list of declarations.
For instance, the OCaml functor

\[
\text{module Make} = \text{functor } (X : \ldots) \rightarrow \text{struct } \ldots \text{ end,}
\]

is translated into the following WhyML excerpt:

\[
\text{scope Make scope } X \ldots \text{ end } \ldots \text{ end}
\]

The given transformation is the dual of what is actually implemented in the Why3 extraction
machinery: every WhyML expression of the form

\[
\text{scope } A \text{ scope } B \ldots
\]

is translated into

\[
\text{module } A \text{ (B: } \ldots) \ldots,
\]

as long as scope B features only abstract symbols.

Signatures. The argument of a functor is expressed as a module type, i.e., a signature
of the form sig..end. This encapsulates a list of declarations belonging to the OCaml signature
language, which are translated into a list of WhyML expressions, according to rule (MTSig)
(Appendix C). Contrarily to OCaml, WhyML does not impose a separation between signature
(interface) and structure (implementation) elements. In particular, the WhyML surface lan-
guage allows one to include non-defined val functions and regular let definitions in the same
namespace. We give the following translation rule for val declarations:

\[
\begin{align*}
\text{(SVAL)} & \\
& \frac{\text{is ghost}(A)}{\text{kind}(A) = \mathcal{K} \quad A' \quad \text{function spec } S \quad \pi, A' \quad \text{function args } x : \pi' \}, \pi_{\text{res}}}{\text{val } A f : \pi A' \quad \text{signature } \text{val } K f(x : \pi) S : \pi_{\text{res}}}
\end{align*}
\]

The name of the arguments are retrieved from the function specification (Sec. 4.2 features an
equal example of such case). Non-defined functions can also be declared as ghost and/or logical
functions. For brevity, the case of ghost val is omitted. The complete set of translation rule
for signature items can be found in Appendix D.

Programs. An OCaml program is simply a list of top-level declarations. These are translated
into a WhyML module, as follows:

\[
\begin{align*}
\text{(PROGRAM)} & \\
& \frac{\overline{d} \quad \text{declaration } \overline{d}'}{\overline{d} \quad \text{program } \text{module } M \overline{d'} \text{ end}}
\end{align*}
\]

The name M of the generated module is issued from the OCaml file that contains the original
program. If file foo.ml contains the program p, it gets translated into

\[
\text{module Foo } p \text{ end}
\]

In summary, we generate a WhyML program containing a single module, which represents the
top-level module of an OCaml file. In turn, each sub-module is translated into a WhyML scope,
with a special treatment for functorial definitions.

3.3 Interaction with Why3

Why3 front-end. One distinguished feature of the Why3 architecture is that it can be ex-
tended to accommodate new front-end languages [36, Chap. 4]. Building on the translation
scheme presented in previous section, we use the Why3 API to build an in-memory representa-
tion of the WhyML program and to register OCaml as an admissible input format for Why3.
We can use any Why3 tool, out of the box, to process a.ml file. For instance, one could use directly
the command

\[
\text{why3 ide bar.ml}
\]

to trigger our OCaml input format and to call the Why3 IDE on the translation of the bar.ml file.
Other than the ide, we could use the extract command to erase any trace of ghost from the original code and print an equivalent OCaml implementation. This would provide us with the necessary guarantees about the semantics and typedness of the extracted program. However, we believe a solution that is directly integrated with the OCaml compilation chain is more organic and natural to the programmer. We currently working on a PPX that generates a new OCaml AST without ghost code, which uses the Why3 extraction as an internal ingredient.

