Mechanized Verification of Fine-grained Concurrent Programs

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Abstract

Efficient concurrent programs and data structures rarely employ coarse-grained synchronization mechanisms (i.e., locks); instead, they implement custom synchronization patterns via fine-grained primitives, such as compare-and-swap. Due to sophisticated interference scenarios between threads, reasoning about such programs is challenging and error-prone, and can benefit from mechanization.

In this paper, we present the first completely formalized framework for mechanized verification of full functional correctness of fine-grained concurrent programs. Our tool is based on the recently proposed program logic FCSSL. It is implemented as an embedded domain-specific language in the dependently-typed language of the Coq proof assistant, and is powerful enough to reason about programming features such as higher-order functions and local thread spawning. By incorporating a uniform concurrency model, based on state-transition systems and partial commutative monoids, FCSSL makes it possible to build proofs about concurrent libraries in a thread-local, compositional way, thus facilitating scalability and reuse: libraries are verified just once, and their specifications are used ubiquitously in client-side reasoning. We illustrate the proof layout in FCSSL by example, and report on our experience of using FCSSL to verify a number of concurrent programs.

Categories and Subject Descriptors
D.3.1 [Programming Languages]: Formal Definitions and Theory; F.3.1 [Logics and Meanings of Programs]: Specifying and Verifying and Reasoning about Programs

General Terms
Algorithms, Theory, Proofs, Verification

Keywords
Compositional program verification, concurrency, separation logic, mechanized proofs, dependent types.

1. Introduction

It has been long recognized that efficient concurrency is of crucial importance for high-performance software. Unfortunately, proving correctness of concurrent programs, in which several computations can be executed in parallel, is difficult due to the large number of possible interactions between concurrent processes/threads on shared data structures.

One way to deal with the complexity of verifying concurrent code is to employ the mechanisms of so-called coarse-grained synchronization, i.e., locks. By making use of locks in the code, the programmer ensures mutually-exclusive thread access to critical resources, therefore, reducing the proof of correctness of concurrent code to the proof of correctness of sequential code. While sound, this approach to concurrency prevents one from taking full advantage of parallel computations. An alternative is to implement shared data structures in a fine-grained (i.e., lock-free) manner, so the threads manipulating such structures would be reaching a consensus via the active use of non-blocking read-modify-write operations (e.g., compare-and-swap) instead of locks.

Despite the clear practical advantages of the fine-grained approach to the implementation of concurrent data structures, it requires significant expertise to devise such structures and establish correctness of their behavior.

In this paper, we focus on program logics as a generic approach to specify a program and formally prove its correctness wrt. the given specification. In such logics, program specifications (or specs) are represented by Hoare triples \{P\} c \{Q\}, where c is a program being described, P is a precondition that constrains a state in which the program is safe to run, and Q is a postcondition, describing a state upon the program’s termination. Modern logics are sufficiently expressive: they can reason about programs operating with first-class executable code, locally-spawned threads and other features omnipresent in modern programming. Verifying a program in a Hoare-style program logic can be done structurally, i.e., by means of systematically applying syntax-directed inference rules, until the spec is proven.

Importantly, logic-based verification of fine-grained concurrency requires reasoning about a number of concepts that don’t have direct analogues in reasoning about sequential or coarse-grained concurrent programs:

1. Custom resource protocols. Each shared data structure (i.e., a resource) that can be used by several threads concurrently, requires a specific “evolution protocol”, in order to enforce preservation of the structure’s consistency. In contrast to the coarse-grained case, where the protocol is fixed to be locking/unlocking, a fine-grained resource comes with its own notion of consistency and protocol.

2. Interference and stability. Absent locking, local reasoning about a shared resource from a single thread’s perspective should manifest the admissible changes that can be made by other threads that interfere with the current one. Every thread-local assertion about a fine-grained data structure’s state should be stable, i.e., invariant under possible concurrent modifications of the resource.

3. Helping. This concurrent pattern appears in fine-grained programs due to relaxing the mutual exclusion policy; thus several threads can simultaneously operate with a single shared resource. The “helping” happens when a thread is scheduled for a task involving the resource, but the task is then accomplished by another thread; however, the result of the work, once the task is completed, is ascribed to the initially assigned thread.

In addition, Hoare-style reasoning about coarse- or fine-grained concurrency requires a form of (4) auxiliary state to partially expose the internal threads’ behavior and relate local program asser-
tions to global invariants, accounting for specific threads’ contributions into a resource [26].

These aspects, critical for Hoare-style verification of fine-grained concurrent programs, have been recognized and formalized in one form or another in a series of recently published works by various authors [10, 13–15, 22, 27, 30, 33, 35, 51, 53, 55], providing logic schemes of increasing expressivity and compositional strength. In formal proofs of correctness of concurrent libraries, that are based upon these logical systems, the complexity is not due to the libraries’ sizes in terms of lines of code, but predominantly due to the intricacy of the corresponding data structure invariant, and the presence of thread interference and help. This fact, in contrast to proofs about sequential and coarse-grained concurrent programs, requires one to establish stability of every intermediate verification assertion. Needless to say, manual verification of fine-grained concurrent programs therefore becomes a challenging and error-prone task, as it is too easy for a human prover to forget about a piece of resource-specific invariant or to miss an intermediate assertion that is unstable under interference; thus the entire reasoning can be rendered unsound.

Since the process of structural program verification in a Hoare-style logic is largely mechanical, there have been a number of recent research projects that target mechanization and automation of the verification process by means of embedding it into a general-purpose proof assistant [6, 38, 49, 47], or implementing a standalone verification tool [8, 23, 28]. However, to the best of our knowledge, none of the existing tools has yet adopted the logical foundations necessary for compositional reasoning about all of the aspects (1)–(4) of fine-grained concurrency. This is the gap which we intend to fill in this work.

In this paper, we present a framework for mechanized verification of fine-grained concurrent programs based on the recently proposed Fine-grained Concurrent Separation Logic (FCSL) by Nanevski et al. [30, 39]. FCSL is a library and an embedded domain-specific language (DSL) in the dependently-typed language of Coq [9]. Due to its logical foundations, FCSL, as a verification tool and methodology for fine-grained concurrency, is:

- **Uniform:** FCSL’s specification model is based on two basic constructions: state-transition systems (STSs) and partial commutative monoids (PCMs). The former describe concurrent protocols and thread interference, whereas the latter provide a generic treatment of shared resources and thread contributions, making it possible to encode, in particular, the helping pattern. Later in this paper, we will demonstrate how these two components are sufficient to specify a large spectrum of concurrent algorithms, data structures, and synchronization mechanisms, as well as to make the proofs of verification obligations to be uniform.

- **Expressive:** FCSL’s specification fragment is based on the propositional fragment of Calculus of Inductive Constructions (CIC) [2]. Therefore, FCSL can accommodate and compose arbitrary mathematical theories, e.g., PCMs, heaps, arrays, graphs, etc.

