Secure Distributed Programming with Value-Dependent Types

NIKHIL SWAMY[1] JUAN CHEN[1] CÉDRIC FOURNET[1]
PIERRE-YVES STRUB[2] KARTHIKEYAN BHARGAVAN[3] JEAN YANG[4]
Microsoft Research[1] MSR-INRIA[2] INRIA[3] MIT[4]
(*e-mail:* {nswamy, juanchen, fournet}@microsoft.com pierre-yves@strub.nu, karthikeyan.bhargavan@inria.fr, jeanyang@csail.mit.edu)

Abstract

Distributed applications are difficult to program reliably and securely. Dependently typed functional languages promise to prevent broad classes of errors and vulnerabilities, and to enable program verification to proceed side-by-side with development. However, as recursion, effects, and rich libraries are added, using types to reason about programs, specifications, and proofs becomes challenging.

We present F*, a full-fledged design and implementation of a new dependently typed language for secure distributed programming. Our language provides arbitrary recursion while maintaining a logically consistent core; it enables modular reasoning about state and other effects using affine types; and it supports proofs of refinement properties using a mixture of cryptographic evidence and logical proof terms. The key mechanism is a new kind system that tracks several sub-languages within F* and controls their interaction. F* subsumes two previous languages, F7 and Fine. We prove type soundness (with proofs mechanized in Coq) and logical consistency for F*.

We have implemented a compiler that translates F* to .NET bytecode, based on a prototype for Fine. F* provides access to libraries for concurrency, networking, cryptography, and interoperability with C#, F#, and the other .NET languages. The compiler produces verifiable binaries with 60% code size overhead for proofs and types, as much as a 45x improvement over the Fine compiler, while still enabling efficient bytecode verification.

We have programmed and verified nearly 50,000 lines of F* including new schemes for multi-party sessions; a zero-knowledge privacy-preserving payment protocol; a provenance-aware curated database; a suite of web-browser extensions verified for authorization properties; a cloud-hosted multi-tier web application with a verified reference monitor; the core F* typechecker itself; and programs translated to F* from other languages such as F7 and JavaScript.

1 Introduction

Distributed applications are difficult to program reliably and securely. To address this problem, researchers have designed new languages with security verification in mind. Early work in this space developed *ad hoc* type systems targeting verification of specific security idioms, including systems for information flow control, starting with Volpano *et al.* (1996), and for proving authentication and authorization properties in cryptographic protocols (Gordon & Jeffrey 2003; Fournet *et al.* 2007; Backes *et al.* 2008). More general type systems for security verification have also been proposed, e.g., Fable (Swamy *et al.* 2008), F7 (Bengtson *et al.* 2008; Bhargavan *et al.* 2010), Aura (Jia *et al.* 2008;

Vaughan *et al.* 2008; Jia & Zdancewic 2009), Fine (Swamy *et al.* 2010; Chen *et al.* 2010), and PCML5 (Avijit *et al.* 2010). All these languages use various forms of dependent types to reason about security, following a long tradition of dependent typing for general-purpose theorem proving and program verification, e.g., Coq (Bertot & Castéran 2004) and Agda (Norell 2007).

Although these languages are successful in many aspects, for large-scale distributed programming we desire languages that (1) feature general programming constructs like effects and recursion, which, while invaluable for building real systems, make it hard to formally reason about programs, specifications, and proofs; (2) support various styles of proofs and evidence, ranging from cryptographic signatures to logical proof terms; (3) produce proofs that can be efficiently communicated between agents in the system.

This paper presents F*, a full-fledged design and implementation of a new dependently-typed programming language that addresses all these challenges. F* subsumes both F7 and Fine. Unlike several other dependently typed languages, such as Fine, F7, and Cayenne (Augustsson 1998), F* provides arbitrary recursion while maintaining a logically consistent core, resolving the tension between programmability and consistency by restricting the use of recursion in specifications and proofs. This feature of retaining a consistent core in the presence of effects is shared with languages like Guru (Stump *et al.* 2008) and Aura (Jia *et al.* 2008), although there are several technical differences in the means by which each language isolates its consistent core. In addition to a consistent core, F* also enables modular reasoning about state and other effects, and allows specifying refinement properties on affine values; it supports proofs of refinement properties using a mixture of cryptography and logical proof terms; and it allows selective erasure and reconstruction of proofs to reduce the overhead of communicating proofs.