Limitations of using Why3. WhyML and GOSPEL are very similar specification language. Moreover, they share some fundamental principals, namely the arguments of functions are not-aliased by construction and each data structure carries an implicit representation predicate. This makes the translation from GOSPEL to WhyML a very natural process. However, one can use GOSPEL to formally specify some OCaml programs which cannot be translated into WhyML. This is much evident when it comes to recursive ephemeral data structures. Consider, for instance, the cell type definition from the Queue module of the OCaml standard library:\footnote{https://caml.inria.fr/pub/docs/manual-ocaml/libref/Queue.html}

\begin{verbatim}
type 'a cell = Nil | Cons of { content: 'a; mutable next: 'a cell }
\end{verbatim}

As we attempt to translate such data type into WhyML, we get the following error:

This field has non-pure type, it cannot be used in a recursive type definition

Recursive mutable data types are beyond the scope of Why3’s type-and-effect discipline \cite{15}. The solution would be to resort to an axiomatic memory model of OCaml in Why3 \cite{20}, or to employ a richer program logic, e.g., Separation Logic \cite{33} or Implicit Dynamic Frames \cite{34}. We leave such an extension to the Cameleer infrastructure for future work.

4 Case Studies

4.1 FIFO Queue

Our first case study is the implementation of a FIFO queue, implemented as an ephemeral data-structure. The complete OCaml development and GOSPEL specification are presented at Cameleer’s GitHub repository \footnote{https://github.com/mariojppereira/cameleer/blob/master/examples/ephemeral_queue.ml}. We also publish online a simpler, purely applicative version of this data structure \footnote{https://github.com/mariojppereira/cameleer/blob/master/examples/applicative_queue.ml}, which we picked from the OCamlGraph library\footnote{https://github.com/backtracking/ocamlgraph}. This case study follows the standard approach of using a pair of lists to store the elements of the queue, as follows:

\begin{verbatim}
type 'a t = { mutable front: 'a list; mutable rear : 'a list;
  mutable view : 'a list [@ghost]; }
(*@ invariant (front = [] -> rear = []) && view = front ++ List.rev rear *)
\end{verbatim}

In order to formally express the behavior of the queue data structure, we equip type t with a model field and a GOSPEL invariant. The view field is used to represent the whole queue as a single list. This is a ghost field since it has no computational interest. Front elements are stored in the correct order and rear elements are stored in reversed order. Elements are pushed into the head of the rear list and popped off the head of front. This data structure also maintains the invariant that if front is empty, then so is rear.

In what follows, the specification of operations on a queue is solely given in terms of the view field. The push operation is implemented and specified as follows:

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\begin{verbatim}
(*@ invariant (front = [] -> rear = []) && view = front ++ List.rev rear *)
\end{verbatim}
let push x q =  
  if is_empty q then q.front <- [x] else q.rear <- x :: q.rear;
  q.view <- q.view @ [x]
(*@ push x q  
  ensures q.view = (old q.view) @ [x] *)

The postcondition asserts the updated view field of q consists of the value of view before the call (old q.view), extended with the new element x. If the queue is empty, then x is pushed into the front list; otherwise, the new element is added as the new head of rear.

Next, we present the implementation of the pop operation. This is as follows:

let pop q = match q.front with  
| [] -> raise Not_found  
| [x] ->  
  q.front <- List.rev q.rear; q.rear <- []; q.view <- tail_list q.view;  
  x  
| x :: f ->  
  q.front <- f; q.view <- tail_list q.view;  
  x
(*@ x = pop q  
  raises Not_found -> is_empty (old q)  
  ensures x :: q.view = (old q).view *)

If the queue is empty we raise the Not_found exception from the OCaml standard library. A raises clause is used to introduce what we call an exceptional postcondition. We must be careful enough to specify that the is_empty property is verified by pre-state of q. Otherwise, had we used is_empty q, this would propagate into our proof context that the queue is not empty after the execution of pop. This would prevent proving the safety of the next function.