- **Realistic:** FCSL’s programming fragment features a complete toolset of modern programming abstractions, including user-defined algebraic datatypes, first-class functions and pattern matching. That is, any Coq program is also a valid FCSL program. The monadic nature of FCSL’s embedding into Coq makes it possible to encode a number of computational effects, e.g., thread spawning and general recursion. This makes programming in FCSL similar to programming in functional languages, such as ML or Haskell.

- **Compositional:** Once a library is verified in FCSL against a suitable spec, its code is not required to be re-examined ever again: all reasoning about the client code of that library can be conducted out of the specification. The approach is thus scalable: even though the proofs for some libraries might be large, they are done just once.

- **Interactive:** FCSL benefits from the infrastructure, provided by Coq’s fragment for mechanized reasoning, enhanced by Ssrreflect extension [16]. While the verification process can’t be fully automated (as full functional correctness of concurrent programs often requires stating specs in terms of higher-order predicates), the human prover nevertheless can take advantage of all of Coq’s tools to discharge proof obligations.

- **Foundational:** The soundness of FCSL as a logic has been proven in Coq wrt. a version of denotational semantics for concurrent programs in the spirit of Brookes [4]. Moreover, since FCSL program specs are encoded as Coq types, the soundness result scales to the entire programming language of Coq, not just a toy core calculus. This ensures the absence of bugs in the whole verification tool and, as a consequence, correctness of any program, which is verified in it.

Our implementation of FCSL, primarily accepted by PLDI’21 AEC, is available online with examples and the user manual [45]. In the remainder of the paper, we will introduce the FCSL framework by example, specifying and verifying full functional correctness of a characteristic fine-grained program—a concurrent spanning tree algorithm. Starting from the intuition behind the algorithm, we will demonstrate the common stages of program verification in FCSL. We next explain some design choices in the implementation of FCSL, and report on our experience of verifying a number of benchmark concurrent programs and data structures: locks, memory allocator, concurrent stack and its clients, an atomic snapshot structure and non-blocking universal constructions. We conclude with a comparison to related logical frameworks and tools, and a discussion on future work.

2. **Overview**

We introduce verification in FCSL by informally explaining a fine-grained concurrent program for computing in place a spanning tree of a binary directed graph [21, 43].

2.1 A graph spanning tree algorithm and its intuition

The recursive procedure span (Figure 1) takes an argument x, which is a pointer to a node in the graph, and constructs the spanning tree rooted in x by traversing the graph and removing redundant edges. The graph is implemented as a memory region where each pointer’s target value is a triple. The triple’s first component is a bit m indicating whether the node is marked; the second and third components are pointers to the node’s left and right successors, or null if a successor doesn’t exist.

If x is null, span returns false (line 2). Otherwise, it tries to mark the node by invoking the compare-and-swap (CAS) operation (line 4). If CAS fails, then x was previously marked, i.e., included in the spanning tree by another call to span, so no need to continue (line 10). If CAS succeeds, two new parallel threads are spawned,

```plaintext
1  span (x : ptr) : bool {
2    if x == null then return false;
3    else
4      b ← CAS(x:=m, 0, 1);
5      if !b then
6        (r_l, r_r) ← (span(x->l) || span(x->r));
7        if ¬r_l then x->l := null;
8        if ¬r_r then x->r := null;
9        return true;
10      else return false;
}
```

Figure 1: Concurrent spanning tree construction procedure.

[1] Hereafter, we will be using the acronym FCSL to refer both to the Nanevski et al.’s logical framework and to our implementation of it.
To flesh out the above informal argument and mechanize it in FCSL, we require a number of logical concepts. We describe these concepts in this section. We then present the algorithm that we consider a proof of correctness for this informal argument in Section 3.1. We extend our discussion of concurrency with a discussion of temporal logic in Section 3.2.

2.2 Infrastructure for mechanizing the proof in FCSL

2.2.1 Concurroids

FCSL requires an explicit description of the common assumptions that threads operating on the shared resource observe. Such agreement between threads is needed so that one thread’s changes match other threads’ expectations. In the case of \texttt{span}, for example, one assumption we elided above is that an edge out of a node can be removed only by a thread that marked it. This thread can rely on the property that edges to \(x.l\) and \(x.r\) won’t be nullified by another thread. These assumptions are formalized by STTs of a special form, which are called concurroids.

The state of each concurroid is divided into three components \([\text{self}] \mid \text{joint} \mid \text{other}\). The \texttt{joint} component describes shared state that all threads can change. The \texttt{self} and \texttt{other} components are owned by the observing thread, and its environment, respectively, and may be changed only by its owner. If there are two threads \(t_1\) and \(t_2\) operating over a state, the proof of \(t_1\) will refer to \texttt{self} to the private state of \(t_1\), and by \texttt{other} to the private state of \(t_2\), and the roles are reversed for \(t_2\). This thread-specific, aka. subjective, split into \texttt{self}, \texttt{joint}, and \texttt{other} is essential for making the proofs insensitive to the number of threads forked by the global program, and the order in which this is done [33]. We also note that the \texttt{self} and \texttt{other} components have to be elements of a PCM, i.e., a set \(U\) with an associative and commutative \texttt{join} operation \(\bullet\), and a unit element \(1\) . PCMs enable general and compositional representation of thread-owned state (auxiliary or real), which can be split between parallel threads [32]. Intuitively, commutativity and associativity account for those of a parallel composition of threads, and partiality captures the fact that not all splits/combinations of state are valid.

All three state components of a concurroid may contain real state, i.e. heap, or auxiliary state \([34\, 41]\), which is kept for logical specification, but is erased before execution. In the case of the \texttt{span} procedure, the \texttt{joint} component is the heap encoding the graph to be spanned, as described above. The \texttt{self} and \texttt{other} components are auxiliary state, consisting of sets of nodes (i.e., pointers) marked by the observing thread and its environment, respectively. These components are elements of a PCM of sets with disjoint union \(\cup\) as \(\bullet\), and the empty set as the unit. Thus, \texttt{self} \(\bullet\) \texttt{other} is the set of marked nodes of the graph in \texttt{joint}.

Transitions of a concurroid are binary relations between states. They describe the state modifications that the threads are allowed to do. The concurroid for \texttt{span}, named \texttt{SpanTree} in the sequel, has two non-trivial transitions, which we call \texttt{markNodeTrans} and \texttt{nullifyTrans}. Additionally, every concurroid has the trivial identity transition \(\texttt{idle}\). A thread performs \texttt{markNodeTrans} when it successfully marks a node. Whenever the bit \(m\) of a node \(x\) is set, the pointer \(x\) is also added to the auxiliary \texttt{self} state of the thread that performed the operation. Thus, the \texttt{self} component correctly tracks the nodes marked by a thread. A thread performs \texttt{nullifyTrans} when it removes an edge out of a marked node. However, this transition can only be taken in states in which \(x\) is in the \texttt{self} component; thus, only a thread that previously marked \(x\) can take this transition.
2.2.2 Atomic actions

Concurroids logically specify the behavior of threads, and one needs a way to tie the logical specs to actual program operations, such as, e.g., CAS. An atomic action is a program operation that can change the heap by one read-modify-write operation, and simultaneously change the auxiliary state. In Section 3 we expand on how actions are defined. For now, we just briefly describe the three actions required for implementation of span in FCSL.