By compiling to verifiable .NET bytecode, F* provides access to existing libraries for concurrency, networking, cryptography, and interoperability with C#, F#, and other .NET languages. We have formalized the metatheory of F* and mechanized a significant part of the metatheory in Coq. We have developed a prototype compiler for F* (35,000 lines of F#) and used F* to program and verify more than 50,000 lines of code. We believe F* is the first language of its kind with such a scale of implementation and evaluation.

Next, we give an overview of F* and our main contributions.

A novel kind system. A central feature of F* is its kind system, which tracks several sub-languages—for terms, proofs, affine resources, and specifications. This kind system controls their interaction while still providing a single unified language to specify, program, verify, and deploy secure distributed systems.

The kind $\star$ is for general programming; its terms may diverge and exhibit other effects, such as state, exceptions and I/O. The kind P identifies a universe of pure, total functions; P terms are used mainly in the construction of proofs. The kind A is for affine (used at most once), stateful resources; it is used to model and reason about effects in a modular style. The kind E is for specifications; it includes all the kinds above, that is, we define a sub-kinding relation $\star <: E$, $P <: E$, and $A <: E$ to promote the reuse of code and specifications. We use E to control the selective erasure of proof terms, when these proofs are impossible to construct in a distributed setting (e.g., due to cryptography or due to the design of legacy libraries); when the presence of a proof term would curtail expressiveness (e.g., when speaking of properties of affine values); or when proof terms would be too voluminous to construct. In such cases, we express specifications as types that reside exclusively in kind E.

Two flavors of refinements. Refinement types are commonly used to specify program properties. In contrast with prior languages, F* features both *concrete* and *ghost* refinements; §2 illustrates the need for both for secure distributed programming. To reason about the security of distributed applications, with minimal trust between components, explicit proofs sometimes need to be communicated and checked at runtime.

Concrete refinements are pairs representing a value and a proof term serving as logical evidence of the refinement property, similar to those in Coq and Fine. One feature of F* is that it assigns a special kind P for proof terms, and restricts types and proof terms in the P universe to guarantee logical consistency.

Ghost refinements are used to state specifications for which proof terms are not maintained at run time. Ghost refinements have the form x:t$\{\phi\}$ where x is a value variable, t is a type, and ϕ is a logical formula, itself represented as a type that must have kind E and may depend on x and other variables in scope. Ghost refinements are similar to those of F7; they are smoothly integrated in F* using the E kind. Ghost refinements provide the following benefits: (1) they enable precise formal models for many cryptographic patterns and primitives, such that evidence for ghost refinement properties can be constructed and communicated using cryptographic materials, such as digital signatures; (2) they benefit from a powerful subtyping relation: x:t$\{\phi\}$ is a subtype of t; and x:t$\{\phi\}$ is a subtype of x:t$\{\psi\}$ when ϕ implies ψ; this *structural subtyping* is convenient to write and verify higher-order programs; (3) they can provide precise specification to legacy code without requiring any modifications; and (4) when used in conjunction with concrete refinements, they support *selective erasure* and *dynamic reconstruction* of evidence, enabling a variety of new applications and greatly reducing the performance penalty for runtime proofs.

Refinements on affine state. Prior work has shown the usefulness of affine types in reasoning about programs that use mutable state (Lahiri *et al.* 2011; Borgstrom *et al.* 2011). Relying on its kind system, F* allows the free use of affine values within specifications, while still guaranteeing that affine values are used at most once elsewhere in the code. In §5, we exploit this feature extensively in implementing a new, flexible approach proposed by Deniélou & Yoshida (2011) to enforce protocols based on multi-party session types. Prior systems that integrate substructural and dependent types (e.g., Fine and Linear LF by Cervesato & Pfenning 2002) disallow refinements that speak directly about affine values, and have to rely instead on various encodings to work around this limitation, which is unsuitable for source programming.