The most interesting function in our development of ephemeral queues is the concatenation of two such queues. The implementation is as follows:

let transfer (q1: 'a t) (q2: 'a t) : unit =  
  while not (is_empty q1) do push (pop q1) q2 done
(*@ transfer q1 q2  
  raises Not_found -> false  
  ensures q1.view = [] && q2.view = old q2.view @ old q1.view *)

The transfer operation takes queues q1 and q2 as arguments, and migrates the elements of the former to the end of the latter. Moreover, it clears the contents of its first argument. By design, GOSPEL assumes q1 and q2 are two separated queues, i.e., not aliased. The raises clause states no Not_found exception is raised during execution of transfer. In fact, since the while loop is guarded by the not (is_empty q1) property, we know it is safe to call pop q1. Feeding this program to Cameleer generates a total of 8 VCs, from which we are only able to prove the exceptional postcondition and the first clause of the regular postcondition condition. With no surprise, this comes from the fact that we are missing a suitable loop invariant. In what follows, we refine the specification to completely prove the transfer function.

In order to prove termination, we use the length of the view model from q1 as a decreasing measure, as follows:

(*@ variant List.length q1.view *)

In order to prove the remaining VCs, it comes with no surprise that we need a suitable loop
invariant. First, we turn the type invariant property into a loop invariant, as follows:

\[
(*@ invariant (q1.front = [] \rightarrow q1.rear = []) \&\& \\
(q2.front = [] \rightarrow q2.rear = *) @*) \\
(*@ invariant q1.view = q1.front @ List.rev q1.rear \&\& \\
q2.view = q2.front @ List.rev q2.rear *)
\]

Although this makes the loop invariant more cumbersome, it is actually almost a mechanical process to include the type invariant in the loop invariant. With such a specification, we are able to discharge every VC of `transfer`, except for the second postcondition.

To complete this proof, we need to be a little more creative. The idea is the following: if we pick an arbitrary loop iteration, at that point of execution we would have already transferred a prefix of the elements from `q1` and would have concatenated those into `q2`. In order to represent such prefix of `q1`, we introduce an auxiliary ghost variable, as follows:

```ocaml
let transfer q1 q2 = 
  let [ghost] done_view = ref [] in ...
```

At each iteration, we must update the value of `done_view` as follows:

```ocaml
  while not (is_empty q1) do (*@ variant ... invariant ... *) 
    done_view := !done_view @ [head_list q1.view];
    push (pop q1) q2
  done
```

Once again, the `done_view` is a ghost variable, so any part of the program that manipulates it should be erased from the code. Thus, the above assignment should not incur a penalty on the execution time of `transfer`. Finally, we complete the loop invariant as follows:

\[
(*@ invariant old q1.view = !done_view @ q1.view *) \\
(*@ invariant q2.view = old q2.view @ !done_view *)
\]

The first condition maintains that `todo_view` is indeed a prefix of `q1.view`; the second condition states that the current state of `q2` consists of the elements from `todo_view` concatenated to the sequence of original elements of `q2`. With the updated invariant, we are finally able to discharge every generated VC for `transfer`.

### 4.2 Leftist Heap

**Functor definition.** The next case study is the implementation of a `heap` data structure. We adopt the `leftist heap` variant [11, 26], which we picked from the OCaml-containers library\(^\text{10}\). This is an applicative implementation, following the approach by C. Okasaki [29, Chap. 3.1].

The fundamental interest of using heaps is to be able to quickly access the minimum element of the collection. Thus, the elements of this data structure must be equipped with a total preorder, which is crucial to guarantee the correct behavior of the heap implementation. In OCaml, such kind of restrictions on types are naturally implemented using functors. For leftist heaps, we begin by introducing the following `module type` to represent a total preorder:

```ocaml
module type TOTAL_PRE_ORD = sig
  type t
  (**@ function le : t -> t -> bool **) \\
  (**@ axiom reflexive : forall x. le x x **) \\
end
```

\(^\text{10}\)https://github.com/c-cube/ocaml-containers
Using GOSPEL, we introduce a purely logical function `le` defined using the classic axioms of reflexivity, totality, and transitivity. Next, the specification of the regular function `leq` should be read as “this function implements the logical function `le`”. Using the above `TOTAL_PRE_ORD` type, the implementation of leftist heaps is encapsulated in the following functor `Make`:

```ocaml
module Make(E : TOTAL_PRE_ORD) = struct type elt = E.t ... end
```

The type equation `elt = E.t` ensures that elements of type `elt` (used to represent the elements of the heap) are inherit the total preorder relation from module `E`.