The trymark action attempts to mark a node $x$, and move $x$ into the self auxiliary component simultaneously. Operationally, i.e., when the auxiliary state is erased, it corresponds to the CAS on line 4 of Figure 1. Logically, if successful, it corresponds to a marknode_trans transition in the concurroid. If unsuccessful, it corresponds to the concurroid’s idle transition. The nullify action invoked with an argument $x$, and a two-valued indicator side (Left or Right), sets the $x л (or $x й$, depending on side) pointer to null, but emits a precondition that $x$ is in self. Operationally, it corresponds to the assignment of null on lines 7 and 8 of Figure 1. Logically, it corresponds to taking the nullify_trans transition. Finally, read_child atomic action, invoked with arguments $x$ and side, returns the pointer $x л (or $x й$, depending on side). It also emits a precondition that $x$ is in self. Operationally, it corresponds to the pointer reads on line 6 in Figure 1. Logically, it corresponds to the concurroid’s idle transition.

Figure 3 shows how the actions are used to translate the span procedure from Figure 1 into FCSL.

2.2.3 Hoare specifications as types and stability

In Figure 3 span is ascribed the type span_tp. While Section 4 defines it formally, here we provide some basic intuition for it.

Among other components, the type span_tp contains the formal pre- and postconditions, ascribed to span. Hence, it is a user-defined type, rather than inferred by the system. Also, span_tp is declared as the type of the fixpoint combinator fixfix’s argument loop, and thus serves as the “loop invariant” as well. The components of span_tp provide the following information: (a) The precondition in span_tp ensures that the input node $x$ is either null or points to a node in the heap. (b) If span returns false, the postcondition ensures that $x$ is either null or is marked in the graph, and the thread hasn’t marked any other nodes during the call. (c) If span returns true, the postcondition states that $x \neq null$, and the thread being specified has marked a set of nodes $t$, which form a maximal tree in the final graph with root $x$; moreover, $t$’s front wrt. initial graph is marked, possibly by other threads.

We further note that the assertions (a)-(c) will be stable wrt. interference, i.e., they remain valid no matter which transitions of the span concurroid the interfering threads take. Proving stability is an important component of FCSL. Typically, every spec used in FCSL will be stable, or else it won’t be possible to ascribe it to a program. In the next section, we will exhibit several stable example specifications wrt. the concurroid for span, including span_tp.

3. Outline of the Mechanized Development

We next discuss how the above informal overview is mechanized in Coq. We start with the definition of span tp and proceed to explain all of its components. The specifications and code shown will be very similar to what’s in our Coq files, though, to improve presentation, we occasionally take liberties with the order of definitions and notational abbreviations. We do not assume any familiarity with Coq, and explain the code displays as they appear. We also omit the proofs and occasional auxiliary definitions, which can be found in the FCSL code, accompanying the paper [45].

3.1 The definition of the type span tp

The type span tp is described in Figure 4. It is an example of a dependent type, as it takes formal arguments in the form of variables $x$, $i$ and $g1$, that the body of the type can use, i.e., depend on. The roles of the variables differ depending on the keyword that binds them. For example, the Coq keyword forall binds the variable $x$ of type ptr, and indicates that span tp is a specification for a procedure that has $x$ as input. Indeed, span is exactly such a procedure, as apparent from Section 2. Using forall to bind $x$ allows $x$ to be used in the body of span tp, but also in the body of span tp (Figure 3). On the other hand, $i$ and $g1$ are bound by FCSL binder {...}. This binding is different; it allows $i$ and...
3.2 Representing graphs in a heap

Next we define the predicate graph h, which appears in span tp (Figure 4), and says when a heap h represents a graph. It does so if every pointer x in h stores some triple (b, xl, xr), where b is the “marked” bit, and xl xr are pointers in the domain of h (and, hence, are x itself or other nodes), or null if x has no successors.

Definition graph (h : heap) := valid h /
  forall x, x ∈ dom h → exists (b : bool) (xl xr : ptr),
  h = x → ((b, xl, xr) \ free x h /
  (subset [:xl;xr] ⊆ [:null] ++ dom h).

The conjunction valid h says that the heap h doesn't contain duplicate pointers. The notation \free{} is overloaded and used for disjoint union of sets of nodes in span tp, and for disjoint union of heaps in graph. In general, we use \free{} for any PCM operation. free x h is the heap obtained by deallocating x from h. Finally, the last line is concrete syntax for \{x, xv\} ⊆ \{null\} \cup dom h.

The graph predicate illustrates certified programming in Coq [7], i.e., the ability to use propositions as types, and pass variables such as g1 and g2 that stand for proofs of the graph property, as inputs to other types (e.g., span tp) or functions. This ability enables formally defining partial functions over heaps that are undefined when the heap doesn't encode a valid graph. An alternative to this somewhat unique capability of dependent types is to encode partial functions as relations, but that usually results in increase in proof tedium and size.

Here are a few examples of such partial functions. Given a node (i.e., a pointer) x and a proof that the heap h represents a graph (written (g : graph h), we name mark g x, edgl g x and edgr g x the three components stored in the pointer x in the heap (i.e., the “marked” bit, left, right successor), and write cont g x for the whole triple. By default, these values are false, null, null if x is not in the heap. Each of these functions takes h as an argument; i.e., one could also write mark h g x etc., but we omit h as it can be inferred from g's type, following Coq's standard notational abbreviation.

We can now define the remaining predicates used in span tp in Figure 4. For all of the definitions, we assume that variables h and (g : graph h) are in scope, and omit them. We also use ptr_set as an alias for finite maps from pointers to the unit type.

Finally, we define the function edge, which represents the incidence relation for the graph g.

Definition edge (x y : ptr) := (x \in dom h) & &
  (y = null) & & (y \in [:edgl g x; edgr g x]).

Second, tree x t requires that t contains x, and for any node y ∈ t, there exists a unique path (i.e., a list of nodes) p from x to y via edge's links, which lies within the tree (i.e., the nodes p are a subset of t). Note how edge is curried, i.e., passed to path as a function, abstracted over arguments. This illustrates that even simple mathematical mechanizations require higher-order functions in order to work.

Definition tree (x : ptr) (t : ptr_set) := x \in dom t /
  forall y, y \in dom t → exists p, path edge x p / y = last x p /
  (subset p <= dom t).

Third, front t t', determines if the nodes reachable from t in zero or one step are included in t'.

Definition front (t t' : ptr_set) :=
  {subset dom t <= dom t'} /
  forall x y, x \in dom t → edge x y /
  y \in dom t'.

Fourth, a tree t is maximal if it includes its front. A graph is connected if there's a path from x to every other node y in it.

Definition maximal (t : ptr_set) := front t t.
Definition connected (x : ptr) (t : ptr_set) :=
  forall y, y \in dom t → exists p, path edge x p / last x p = y.

Finally, subgraph codifies a number of properties between pre-state s1 and post-state s2, and their graphs g1, g2. In particular: g1, g2 contain the same nodes (‘=’ is equality on lists modulo permutation), the set of self-marked and other-marked nodes only increase, edges out of a node y can be changed only if the node is marked, and the only change to the edges is nullification (that is, removal).