Automation and logic parametricity. Proof automation is critical for developing large-scale programs. F* is carefully designed to be parametric in the logic used to describe programming properties and their proofs; §2.6 shows examples with a simple modal authorization logic, and with an *ad hoc* logic for database provenance. Logic parametricity enables us to work with custom authorization logics and, importantly, makes it easy to integrate F* with SMT solvers for logics extended with specific theories. Thus, program verification in F* benefits from significant automation—our implementation uses the Z3 SMT solver (de Moura & Bjørner 2008) and scales up to large programs and specifications.

Languages like Aura, PCML5, Coq, and Agda commit to a specific logic, limiting their flexibility. This limitation is significant since diverse logics are used and even designed when reasoning about security policies and properties—see for instance Chapin *et al.* (2008) for a recent survey.

Metatheory. We establish several properties of F*. First, we prove the soundness of F* in terms of progress and preservation, the latter being formalized mechanically using Coq. From this, we derive a safety property for ghost refinements called global deducibility. Next, we show that the *P*-fragment of F* is normalizing using the proof technique of reducibility candidates (Girard 1972). We also give a typed embedding of a subset of RCF (the core calculus of F7) into F*.

Since our *P*-fragment is normalizing, one might imagine extending F* to permit arbitrary *P*-terms to index types. However, term reduction in types, particularly with dynamic assumptions and affinity, poses a significant challenge for the metatheory. So, we remain with value dependency in F*, while acknowledging that it is less expressive than having expressions in types. Nevertheless, this loss of expressiveness has not hindered the construction and verification of the programs we have built. In place of type-level reduction of expressions, F* provides a type-conversion relation that is parameterized by a theory of logical equivalence. This allows a value of type such as array (1 + 1) int to be used in a context that expects an array 2 int, since the terms 1 + 1 and 2 are deemed equal in the theory of integer arithmetic. This also means that our types do not necessarily have canonical forms, since the equalities are not oriented, (e.g., array (1 + 1 - 0) int is also convertible with the two previous types). However, this does not pose a problem since we always try to prove a given type convertible with the type demanded by the context (rather than attempting to compute normal forms, as is conventional in a dependent type theory such as Coq).

Compiler implementation. We have implemented a compiler for F* based on our prior work on a compiler for Fine. The F* compiler still accepts both Fine and F7 programs as input. To validate this feature, we typecheck and compile a large F7 library implementing symbolic cryptography (Bhargavan *et al.* 2010).

Our compiler translates F* to RDCIL, a dependently typed dialect of .NET bytecode. This translation is considerably more efficient than the one we used for Fine. Due to the use of ghost refinements and the availability of polymorphic kinds, bytecode emitted by the F* compiler is an order of magnitude (in some cases 45x) smaller than the bytecode emitted by the Fine compiler.

Experimental evaluation on a large suite of examples. We have programmed and verified nearly 50,000 lines of F* code. Our developments include secure implementations for multi-party session protocols; a zero-knowledge privacy-preserving payment protocol; a provenance-aware curated database; a suite of 17 web-browser extensions verified for authorization properties; a cloud-hosted multi-tier web application with a verified reference monitor; a proof of soundness for the simply typed lambda calculus; a self-certified core F* typechecker; a partial decision procedure for DKAL (Gurevich & Neeman 2008), a distributed authorization logic; proofs of security for a variety of cryptographic constructions in a relational variant of F*; various stateful data structures proved functionally correct using a monadic variant of F*; an operational semantics for JavaScript proved to satisfy several stateful invariants; JavaScript programs translated to F* and verified for safety; and various F7 programs translated to F* and verified for refinement type safety.

An earlier, shorter version of this paper appeared at ICFP 2011. The main differences are a revised kind system (§3.2), a slightly generalized rule for pattern matching (§3.2), and a direct proof of normalization (§4.3).

The F* source release, the formal Coq development, the programming examples, and an extended technical report are available at `http://research.microsoft.com/fstar`.

2 F* by example

This section introduces F* informally.