**Leftist property.** We use the following data type definition to represent leftist heaps:

```ocaml
type t = E | N of int * elt * t * t
```

A leftist heap is represented as a binary tree where each node is attached a *rank* value. Generally speaking, the rank of a node is defined as the length of the shortest path from that node to an empty node. In GOSPEL, this is as simple as follows:

```ocaml
(*@ function rank (h: t) : integer =
  match h with E -> 0 | N _ _ l r -> 1 + min (rank l) (rank r) *)
```

Using the general notion of rank, one can define the notion of leftist property: the rank of any left child is always greater or equal to the rank of the right sibling. This is captured by the following GOSPEL definition:

```ocaml
(*@ predicate leftist (h: t) = match h with
  | E -> true
  | N n _ l r ->
    n = rank h && leftist l && leftist r && rank l >= rank r *)
```

This property also gives the value of the element storing the rank in the structure. Other than the leftist property, leftist heaps should obey the general laws of heaps: the element in each node is less or equal to the elements at its children. The GOSPEL definition is as follows:

```ocaml
(*@ predicate is_heap (h: t) = match h with
  | E -> true
  | N _ x _ r -> le_root x l && is_heap l && le_root x r && is_heap r *)
```

where `le_root` is a predicate that states a given element is less or equal to the root of a heap:

```ocaml
(*@ predicate le_root (e: elt) (h: t) =
  match h with E -> true | N _ x _ _ -> E.le e x *)
```

Finally, we define what is a leftist heap:

```ocaml
(*@ predicate leftist_heap (h: t) = is_heap h && leftist h *)
```

**Logical definition of minimum element.** When describing the logical behavior of a heap data structure, one must pay particular attention to the definition of the minimum element. We need to define what is the physical minimum element of the heap, as follows:
The `minimum` function is only significantly defined for the case of non-empty heaps. We have now the necessary building blocks to formally specify leftist heaps operations.

**Heap operations.** We present here only two heap operations, `_make_node` and `merge`. The complete OCaml development can be found online. The first function builds a new node, given an element `x` and subtrees `a` and `b`:

```ocaml
let _make_node x a b =
  if _rank a >= _rank b then N (_rank b + 1, x, a, b)
  else N (_rank a + 1, x, b, a)
```

The leftist property is ensured by the `if..then..else` expression, where `_rank` is a function that simply retrieves the rank of a node, i.e., the first argument of the `N` constructor or 0 in case the heap is empty. Both `a` and `b` must be `leftist_heap`s and `x` must not greater than the roots of the two arguments. We give a specification of the heap in terms of the multiset of its elements. The resulting heap `h` is a `leftist_heap`, with minimum element `x`. The number of occurrences of `x` increases by one, whereas the occurrences of any element different from `x` remain the same. Finally, the nuclear operation `merge` is defined as follows:

```ocaml
let rec merge t1 t2 = match t1, t2 with
  | t, E | E, t -> t
  | N (_, x, a1, b1), N (_, y, a2, b2) ->
    if E.leq x y then _make_node x a1 (merge b1 t2)
    else _make_node y a2 (merge t1 b2)
```

If the root `x` of heap `t1` is no greater than the root of `t1`, we build a new heap with root `x`; otherwise, we the new root is the root of `t2`. The call to function `_make_node` ensures the `leftist_heap` property for the returned heap. We use the logical function `size` in the variant of `merge`, which is the straightforward definition of the number of nodes in a heap.