Definition subgraph s1 s2
  (g1 : graph (joint s1)) (g2 : graph (joint s2)) :=
  dom (joint s1) =i dom (joint s2) /
  {subset dom (self s1) <= dom (self s2)} /
  {subset dom (other s1) <= dom (other s2)} /
  (forall y, \mark g2 y \to cont g1 y = cont g2 y) /
  (forall x, (edgl g2 x \in [:null; edgl g1 x]) /
  (edgr g2 x \in [:null; edgr g1 x])).

2 This is a bit expedient way of implementing finite sets, but it saves work by reusing an extensive library of finite maps, also used for formalizing heaps.
We close the description of the predicates used in span tp, by listing two important lemmas that relate them. The first lemma, max_tree2, says that if \( y_1 \) and \( y_2 \) are successors of \( x \) (i.e., edge \( x \) equals the set \([:: y_1; y_2]\)) modulo permutation), and \( ty_1 \) and \( ty_2 \) are maximal trees rooted in \( y_1 \) and \( y_2 \), and moreover, \( ty_1 \) and \( ty_2 \) are disjoint, then the set of nodes built from \( x \), \( ty_1 \) and \( ty_2 \) by disjoint union (\( \land \ast \)) is a tree itself, i.e., no edges connect \( ty_1 \) and \( ty_2 \) (the notation \#x is concrete syntax for the singleton finite map containing node \( x \)). This lemma is essential in proving that span produces a tree, as mentioned in Section 2 for the case \( s_1 = s_2 = \text{true} \).

**Lemma** max_tree2 \( x \) \( y_1 \) \( y_2 \) \( ty_1 \) \( ty_2 \):

\[
\begin{align*}
  \text{edge} \ x = i \ [:: y_1; y_2] &\to \text{tree} \ y_1 \ y_1 \to \text{maximal} \ ty_1 \to \\
  \text{tree} \ y_2 \ y_2 \to \text{maximal} \ ty_2 \to \text{valid} \ (ty_1 \ \land \ ty_2) &\to \\
  \text{tree} \ x \ (\#x \ \land \ ty_1 \ \land \ ty_2).
\end{align*}
\]

The second lemma shows that subgraph is monotone wrt. the stepping of environment threads in the SpanTree concurroid.

**Lemma** subgraph_steps \( s_1 \) \( s_2 \):

\[
\begin{align*}
  (g_1 : \text{graph} \ (\text{joint} \ s_1)) \ (g_2 : \text{graph} \ (\text{joint} \ s_2)) : \\
  \text{env_steps} \ (\text{SpanTree} \ sp) \ s_1 \ s_2 \to \text{subgraph} \ g_1 \ g_2.
\end{align*}
\]

We used this lemma as the main tool in establishing a number of stability properties in Coq, related to the conjunctions from the definition of subgraph \( g_1 \ g_2 \). For example, the lemma implies that if \( x \) is a node of \( \text{joint} \ s_1 \), then it is so in a stable manner; that is, \( x \) is a node in \( \text{joint} \ s_2 \) for any \( s_2 \), obtained from \( s_1 \) by changes via environment interference.

### 3.3 SpanTree concurroid

Next we define the SpanTree concurroid. Being an STS, the definition includes the specification of the state space, and transitions between states. In the case of concurroids, we have an additional component: *labels* (semantically, natural numbers) that differentiate instances of the concurroid. Thus the definition of SpanTree is parametrized by the variable \( sp \), which makes it possible to use several instances of SpanTree with different labels in a specification of a single program. For example, say we want to run two span procedures in parallel on disjoint heaps. Such a program could be specified by a Cartesian product of SpanTree \( sp_1 \) and SpanTree \( sp_2 \), where the different labels \( sp_1 \) and \( sp_2 \) instantiate the variable \( sp \).

The state space of SpanTree is defined by the following state predicate \( \text{coh} \), which we call *coherence predicate*.

**Variable** \( sp : \text{nat} \).

**Definition** \( \text{coh} \ s \) :

\[
\begin{align*}
  \text{exists} \ g : \text{graph} \ (\text{joint} \ s), \\
  s = sp \to \text{valid} \ (\text{self} \ s \ \land \ \text{other} \ s) \land \\
  \text{forall} \ x, x \ \land \ \text{dom} \ (\text{self} \ s \ \land \ \text{other} \ s) = \text{mark} \ g \ x.
\end{align*}
\]

The coherence predicate codifies that the state \( s \) is a triple, \( \text{self} \ s \ \land \ \text{other} \ s \), and that it is labelled by \( sp \). The proof \( g \) is a witness that the joint component is a graph-shaped heap. The conjunct valid \( (\text{self} \ s \ \land \ \text{other} \ s) \) says that the self and other components of the auxiliary state are disjoint; their union is a finite map which is valid, i.e., doesn't contain duplicate keys. Finally, the most important invariant is that a node \( x \) is contained in either self or other subjective view (if it's marked in the joint graph).

The metatheory of FCSL \[46, \S 4\] requires the coherence predicate to satisfy several properties that we omit here, but prove in our implementation. The most important property is the *fork-join closure*, stating that the state space is closed under realignment of self and other components. In other words, one may subtract a value from self and add it to other (and vice versa), without changing the coherence of the underlying state.

SpanTree \( sp \) contains two non-idle transitions. The first transition \( \text{marknode_trans} \), parametrized by the node \( x \), describes how an unmarked \( x \) is physically marked in the joint graph, and simultaneously added to the self component. The second transition \( \text{nullify_trans} \) is parametrized by node \( x \) and the direction \( c \), indicating the successor of \( x \) (left or right) that must be cut off from the graph. We omit the definitions of the functions \text{mark_node} and \text{null_edge} that describe the physical changes performed by the two transitions to the underlying shared graph. These can be found in the accompanying Coq code \[45\].

**Definition** \( \text{marknode_trans} \ x \ s \ s' := 

\[
\begin{align*}
  \text{exists} \ g : \text{graph} \ (\text{joint} \ s), \\
  \text{joint} \ s = \text{mark_node} g x \land \text{self} \ s = \#x \land \text{self} \ s' = \text{other} \ s \land \text{coh} \ s \land \text{coh} \ s'.
\end{align*}
\]

**Definition** \( \text{nullify_trans} \ x \ (c : \text{side}) \ s \ s' := 

\[
\begin{align*}
  \text{exists} \ g : \text{graph} \ (\text{joint} \ s), \\
  \text{joint} \ s = \text{null_edge} g c x \land \text{self} \ s = \text{self} \ s' \land \text{other} \ s = \text{other} \ s \land \text{coh} \ s \land \text{coh} \ s'.
\end{align*}
\]

The FCSL metatheory requires that transitions also satisfy several properties. For example, \( \text{marknode_trans} \) and \( \text{nullify_trans} \) preserve the other-component and the coherence predicate, as immediately apparent from their definitions. They also preserve the footprint of the underlying state, i.e., they don't add or remove any pointers. Adding and removing heap parts can be accomplished by communication between concurroids, which we will briefly discuss in Section 3 of this paper.