The syntax of F* is based loosely on OCaml, F# and related languages in the ML family—notations specific to F* are primarily in support of its more expressive type and kind language. The dynamic semantics is also in the spirit of ML, using a call-by-value evaluation strategy, but the static semantics is significantly more complex. The examples below, together with those in §5, are intended to motivate and exercise its main features.

We organize our presentation around the new kind system of F*. Our examples are chosen to illustrate key features of the system, while still being reasonably simple. In practice, larger F* programs routinely mix several of these features. We start with simple programs that use P-kind and the sub-language of total functions to construct proof terms for concrete refinements. Next, we discuss E-kind and its use in two different scenarios with ghost refinements—first, when giving specifications to legacy libraries where the construction of explicit proof terms is impractical; and, second, when verifying implementations of cryptographic protocols, where the construction of proof terms is simply impossible. We then turn to A-kind, which, in conjunction with E-kind, can specify and verify properties of stateful computations. We conclude the section with an example that exploits the interaction between P-kind and E-kind, via the sub-kinding relation $P <: E$, to construct a model of a high-integrity database with precise provenance properties.

2.1 Concrete refinement types and total proof terms

Consider a very simple program, tail, that returns the tail of a list, and a partial specification that states that every member of the tail is also a member of the input list.

```
val tail: ∀a::⋆. l1:list a →(l2:list a ∗ (x:a →Mem x l2 →Mem x l1))
```

This specification is expressed as an F* type for tail, explained below. This type is polymorphic, of the form ∀a ::k. t where k is the kind of the abstracted type variable—kinds are ascribed to types using double colons. Here, variable a has kind $\star$, the kind given to types that admit arbitrary recursion and effects, i.e., the standard kind of fully-applied types in an ML-like system. Following ML, by default we omit explicit quantifiers for prenex-quantified type variables, and we omit type applications when they can be determined by the context.

The rest of the type of tail shows a dependent function, of the form x:t →t′ where the formal parameter of type t is named x, and is in scope in t′, the type of the result. When the function is not dependent, we simply write t →t′. The result type of tail shows a *concrete* *refinement* type, also called subset types or Σ-types (Sozeau 2007). This type takes the form of a dependent pair x:t ∗ t′, with a first component of type t named x and in scope in t′, the type of the second component. Here, the type l2:list a ∗ (x:a → Mem x l2 → Mem x l1) states that the tail l2 contains at most the elements of the input list l1. Intuitively, the second component carries a proof of the logical formula ∀x:a. Mem x l2 ⟹ Mem x l1. The predicate Mem x l2 is itself a type, which we show below. As such, concrete refinements are represented as pairs of the underlying value, and a proof term witnessing the validity of the refinement formula.

A total sub-language for proof terms. We must be careful when representing quantifiers and implication with function arrows. For logical consistency, we require the function arrows that represent the type of proof terms to be total, whereas arrows used in the rest of the program (where we certainly want to use arbitrary recursion, exceptions, etc) can be partial. Thus, we need to ensure that potential divergence in the program never leaks into code fragments used for building proof terms. We achieve this by introducing a kind P such that the terms typed within P are guaranteed to be total.

Using P-kind, we define Mem, an inductive type that axiomatizes list membership in constructive style. Its kind is of the form a ::k ⇒ k′, where a binds a k-kinded formal type parameter in the kind k′ of the constructed type. Type constructors can also be applied to values; such constructors have kinds of the form x:t ⇒ k where x names the formal argument, a value of type t in scope in the kind k. Below, the kind of Mem says that it is a dependent type constructor that constructs a type of kind P from a type a and two values of type a and list a . (When x:t, we write Mem x l instead of Mem t x l; we also use familiar list notations, writing [] for the empty list and hd::tl to cons an element hd to the front of a list tl.)

```
type Mem :: a ::⋆ ⇒ a ⇒ list a ⇒ P =
  | Mem_hd : x:a → tl:list a → Mem x (x::tl)
  | Mem_tl : x:a → y:a → tl:list a → Mem y tl → Mem y (x::tl)
```