4.3 Other case studies

Table 1 in Appendix E summarizes the case studies performed with Cameleer. The second column features the number of non-blank lines of OCaml code, while the third one stands for

---

11In GOSPEL, logical functions are total. The value returned by `minimum E` exists, but one can prove no property about it.

12https://github.com/mariojppereira/cameleer/blob/master/examples/leftist_heap.ml
the number of non-blank lines of GOSPEL specification. We have put an effort to use Cameleer to
verify programs of different natures. These include numerical programs (binary multiplication,
different factorial implementations, fast exponentiation, and integer square root), sorting and
searching algorithms, data structures implemented as functors, historical algorithms (checking
a large routine by Turing, Boyer-Moore’s majority algorithm, and binary tree same fringe), and
logical algorithms (conversion of a propositional formula into conjunctive normal form).

5 Related Work

Automated deductive verification tools. One can cite Why3, F* [1], Dafny [27], and
Viper [28] as well-succeed automated deductive verification tools. Formal proofs are conducted
in the proof-aware language of these frameworks, and then executable reliable code can be
automatically extracted. In the Cameleer project, we chose to develop a verification tool that
accepts as input a program written directly in OCaml, instead of a dedicated proof language.
Our specification language, GOSPEL, is very close to the OCaml language itself, hence we believe
this does not impose a big burden for the regular OCaml practitioner.

Regarding verification tools that tackle the verification of programs written in mainstream
languages, we can cite Frama-C [24] and VeriFast [22]. The former is a framework for the
static analysis of C code; the latter can be used to verify functional correctness of C and Java
programs. Despite the remarkable case studies verified with these tools, C and Java code can
quickly degenerate into a nightmare of pointer manipulation and tricky semantic issues. We
argue OCaml is a language better suited for formal verification.

Deductive verification of OCaml programs. To the best of our knowledge, CFML [5] was
the only tool available for the deductive verification of code directly written in OCaml. It takes
as input an OCaml program and translates it into Coq, together with its characteristic formulae.
A characteristic formulae is a higher-order statement that captures the semantics of the original
program. Proofs are conducted using an embedding of Separation Logic inside Coq. The CFML
tool has already been used to verify several interesting OCaml modules, including ephemeral
data structures and higher-order functions. Recently, CFML was extended with support for time credits and it was successfully applied in the verification of functional correctness and time complexity claims of non-trivial data structures and algorithms [8, 21].

The VOCaL project aims at developing a mechanically verified OCaml library [7]. One
of the main novelties of this project is the combined use of three different verification tools:
Why3, CFML, and Coq. The GOSPEL specification language was developed in the scope of this
project, as a tool-agnostic language that could be manipulated by any of the three mentioned
frameworks. It was our participation on the VOCaL project that inspired us, in the first place,
to develop Cameleer. We believe Cameleer can be readily included in the VOCaL ecosystem,
complementing the toolchains [14] that are currently used to build the verified library.

6 Conclusions and Future Work

In this paper we presented Cameleer, a tool for deductive verification of OCaml-written code.
The core of Cameleer is a translation from OCaml annotated code into WhyML, the program-
ning and specification language of the Why3 verification framework. OCaml and WhyML have
many common traits (both in their syntax and semantics), which provides us with good guaran-
tees about soundness of Cameleer translation. We have already applied Cameleer to successfully
verify functional correctness and safety of 14 realistic OCaml modules. These include implementa-
tions issued from existing libraries, and scale up to data structures implemented as functors
and tricky effectful computations. These results encourage us to continue developing Cameleer and apply it to the verification of larger case studies.

**What we do not support.** Currently, we target a subset of the OCaml language which roughly corresponds to caml-light, with basic support for the module language (including functors). Also, WhyML limits effectful computations to the cases where alias is statically known, which limits our support for higher-order functions and mutable recursive data structures. Adding support for the objective layer of the OCaml language would require a major extension to the GOSPEL language and a redesign of our translation into WhyML. Nonetheless, Why3 has been used in the past to verify Java-written programs [17], so in principle an encoding of OCaml objects in WhyML is possible.