The coherence predicate, the transitions, and the proofs of their properties are packaged into a dependent record \[\text{SpanTree} \ sp\], which encapsulates all that's important about a concurroid. Thus, we use the power of dependent types in an essential way to build mathematical abstractions, such as concurroids, that are critical for reusing proofs.

### 3.4 Defining atomic actions

Next we illustrate the mechanism for defining atomic actions in FCSL. The role of atomic actions is to perform a single physical memory operation on the real heap, simultaneously with an arbitrary modification of the auxiliary part of the state. In FCSL, we treat the real and auxiliary state uniformly as they both satisfy the same PCM laws. We specify their effects in one common step, but afterwards prove a number of properties that separate them. For instance, for each atomic action we always prove the *erasure property* that says that the effect of the action on the auxiliary state doesn’t affect the real state.

Specifically, the effect of the trymark action is defined by the following relation between the input pointer \( x \), the pre-state \( s_1 \), post-state \( s_2 \) and the return result \( r \) of type bool.

**Definition** \( \text{trymark_step} \ (x : \text{ptr}) \ s_1 \ s_2 \ (r : \text{bool}) := 

\[
\begin{align*}
  \text{exists} \ g : \text{graph} \ (\text{joint} \ s_1), \\
  x \ \land \ \text{dom} \ (\text{joint} \ s_1) \land \text{other} \ s_2 = \text{other} \ s_1 \land \\
  \text{mark} g x \land (\text{joint} \ s_2 = \text{joint} \ s_1 \land \text{self} \ s_2 = \text{self} \ s_1 \lor \\
  r = \text{false} \land (\text{joint} \ s_2 = \text{joint} \ s_1 \land \text{self} \ s_2 = \text{self} \ s_1) \land \\
  \text{true} \lor (\text{joint} \ s_2 = \text{mark_node} g x \land \text{self} \ s_2 = \#x \land \text{self} \ s_1).
\end{align*}
\]

The relation requires that \( x \) is a node in the pre-state graph \((x \ \land \ \text{dom} \ (\text{joint} \ s_1))\). If \( x \) is unmarked in this graph, then the action returns \( \text{true} \), together with marking the node physically in the real state (employing the function \text{mark_node} already used in \text{marknode_trans}). Otherwise, the state remains unchanged, and the action’s result is \( \text{false} \). Notice that when restricted to the real heap, i.e., if we ignore the auxiliary state in \text{self} \ \text{and} \text{other} \ s_1, the relation essentially describes the effect of the CAS command on the mark bit of \( x \). Thus, trymark erases to CAS.

\footnote{\text{A type-theoretic variant of a C struct}, where fields can contain proofs.}
There are several other components that go into the definition of an atomic action. In particular, one has to prove that transitions are total, local, and frameable in the sense of Separation Logic, and then ascribe to each action a stable specification. However, the most important aspect of action definitions is to identify their behavior with some transition in the underlying concurroid. For example, trymark behaves like marknode_trans of SpanTree if it succeeds, and like idle if it fails. Actions may also change state of a number of concurroids simultaneously, as we will discuss in Section 4. We omit the formal definition of all these properties, but they can be found in the accompanying code [35].

3.5 Scoped concurroid allocation and hiding

The $\text{span}_\text{tp}$ type from Figure 4 operates under open-world assumption that $\text{span}$ runs in an environment of interfering threads, which, however, respect the transitions of the SpanTree concurroid. If one wants to protect $\text{span}$ from interference, and move to closed-world assumption, the top-most call must be enclosed within hide. We next show how to formally do so.

The hide construct allocates a new lexically-scoped concurroid from a local state of a particular thread. The thread-local state is modelled in FCSL by a basic concurroid $\Prv pv$ with a label $p$ [36 §4], and its self/other components are retrieved via $\text{pv}_\text{self}$ and $\text{pv}_\text{other}$ projections. The description of how much local heap should be "donated" to the concurroid creation is provided by a user-supplied predicate $\Phi$, called $\text{allocation predicate}$. In addition to the heap, the predicate scopes over the auxiliary self value, while the auxiliary other is fixed to the PCM unit, to signal that there's no interference from outside threads. In the case of $\text{span}$, the decoration predicate is the following.

Definition $\text{graph}_\text{dec} \; \text{sp} \; (g : \text{heap} \times \text{ptr}_\text{set}) = \begin{cases} \text{exists} \; (pf : \text{graph} \; g.1) , \; s = \text{sp} \rightarrow \begin{cases} [g.2, g.1, \text{Unit}] \end{cases}, \; \text{dec} \; s \rightarrow s' \end{cases}$.

We can now write out a new type $\text{span}_\text{root}_\text{tp}$, to specify the topmost call to $\text{span}$, under the closed-world assumption that there's no interference. Parametrizing wrt. the locally-scoped variable $h_1 : \text{heap}$ that snapshots the initial heap, the type is as follows.

Definition $\text{span}_\text{root}_\text{tp} (x : \text{ptr}) := \begin{cases} \text{U} \; g_1 : \text{graph} \; h_1 , \; \text{StStep} \; [\Prv pv] \; \begin{cases} \text{dec} \; \text{precondition predicate} \; \rightarrow \begin{cases} \text{fun} \; s1 \rightarrow \text{forall} \; y , \; \text{mark} \; g_1 \; y \end{cases} , \; \text{fun} \; s2 \rightarrow \text{exists} \; (r : b) , \; \text{pv}_\text{self} \; s2 \Rightarrow r \rightarrow v \text{\&\&} h \end{cases} \; \begin{cases} \text{Do} \; (\text{res} \leftarrow \text{try_alloc} ; \; \text{if} \; \text{res} \; \text{Some} \; r \; \text{then} \; \text{ret} \; \text{r else} \; \text{loop} \; tt) \; \text{tt} \end{cases} \end{cases}.

The precondition says that the argument $x$ is the root of the graph $g_1$ stored in $h_1$, and all the nodes of $g_1$ are reachable from $x$. The postcondition says that the final heap's topology is a tree $t$, whose edges are a subset of the edges of $g_1$, but whose nodes include all the nodes of $g_1$. Thus, the tree is a spanning one. The program satisfying this spec is a call to $\text{span}$, wrapped into hide, annotated with the decorating functions. We also supply $h_1$ as the initial heap, and $\text{Unit}$ of the PCM of finite sets (hence, the empty set), as the initial value for self, which indicates that $\text{span}$ is invoked with the empty set of marked nodes.

Program Definition $\text{span}_\text{root}_\text{x} : \text{span}_\text{root}_\text{tp} \; x := \begin{cases} \text{Do} \; (\text{priv}_\text{hide} \; \text{pv} \; (\text{graph}_\text{dec} \; \text{sp}) \; (h_1, \text{Unit}) \; \text{[span sp x]}). \end{cases}.$

4. More Examples

We next briefly illustrate two additional features of FCSL that our implementation uses extensively: concurroid composition and reasoning about higher-order concurrent structures with helping.