Inductive types defined in P-kind are required to be positive. That is, given a constructor $C : t_1 \to \ldots \to t_n \to T$ for a type T of kind P, the constructed type T may occur in each t_i only in positive positions. Violating positivity may lead to logical inconsistency, as illustrated below.

```
type Fix = MkFix : (Fix → unit) → Fix
let loop′ (me:Fix) = match me with MkFix f → f me
let loop = loop′ (MkFix loop′)
```

The type Fix is not positive; it is used to define loop, a divergent term, which clearly should not be used as a proof term. On the other hand, requiring all datatypes to be positive would be too restrictive. For example, when modeling dynamically typed programs, it is common to use the following dyn datatype, where the Fun constructor contains a negative occurrence of the defined type.

```
type dyn = Int : int → dyn | String : string → dyn | Fun : (dyn → dyn) → dyn
```

Thus, we require positivity for P and allow recursive datatypes elsewhere. In addition to positivity, we place certain restrictions (§3.2) on the elimination rules for P-kinded types to ensure totality.

A function type x:t → t′ inherits the kind of its range type—it has P kind when t′::P. Thus, in the type of tail, the type x:a → Mem x l2 → Mem x l1 is in P (since the range is in P), ensuring that any well-typed term at that type is a total function, and hence a valid proof term. Theorem 3 justifies this reasoning. In contrast, the type of tail itself has kind ⋆, since the pair in its range has kind ⋆. Thus, tail is not required to be a total function. Indeed, as shown by its implementation below, tail may raise an exception when called with an empty list. However, when called with a non-empty list hd::tl, it returns a pair containing tl and a total function (i.e., a proof term) witnessing the refinement formula.

```
let tail l = match l with
  | [] → raise (Error "Can't take the tail of an empty list")
  | hd::tl → let proof (x:a) (pf:Mem x tl) = Mem_tl hd x tl pf in (tl, proof)
```

Typechecking this code requires typing the body of the proof function at the type Mem x l. From the type of Mem_tl and the types of the bound variables, it is easy to compute the type of the body as Mem x (hd::tl). To prove that this latter type is convertible to Mem x l, the F⋆ typechecker implicitly uses the equations induced by pattern matching, such as l = hd::tl in the second branch above.

Programming explicitly with proof terms for non-trivial program properties quickly becomes impractical. Fine, a predecessor of F⋆, provided a feature that allowed constructing such proof terms automatically. This worked by first calling Z3, an SMT solver, to try to decide refinement properties, and then by building and typechecking a proof term from the deduction traces reported by Z3. However, since Z3 (and many other automated provers) use classical logics, the proof terms produced in this manner are not constructive. To support non-constructive proof terms, Fine provided a custom proof kernel. These proof kernels can be expressed in F⋆ as well. More generally, the P-fragment allows F⋆ programmers to define custom logics and to build and typecheck sound proof terms for these logics within the language itself. This is illustrated further in §2.6.

2.2 Ghost refinements for lightweight specifications

Concrete refinements have a long tradition and a well-understood theory. However, as discussed below, we find them inappropriate for use in some scenarios. As an alternative, F⋆ also provides ghost refinements, based on a construct of F7, and integrates them with the other features of the system, notably higher kinding, quantification over predicates, and refinements for substructural state.

We illustrate the use of ghost refinements for verifying clients of libraries, where the libraries are authored separately and are unmodifiable. In recent work, Guha *et al.* (2011) consider programming secure web browser extensions using F⋆. For this application, we use ghost refinement types to specify pre- and post-conditions on the interface provided by the browser, and we verify access control properties of extensions by typing them against this specification. The listing below illustrates this approach on a tiny program; §6 reports our results for compiling 17 such extensions in a type-preserving style to .NET bytecode.

We aim to enforce a policy that untrusted extensions (line 10) only read data from the header of a web page and not the body. This policy is specified using an assumption at line 8, which states, informally, that extensions hold the CanRead e privilege on any DOM nodes e for which the property EltTagName e "head" is derivable; only trusted code may

```
1  (* Fragment of DOM API *)
2  type elt
3  type EltTagName :: elt ⇒ string ⇒ E
4  type CanRead :: elt ⇒ E
5  val innerText: e:elt{CanRead e} → string
6  val tagName: e:elt → t:string{EltTagName e t}
7  (* Sample extension policy (trusted) *)
8  assume ∀e. EltTagName e "head" ⟹ CanRead e
9  (* Sample extension code (untrusted) *)
10 let read e = if tagName e = "head" then innerText e else ""
```

include assumptions. Unlike the Mem predicate in §2.1 (which has P kind), EltTagName and CanRead construct erasable, or E-kinded, types. Erasable types are generally uninhabited and have no data constructors. Instead, we use them for specifications, as in the types of innerText and tagName, our two library functions from nodes to strings.