GADTs extend usual algebraic data types with a lightweight form of dependent typing in OCaml. The use of GADTs allows one to logically constraint the values that can inhabit a type in a certain point of the program. The WhyML type system does not, currently, include a notion close to GADTs. However, since this a proof-aware language an interesting route for future work would be to explore if it is possible to encode in WhyML the reasoning of GADTs without extending its type system. In particular, if it would be possible to leverage on the notion of type invariant to achieve similar results as those statically provided by GADTs.

Another interesting feature of OCaml we currently do not support are polymorphic variants. Polymorphic variants are more flexible than ordinary variants, as they are not tied to a particular type declaration and can be easily extended according to use scenarios. This flexibility, however, leads to a more complicated typing process for polymorphic variants, when compared to regular ones. Once again, extending Cameleer to deal with polymorphic variants requires extending Why3 itself. This would likely mean a considerable redesign of its type system.

Finally, Why3 constrains the use of higher-order functions to pure computations and this is also the case with Cameleer. A possible solution for such limitation would be to use defunctionalization to convert an higher-order program into an equivalent first-order one. In previous work, we have already explored the use of defunctionalization for verification of stateful higher-order programs in Why3 [31]. However, defunctionalization is a whole-program transformation which severely constrains its applicability. Next, we describe a more robust solution, which amounts at using a richer verification framework to reason about higher-order with effects.

**Interface with Viper and CFML.** We want to keep improving Cameleer with the ability to verify a growing class of OCaml implementations. This includes pointer-based data structures and effectful higher-order computations. Given the limitations of Why3 to deal with such class of programs, we believe the solution is to extend Cameleer to include translation into different intermediate verification languages. We are considering targeting the Viper infrastructure and the CFML tool. On one hand, Viper is an intermediate verification language based on Separation Logic but oriented towards SMT-based software verification, allowing one to automatically verify heap-dependent programs. On the other hand, the CFML tool already provides a translation from OCaml into Coq, allowing one to verify effectful higher-order functions. Even if it relies on an interactive proof assistant, CFML provides a comprehensive library of tactics that ease the proof effort. Our ultimate goal is to turn Cameleer into a verification tool that can simultaneously benefit from the best features of different verification frameworks. Our motto: we want Cameleer to be able to verify parts of an OCaml module using Why3, others with Viper, and finally some specific functions with CFML.

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A  Translation of expressions