4.1 Composing concurrent resources

The $\text{span}$ algorithm uses only one concurroid $\text{SpanTree}$, allocated by hide out of the concurroid $\text{Priv}$ for thread-local state. In general, FCSL specs can span multiple primitive concurroids, of the same or different kinds, which are entangled by interconnecting special channel-like transitions [36]. The interconnection implements synchronized communication, by which concurroids exchange heap ownership. Entangling several concurroids yields a new concurroid. Omitting the formal details of the entanglement operators, let us demonstrate a program whose spec uses a composite concurroid.

Definition alloc : $\begin{cases} \text{fun} \; s1 \rightarrow \text{pv}_\text{self} \; s1 \Rightarrow h , \; \text{fun} \; r \; s2 \rightarrow \text{exists} \; (r : b) , \; \text{pv}_\text{self} \; s2 \Rightarrow r \rightarrow v \text{\&\&} h \end{cases} \; \begin{cases} \text{Do} \; (\text{res} \leftarrow \text{try_alloc} ; \; \text{if} \; \text{res} \; \text{Some} \; r \; \text{then} \; \text{ret} \; \text{r else} \; \text{loop} \; tt) \; \text{tt} \end{cases}$.

The alloc procedure implements a pointer allocator. Its postcondition says that the initial heap $h$ is augmented by a new pointer $r$ storing some value $v$, that is part of the $\text{Priv}$ concurroid, as evident by the projection $\text{pv}_\text{self}$ in the precondition. The pointer $r$ is logically transferred from the concurroid $\text{ALock}$ which implements a coarse-grained (i.e., lock-protected) concurrent allocator. Hence, the whole procedure alloc uses the composed concurroid $\text{entangle} \; \text{Priv} \; \text{pLock}$. The body of alloc implements a simple spin-loop, trying to acquire the pointer by invoking the $\text{try_alloc}$ procedure, omitted here.

Whereas separation logic [44] always assumes allocation as a primitive operation, the above example illustrates that in FCSL, allocation is definable. One can also define a new variant of the $\text{Start}$ type that automatically entangles the underlying concurroid with $\text{ALock}$, thus enabling allocation without the user having to explicitly do so herself.

4.2 Higher-order specifications

Due to embedding in Coq, FCSL is also capable of specifying and verifying higher-order concurrent data structures, which we illustrate by an example of a universal non-blocking construction of flat combining by Hendler et al. [19].

A flat combiner (FC) is a higher-order structure, whose method $\text{flat_combine}$ takes a sequential state-modifying function $f$ and its argument $v$, and works as follows. While for the client, invoking $\text{flat_combine}(f, v)$ looks like a sequence $\text{lock} ; f(v) ; \text{unlock}$, in reality, the structure implements a sophisticated concurrent behavior. Instead of expensive locking and unlocking, the calling thread doesn’t run $f$, but only registers $f$ to be executed on $v$. One of the threads then becomes a combiner and executes the registered methods on behalf of everyone else. Since only the combiner needs exclusive access to the data structure, this reduces contention and improves cache locality. This design pattern is known as helping or work stealing: a thread can complete its task even without accessing the shared resource.

To specify FC, we parametrize it by a sequential data structure and a validity predicate $\text{fc}_\text{R}$, which relates a function $f$ (from a fixed set of allowed operations), the argument of type $\text{fc}_\text{inT} \; f$, result of type $\text{fc}_\text{outT} \; f$ and the contribution of type $\text{fc}_\text{pcm}$. The

\footnote{For simplicity, we present here a specification that is much weaker than what we have actually verified in our implementation.}
last entry is a description of what \( f \) does to the shared state, expressed in abstract algebraic terms as an element from a user-supplied PCM \( fc_{pcm} \).

\[
\begin{align*}
\text{Variable} & \quad fc_R : \forall f, \\
& \quad fc_{lnT} f \rightarrow fc_{outT} f \rightarrow fc_{pcm} \rightarrow \text{Prop}.
\end{align*}
\]

The spec of the \( flat\_combine \) is then given in the context of three entangled concurroids: \( Priv \) for thread-local state, a lock-based allocator \( Alloc \), adapted from the previous example (since a sequential function \( f \) might allocate new memory), and a separate concurroid \( FlatCombine \).

**Definition** \( PA := (\text{entangle} (Priv pv) Alloc) \).

**Program Definition** \( flat\_combine f (v : fc_{inT} f) : \\
\text{STstep} [\text{entangle PA (FlatCombine fc)}] \\
(f \mapsto pv_{self} s1 = Unit \wedge fc_{self} s1 = Unit, \\
\text{fun } (w : fc_{outT} f) s2 \mapsto \text{exists } g, pv_{self} s2 = Unit \wedge \\
f(\text{fc}_R f v v g) := \ldots)
\]

The precondition says that \( flat\_combine \) executes in the empty initial heap \( (pv_{self} s1 = \text{Unit}) \), and hence by framing, in any initial heap. Similarly, the initially assumed effects of the calling thread on the shared data structure are empty \( (fc_{self} s1 = \text{Unit}) \), but can be made arbitrary by applying FCSL’s \textit{frame rule} to the spec of \( flat\_combine \). The postcondition says that there exists an abstract PCM value \( g \) describing the effect of \( f \) in terms of PCM elements \( (fc_R f v v g) \). Moreover, the effect of \( g \) is attributed to the invoking thread \( (fc_{self} s2 = g) \), even though in reality \( f \) could be executed by the combiner, \textit{on behalf} of the calling thread. In our Coq implementation, we instantiated the FC structure with a sequential stack, showing that the result has the same spec as a concurrent stack implementation.

## 5. Elements of FCSL Infrastructure

In this section we sketch the ideas behind implementation of FCSL as an embedding into Coq, and describe important parts of FCSL machinery, used to simplify construction of proofs.

### 5.1 FCSL model and embedding into Coq

Programs in FCSL are encoded as their values in the denotational semantics of sets of \textit{action trees} \[36\] Appendix F of extended version]. The trees are a structured version of \textit{action traces} by Brookes [4]. They implement finite, partial approximations of the space of the composition concurroid using existentials that abstract over the concurroid-specific fields. For instance, in the case of flat combiner, which composes three concurroids \( Priv \), \( Alloc \) and \( FlatCombine \), we could use three existentials to abstract over \textit{self\_joint\_other} fields for \( Priv \), another three for \( Alloc \), and three more for \( FlatCombine \). To access any of the fields, we have to destruct all nine of the existentials. This quickly becomes tedious and results in proofs that are obscured by such existential destruction.

Our alternative approach develops a systematic way of projecting the fields associated with each concurroid, based on the concurroid’s label. Thus, for example, we can write \textit{self pv a} to obtain the \textit{self} component of \textit{a}, associated with a concurroid whose label is \textit{pv}. The identifier \textit{pv\_self} we used in the spec for \textit{span\_root} and for \textit{flat\_combine} is a notational abbreviation for exactly this projection. While this is an obvious idea, its execution required a somewhat involved use of dependently-typed programming, and an intricate automation by employing canonical structures and lemma overloading [17, 35].