The type of innerText has the form $\mathsf{x{:}t}\{\phi\} \to \mathsf{t}'$, where the formula ϕ is a ghost refinement applied to the formal parameter x:t, and x is in scope in both ϕ and t'. Its refinement CanRead e is a pre-condition indicating that clients must hold the CanRead e privilege before calling the function. Analogously, the post-condition of tagName relates the returned string t to the argument e, and clients may derive facts using this property and any other property in scope, such as our policy assumption at line 8. For example, at the call to innerText in the **then**-branch at line 10, the F* checker (and Z3) uses the policy assumption; the post-condition EltTagName e t for the value t returned by tagName e; and the equation `t="head"` from the equality test to derive CanRead e, the pre-condition of innerText, and thus authorize the call. Using this approach, once typechecked, untrusted extension code need not be examined—only the policy and the annotations on the DOM API are trusted. Next, we discuss two features of ghost refinements that are suitable in our example.

Ghost refinements and erasure. The type $\mathsf{x{:}t}\{\phi\}$ is a subtype of t, and the values of these two types share the same runtime representation. This makes specifications using ghost refinements lightweight, inasmuch as they do not require modifications to underlying code and data. For example, we did not need to modify, or even wrap, the DOM implementation above to verify its client code in this style. Furthermore, structural subtyping on function types promotes reuse in higher order code.

Semantics of ghost refinement derivability. For every value v that inhabits $\mathsf{x{:}t}\{\phi\}$, our type system ensures that the formula $\phi[\mathsf{v}/\mathsf{x}]$ is derivable. The definition of derivability is subtle and is made precise in §3. However, intuitively, derivability is a logical entailment relation defined relative to a context of dynamic assumptions $\mathscr{A}$. We think of $\mathscr{A}$ as a monotonically increasing *log* of events and formulas that are assumed during evaluation of the program. Formally, a call to tagName e reduces to t and has the *effect* of adding the formula EltTagName e t to the log. For values given ghost refinement types, there may be no concrete proof at run time to witness the derivability of the refinement formula. Indeed, when working with libraries like the DOM, explicit proof terms witnessing DOM invariants seem both infeasible and undesirable (as they may be very large); ghost refinements fit the bill nicely.

Proof-irrelevance and P vs. E-kind. The distinction between P and E in F* may, at first, seem reminiscent of the distinction between Type and Prop in a system like Coq. The proof terms for concrete refinements in Coq are often from the Prop universe, indicating that they are computationally irrelevant, so that they may be erased during code extraction. In contrast, concrete refinements in F* are accompanied by P-kinded proof terms, which are computationally *relevant*. We view proofs as useful runtime entities that carry important information. We choose to make proofs explicit and useful—§2.6 demonstrates a novel way of using concrete proof terms to construct precise provenance trails in a curated database. As such P-kind is closer to Coq's Type.

E-kind in F* plays a role more similar to proof irrelevance in Coq. However, the semantics of E-kinded types and ghost refinements is considerably different. Not only are proofs for ghost refinements irrelevant, these proofs may not be constructible at all and E-kinded types may be uninhabited. Instead, the log-based semantics of ghost refinements makes trust assumptions in external code formal and explicit, and allows the definition of security properties for code that is robust even when composed with arbitrary attacker code. For example, Guha *et al.* (2011) applied the log-based semantics to prove a robust safety property that ensures that verified extensions are authorization-safe even when composed with arbitrary untrusted JavaScript on a web page.