\[
\begin{align*}
\text{(EABSURD)} & \quad \text{assert false expression absurd} \\
\text{(EFUN)} & \quad \text{\quad ghost(A) = } \beta \quad \text{A function spec } S \quad e \quad \text{expression } e' \quad \pi \quad \text{expression } \overline{f} \quad \text{(EAPP)} \\
\text{(EREc)} & \quad \neg\text{is_ghost(A)} \quad \text{kind(A) = } K \quad \text{A function spec } S_1 \quad e_0 \quad \text{function } x, e_1 \quad \text{e_0 function } x, e_1' \quad \text{expression } e_2 \quad \text{expression } e_2' \\
\text{(EREcGhost)} & \quad \text{let } A_0 \text{ rec } f_0 = e_0 A_1 \text{ and } f_1 = e_1 A_2 \text{ in } e_2 \quad \text{expression } \text{rec } K f(\overline{f}) S_1 = e_0' \text{ with } K f_1(\overline{f}) = e_1' S_2 \text{ in } e_2' \\
\text{(ELet)} & \quad \text{\quad is_ghost(A) \quad kind(A) = } K \quad \neg\text{is_functional}(e_0) \quad e_0 \quad \text{expression } e_0' \quad e_1 \quad \text{expression } e_1' \\
\text{(ELetGhost)} & \quad \text{let } A x = e_0 A' \text{ in } e_1 \quad \text{expression } \text{let } K x = e_0' \text{ in } e_1' \\
\text{(ELetGhostFun)} & \quad \text{\quad is_ghost(A) \quad kind(A) = } K \quad \neg\text{is_functional}(e_0) \quad A' \quad \text{function spec } S \quad e_0 \quad \text{function } x, e_0' \quad e_1 \quad \text{expression } e_1' \\
\text{(ELetFun)} & \quad \text{let } A f = e_0 A' \text{ in } e_1 \quad \text{expression } \text{let } K f = \text{fun}(\overline{f}) S \rightarrow \text{ghost } e_0' \text{ in } e_1' \\
\text{(EWhile)} & \quad A \quad \text{loop annotation } I \quad e_0 \quad \text{expression } e_0' \quad e_1 \quad \text{expression } e_1' \\
\text{while } e_0 \text{ do } A e_1 \text{ done expression while } e_0' \text{ do } I e_1' \text{ done} \\
\text{( EIF )} & \quad e_0 \quad \text{expression } e_0' \quad e_1 \quad \text{expression } e_1' \quad e_2 \quad \text{expression } e_2' \\
\text{if } e_0 \text{ then } e_1 \text{ else } e_2 \quad \text{expression if } e_0' \text{ then } e_1' \text{ else } e_2' \\
\text{(EMatch)} & \quad e_0 \quad \text{expression } e_0' \quad e_1 \quad \text{expression } e_1' \\
\text{match } e_0 \text{ with } [ p \Rightarrow e_1 ] \text{ expression match } e_0' \text{ with } [ p \Rightarrow e_1' ] \text{ end} \\
\text{( ERAise )} & \quad e \quad \text{expression } e' \quad \text{try } e \text{ with } E \text{ expression } e' \quad \text{(ETry)} \\
\text{raise } E \quad \text{expression raise } E' \quad \text{try } e \text{ with } E \text{ expression } e' \quad \text{try } e' \text{ with } E \text{ expression } e' \text{ end}
\end{align*}
\]

Figure 3: Translation of OCaml expressions into WhyML.
B  Translation of top-level declarations and type definitions

\[
\begin{align*}
\text{(DMODULE)} & \quad m \xrightarrow{\text{module}} M = m \xrightarrow{\text{declaration}} \text{scope } M \xrightarrow{\text{end}} \\
\text{(DLetGhost)} & \quad \text{is}_\text{ghost}(A) \quad \text{kind}(A') = K \quad \text{is}_\text{functional}(e) \\
& \quad A \xrightarrow{\text{function spec}} S \quad e \xrightarrow{\text{function}} \beta x, e' \\
& \quad \text{let } f = e \xrightarrow{\text{A' declaration}} \text{let } K = \text{fun}(\beta T) S \rightarrow \text{ghost } e' \\
\text{(DLet)} & \quad \neg \text{is}_\text{ghost}(A) \quad \text{kind}(A') = K \quad \text{is}_\text{functional}(e) \\
& \quad A \xrightarrow{\text{function spec}} S \quad e \xrightarrow{\text{function}} \beta x, e' \\
& \quad \text{let } f = e \xrightarrow{\text{A' declaration}} \text{let } K = \text{fun}(\beta T) S \rightarrow e' \\
\text{(DRec)} & \quad \neg \text{is}_\text{ghost}(A_0) \quad \text{kind}(A_0) = K \quad A_1 \xrightarrow{\text{function spec}} S_1 \quad e_0 \xrightarrow{\text{function}} \beta_1, e'_0 \\
& \quad \text{let } A_0 \xrightarrow{\text{rec}} f_0 = e_0 A_1 \quad \text{and } f_1 = e_1 A_2 \xrightarrow{\text{rec}} K f(\beta x) S_1 = e'_0 \text{ with } K f_1(\beta y : \pi) = e'_1 S_2 \\
\text{(DRecGhost)} & \quad \text{is}_\text{ghost}(A_0) \quad \text{kind}(A_0) = K \quad A_1 \xrightarrow{\text{function spec}} S_1 \quad e_0 \xrightarrow{\text{function}} \beta_1, e'_0 \\
& \quad \text{let } A_0 \xrightarrow{\text{rec}} f_0 = e_0 A_1 \quad \text{and } f_1 = e_1 A_2 \xrightarrow{\text{rec}} K f(\beta x) S_1 = \text{ghost } e'_0 \text{ with } K f_1(\beta y : \pi) = e'_1 S_2 \\
\text{(DType)} & \quad t_0 \xrightarrow{\text{type definition}} t_0' \quad t_1 \xrightarrow{\text{type definition}} t_1' \\
& \quad \text{type } t_0 \text{ and } t_1 \xrightarrow{\text{declaration}} \text{type } t_0' \text{ with } t_1' \\
\text{(DExn)} & \quad \text{exception } E : \pi \xrightarrow{\text{declaration}} \text{exception } E : \pi
\end{align*}
\]