### 5.2 Verification conditions and structural lemmas

Even though each well-typed FCSL program has already the strongest specification inferred automatically by the system, such spec isn’t what one would typically like to ascribe to a program and expose to the clients. Therefore, verification in FCSL reduces to \textit{weakening} the derived strongest spec to the one of interest.

The verification conditions for weakening are encoded by wrapping a program into the \textit{Do} constructor (e.g., in Figure 3), which emits a corresponding proof obligation. Such proofs in FCSL are structured to facilitate systematic application of Floyd-style structural rules, one for each command. All the rules are proved sound from first principles, and are applied as lemmas to advance the verification. As the first step of every proof, the system implicitly applies the weakening rule to the automatically synthesized weakest pre- and strongest postconditions, essentially converting the program into the continuation-passing style (CPS) representation and sequentializing its structure. Every statement-specific structural rule “symbolically evaluates” the program by one step, and replaces the goal with a new one (or several ones) to be verified.

**Lemma** \textit{step} \( W A B (e1 : ST W A) \\
\text{fun } y \mapsto m \mapsto m (e2 y) k \mapsto k \leftrightarrow y \leftrightarrow e1; e2 y) \).

\( ST \) is a type synonym for \( \text{STstep} \), hiding its pre’s and post’s.

### 5.3 Extracting concurroid structure via getters

When working with compositions of multiple concurroids, as in examples listed in Section [4] one frequently has to select the \textit{self}, \textit{joint} or \textit{other} components that belong to one of the composed concurroids. A naïve way of doing this is to describe the state space of the composition concurroid using existentials that abstract over the concurroid-specific fields. For instance, in the case of flat combiner, which composes three concurroids \( Priv \), \( Alloc \) and \( FlatCombine \), we could use three existentials to abstract over \textit{self\_joint\_other} fields for \( Priv \), another three for \( Alloc \), and three more for \( FlatCombine \). To access any of the fields, we have to destruct all nine of the existentials. This quickly becomes tedious and results in proofs that are obscured by such existential destruction.

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## 6. Evaluation and Experience

The Coq proof assistant serves as a tool for implementing FCSL’s metatheory and as a language for writing and verifying concurrent programs. The formalization of the metatheory, which includes the semantic model, implementation of getters, structural lemmas and a number of useful libraries (e.g., theory of PCMs, heaps, arrays, etc.), is about 17.2 KLOC size.

---

3 The predicate states that a program can execute (possibly, concurrently) in a state, satisfying a given precondition, without crashing [36, §F.5].
We evaluated FCSL by implementing, specifying and verifying a number of characteristic concurrent programs and structures. The simplest fine-grained structure is a lock, and we implemented two different locking protocols: CAS-based spinlock and a ticketed lock [33]. Both locks instantiate a uniform abstract lock interface, and are used by coarse-grained programs, performing concurrent incrementation of a pointer and memory allocation. In addition to the spanning tree algorithm and the flat combining construction, we also implemented such fine-grained programs as an atomic pair (CG increment), mutual exclusion PCM [32, 36] (CAS-lock, FC), (thread-local state), natural numbers with addition and zero [32] (CG allocator), (CG increment), heaps [32] (ticketed lock), are interchangeable, as they implement the same abstract interface (indicated by “L”).

The PCMs employed in formalizations of the case studies are: disjoint sets [35] (spanning tree, FC, ticketed lock), heaps [32] (thread-local state), natural numbers with addition and zero [32] (CG increment), mutual exclusion PCM [32, 35] (CAS-lock, FC), time-stamped histories [46] (pair snapshot, Treiber stack, producer/consumer), client-provided PCMs [32, 35] (FC, locks), lifted PCMs—products of basic PCMs [32, 35] (FC, locks). All these PCMs are instances are treated uniformly by in the proofs conducted in FCSL, due to the unifying algebraic structure.

Table 1 presents some statistics wrt. implemented programs in terms of LOCs and build times. The program suite was compiled on a 2.7 GHz Intel Core i7 OS X machine with 8 Gb RAM, using Coq 8.4pl4 and Sreffect 1.4. We didn’t rely on any advanced proof automation in the proof scripts, which would, probably, decrease line counts at the expense of increased compilation times. Notably, for those programs that required implementing new primitive concurroids (e.g., locks or Treiber stack), a large fraction of an implementation is due to proofs of properties of transitions and actions, as well as stability-related lemmas, while the sizes of proofs of the main programs’ specs are always relatively small.

Our development is inherently compositional, as illustrated by the dependency diagram on Figure 5. For example, both lock implementations are instances of the abstract lock interface, which is used to implement and verify the allocator, which is then employed by a Treiber stack, used as a basis for sequential stack and producer/consumer implementations. In principle, we could implement an abstract interface for stacks, too, to unify the Treiber stack and the FC-stack, although, we didn’t carry out this exercise.

As hinted by Table 1 not every concurrent program requires implementing a new primitive concurrid: typically this is done only for libraries, so library clients can reason out of the specific-

<table>
<thead>
<tr>
<th>Program</th>
<th>Libs</th>
<th>Conc</th>
<th>Acts</th>
<th>Stab</th>
<th>Main</th>
<th>Total</th>
<th>Build</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS-lock</td>
<td>63</td>
<td>291</td>
<td>509</td>
<td>358</td>
<td>27</td>
<td>1248</td>
<td>1m 1s</td>
</tr>
<tr>
<td>Ticketed lock</td>
<td>58</td>
<td>310</td>
<td>706</td>
<td>457</td>
<td>11</td>
<td>1647</td>
<td>2m 46s</td>
</tr>
<tr>
<td>CG increment</td>
<td>44</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>129</td>
<td>1m 14s</td>
</tr>
<tr>
<td>CG allocator</td>
<td>34</td>
<td>192</td>
<td>274</td>
<td>305</td>
<td>107</td>
<td>538</td>
<td>4m 7s</td>
</tr>
<tr>
<td>Pair snapshot</td>
<td>92</td>
<td>442</td>
<td>672</td>
<td>538</td>
<td>281</td>
<td>2025</td>
<td>1m 55s</td>
</tr>
<tr>
<td>Treiber stack</td>
<td>56</td>
<td>323</td>
<td>313</td>
<td>125</td>
<td>190</td>
<td>643</td>
<td>1m 21s</td>
</tr>
<tr>
<td>Spanning tree</td>
<td>348</td>
<td>215</td>
<td>162</td>
<td>271</td>
<td>305</td>
<td>1247</td>
<td>1m 11s</td>
</tr>
<tr>
<td>Flat combiner</td>
<td>65</td>
<td>125</td>
<td>190</td>
<td>114</td>
<td>164</td>
<td>444</td>
<td>1m 55s</td>
</tr>
<tr>
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<td>50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>243</td>
<td>2m 43s</td>
</tr>
<tr>
<td>FC-stack</td>
<td>365</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>608</td>
<td>5m 55s</td>
</tr>
</tbody>
</table>

Table 1: Statistics for implemented programs: lines of code for program-specific libraries (Libs), definitions of concurroids and decorations (Conc), actions (Acts), stability-related lemmas (Stab), and proof sizes of the main functions (Main), total LOC count (Total), and build times (Build). The “−” entries indicate the components that were not needed for the example.