Figure 4: Translation of OCaml top-level declarations into WhyML.

\[
\begin{align*}
\text{(TAbstract)} & \quad \pi T \xrightarrow{\text{type definition}} T \pi \\
& \quad \pi T = \tau \xrightarrow{\text{type definition}} T \pi = \tau \\
\text{(TAlias)} & \quad \tau \xrightarrow{\text{type name}} \tau \\
\text{(TRecord)} & \quad A \xrightarrow{\text{type invariant}} I \\
& \quad \alpha T = \{ f : \pi \} A \xrightarrow{\text{declaration}} T \alpha = \{ f : \pi \} \xrightarrow{\text{invariant}} I \\
\text{(TVariant)} & \quad \pi T = \| C_{\tau} \xrightarrow{\text{type definition}} T \pi = \| C_{\tau}
\end{align*}
\]

Figure 5: Translation of OCaml type definitions into WhyML.
C Translation of module expressions and module types

\[
\text{(MSTRUCT) } \frac{d \text{ declaration } \overrightarrow{d}}{\text{struct } \overrightarrow{d} \text{ end } \overrightarrow{d}}
\]

\[
\text{(MFUNCTOR) } \frac{\text{module type } \overrightarrow{d} \text{ module } \overrightarrow{d}}{\text{functor}(\mathcal{X} : \text{mt}) \to \text{module scope } \mathcal{X} \overrightarrow{d} \text{ end } \overrightarrow{d}}
\]

\[
\text{(MTSIG) } \frac{\text{signature } \overrightarrow{d}}{\text{sig } \overrightarrow{d} \text{ end } \overrightarrow{d}}
\]

Figure 6: Translation of OCaml module expressions and module types into WhyML.
D Translation of signatures

Figure 7: Translation of OCaml signatures into WhyML.
E  Summary of CAMELEER case studies

| Case Study             | Lines of Code | Lines of Specification |
|------------------------|---------------|------------------------|
| Applicative Queue      | 25            | 21                     |
| Binary Multiplication  | 10            | 6                      |
| Binary Search          | 15            | 10                     |
| Checking a Large Routine | 25          | 15                     |
| CNF Conversion         | 113           | 47                     |
| Ephemeral Queue        | 39            | 32                     |
| Factorial              | 10            | 13                     |
| Fast Exponentiation    | 19            | 47                     |
| Fibonacci              | 46            | 58                     |
| Insertion Sort         | 13            | 80                     |
| Integer Square Root    | 8             | 14                     |
| Leftist Heap           | 68            | 108                    |
| Mjrtt                  | 45            | 32                     |
| Same Fringe            | 23            | 16                     |

| total                  | 459           | 499                    |

Table 1: Case studies verified with the CAMELEER tool.