7. Related and Future Work

Using the Coq proof assistant as a uniform platform for implementation of logic-based program verification tools is a well-established approach, which by now has been successfully employed in a number of projects on certified compilers [6, 24, 47], although, with no specific focus on abstractions for fine-grained concurrency, such as protocols and auxiliary state.

Related program logics The FCSL logic has been designed as a generalization of the classical Concurrent Separation Logic by O’Hearn [40], combining the ideas of local concurrent protocols with arbitrary interference [13, 25] and compositional (i.e., subjective) auxiliary state [32] with the possibility to compose protocols. Other modern concurrency logics, close to FCSL in their expressive power, are iCAP [51], Iris [27], CoLoSL [33], and CaReSL [53].

Both iCAP and Iris leverage the idea, originated by Jacobs and Piessens [23], of parametrizing specs for fine-grained concurrent data types by client-provided auxiliary code, which can be seen as a “callback”, and nowadays is usually referred to as a view shift. View shifts also serve purposes similar to FCSL’s concurrid transitions. A form of composition of concurrent resources can be encoded by combining view shifts with fractional permissions [3] (in iCAP) or invariant masks (in Iris). Similarly to FCSL, Iris makes use of PCMs as a generic mechanism to describe state, which can be split between parallel threads. However, neither iCAP, nor Iris have explicit subjective dichotomy of the auxiliary state, which makes...
encoding of thread-specific contributions (e.g., marked nodes from the graph example) in them less direct comparing to FCSL.

CoLoSL defines a different notion of thread-local views to a shared resource, and uses overlapping conjunction [21] to reconcile the permissions and capabilities, residing in the shared state between parallel threads. Overlapping conjunction affords a description of the shared structure mirroring the recursive calls in the structure’s methods. In FCSL, such machinery isn’t required, as self and other suffice to represent the thread-specific views, and joint state doesn’t need to be divided. In our opinion, this leads to simpler specs and proofs. For example, the proof that \( \text{atom} \) constructs a tree in CoLoSL involves abstractions such as shared capabilities for marking nodes and extension of the graph with virtual edges, none of which is required in FCSL. Moreover, CoLoSL doesn’t prove that the tree is spanning, which we achieve in FCSL via hiding.

CaReSL combines the Hoare-style reasoning and proofs about contextual refinement. Similarly to FCSL, CaReSL employs resource protocols to specify thread interference, although, targeting the “life stories” of particular memory locations instead of describing a whole concurrent data structure by means of an STS. While FCSL is not equipped with abstractions for contextual refinement, in our experience it was never required to prove the desired Hoare-style specs for fine-grained data structures.

Neither of the mentioned logics features hiding as a language constructor for controlling interference. Reasoning in iCAP, Iris, CoLoSL and CaReSL follows the tradition of Hoare-style logics, so the specs never mention explicitly the heap and state components. In contrast, FCSL assertions use explicit variables to bind heap and auxiliary state, as well as their components. In our experience, working directly with the state model is pleasant, and has to be done in Coq anyway, since Coq lacks support for contexts of bunched implications, as argued by Nanevski et al. [19]. None of iCAP, CoLoSL or CaReSL features a mechanized meta-theory, and neither of these logics has been implemented as a mechanized verification tool. The soundness of Iris’ primitive proof rules has been mechanized in Coq, however, the logic itself has only been employed for paper-and-pencil verification of example programs.

Related tools for concurrency verification: SAGL and RGSep, the first logics for modular reasoning about fine-grained concurrency [15,53], inspired creation of semi- and fully-automated verification tools: SmallfootRG [5] and Cave [54]. These tools target basic safety properties of first-order code, such as data integrity and absence of memory leaks.

Chalice [23] is an experimental first-order concurrent language, supplied with a tool that generates verification conditions (VCs) for client-annotated Chalice programs. Such VCs are suitable for automatic discharge by SMT solvers. For local reasoning, Chalice employs fractional permissions [1], implicit dynamic frames [48], and auxiliary state [29], which, unlike the one of FCSL, is not a subject of PCM laws, and thus is not compositional, as its shape should match the forking pattern of the client program being verified. Chalice also supports a form of symmetric Rely/Guarantee reasoning, i.e., it does not allow the threads to take different roles in a protocol (which is expressible in FCSL via self-enabled transition, such as \( \text{nullify}_\text{trans} \) from Section 3.3). Chalice’s specification fragment is a first-order logic, whereas FCSL admits higher-order functions and predicates in specs, therefore, enabling program composition and proof reuse, as shown in Figure 5.

VCC [8] is a tool for verifying low-level concurrent C code. VCC doesn’t provide machinery for reasoning about custom interference or compositional auxiliary state, and, similarly to Chalice, allows specifications only in a first-order logic to support an SMT-based automation back-end.

VeriFast [24] is a tool for deductive verification of sequential and concurrent C and Java programs, based on separation logic [44]. To specify and verify fine-grained concurrent algorithms, VeriFast employs fractional permissions [1] and a form of first-class auxiliary code [22], enabling manipulation of (non-compositional) auxiliary state. VeriFast has been recently extended with Rely/Guarantee reasoning [49], although, without a possibility to compose resources. To the best of our knowledge, soundness of VeriFast core has been formally proved only partially [50].

Rely-Guarantee references (RGRefs) by Gordon [18] are a mechanism to prove transition invariants of concurrent data structures. While the language of RGRefs is implemented as an axiomatized Coq DSL, the system’s soundness is proved by hand using the Views framework [12]. Since RGRefs focuses on correctness of data structures wrt. specific protocols and doesn’t provide auxiliary state, it’s unclear how to employ it for client-side reasoning.

Future work In the future, we plan to augment FCSL with the program extraction mechanism [31] and implement proof automation for stability-related facts via lemma overloading [17]. Due to the limitations of Coq’s model wrt. impredicativity, at this moment, FCSL doesn’t support higher-order heaps (i.e., the possibility to reason about arbitrary storeable effectful procedures). While programs requiring this feature are rare, we hope that it will be possible to encode and verify the characteristic ones, once the development is migrated to Coq 8.5, featuring universe polymorphism [50].

8. Conclusion

Our experience with implementing a number of concurrent data structures in FCSL indicates a recurring pattern, exhibited by the formal proof development. Verification of a new library in FCSL starts from describing its invariants and evolution in terms of an STS. It’s common to consider parts of real or auxiliary state, which are a subject of the logical split between parallel threads, as elements of a particular PCM. Such representation of resources makes the verification uniform and compositional, as it internalizes the library protocol, so the clients can reason out of the specifications.

This observation indicates that STSs and PCMs can be a robust basis for understanding, formalizing and verifying existing fine-grained programs. We conjecture that the same foundational insights will play a role in future designs and proofs of correctness of novel concurrent algorithms.

Acknowledgments We thank the anonymous reviewers from PLDI’15 PC and AEC for their feedback. We are also grateful to Steve Blackburn for his efforts as PLDI PC chair. This research is partially supported by Ramon y Cajal grant RYC-2010-0743 and the US National Science Foundation (NSF). Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

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