2.3 Ghost refinements and indexed types for cryptography

Ghost refinements have been used in F7 to verify implementations of various security protocols against cryptographic assumptions (Bhargavan *et al.* 2010; Fournet *et al.* 2011). This section presents a small fragment of a library for public key cryptography in a new style, relying on features of F* not available in F7 such as higher-kinded and indexed types; the F* distribution includes a more complete library together with several programs that rely on cryptography. Our example also illustrates the need for ghost refinements. As we will see, it is infeasible to construct concrete proof terms (whether constructive or not) to justify the soundness of cryptographic evidence.

The listing below gives the interface of a cryptographic library for digital signatures. Informally, signatures provide a means for a party in a protocol to communicate a value and a property of its local environment to a remote party. For example, Alice can sign a message m and send it to Bob, and, if Bob trusts Alice, Bob can conclude that the message originated with Alice. Additionally, given a prior agreement on the purpose of these signatures, Alice's signature can convince Bob of some additional property ϕ of the message m, e.g., that the message originated in Alice's file system, or that it represents a genuine mail from Alice. The signature is useful inasmuch as ϕ is *not* an intrinsic property of the contents of m; a constructive logical proof of ϕ in this setting may be nonsensical.

```
type dsig = bytes (∗ type of digital signatures ∗)
type prin (∗ name of a principal ∗)
type sk :: prin ⇒ a ::⋆ ⇒ (a ⇒ E ) ⇒ ⋆
type pk :: prin ⇒ a ::⋆ ⇒ (a ⇒ E ) ⇒ ⋆
val sign: ∀a ::⋆, ϕ ::a ⇒ E . p:prin → sk p a ϕ → x:a {ϕ x} → dsig
type Says :: prin ⇒ E ⇒ E
val verify: ∀a ::⋆,ϕ ::a ⇒ E . p:prin → pk p a ϕ → x:a → dsig → r:bool{r=true ⟹ Says p (ϕ x)}
```

The library provides a representation type dsig for digital signatures, here just an alias for bytes, the type of concrete byte arrays. It also exposes an abstract type prin for principal identifiers, and type constructors sk and pk for secret keys and public keys, respectively.

For simplicity, we omit functions for managing principals, for generating keys, and for accessing their representation.

A private key of type sk Alice a ϕ informally belongs to the principal Alice:prin, who can use it to sign values m of type a that satisfy the property ϕ m. Given such a key, the function sign allows clients to construct a dsig value by signing a message x:a, with a pre-condition that requires that the formula ϕ x be derivable when sign is called. Public keys are complementary: given a key of type pk Alice a ϕ, the function verify dynamically verifies the validity of a message signature; if it succeeds, then the caller knows that Says Alice (ϕ x) holds. In the post-condition, the predicate Says p φ is the usual lifting of a proposition φ into a modality Says, similar to forms used in a variety of modal authorization logics (Chapin *et al.* 2008). Intuitively, Says p φ is weaker than φ, and the two coincide when principal p is trusted. (Untrusted principals are not featured in the code above; they are used to model key compromise.)

As in F7, a *symbolic implementation* of the library can be verified against the specification shown above, and it can be proved correct with respect to a Dolev-Yao adversary (Bhargavan *et al.* 2010); a *concrete implementation* of the library can similarly be verified and proved correct with respect to a more realistic probabilistic polynomial-time adversary (Fournet *et al.* 2011). In their work, however, F7 types cannot be parameterized by predicates, so they have to simulate the ϕ parameter through a level of indirection: instead of the F* type sk p a ϕ, private keys in F7 are given a type of the form sk p a usage, where usage ranges over bytes, and the predicate ϕ is replaced with a global predicate SignSays, indexed by p and usage, The soundness of F7 verification relies on a programming convention that each key usage must be unambiguously defined by recording an assumption of the form $\forall$p,v. SignSays p usage v $\Longleftrightarrow$ Says p (ϕ v). This convention is not enforced automatically, hence their style may lead to logical inconsistencies. In contrast, F* types are more concise, and require fewer dynamic assumptions and no programming discipline beyond typing.

2.4 First-order theories over logical values

Value dependency in F* precludes reasoning about programs terms simply by reduction. In general, since F* terms can have effects, these reductions would not be sound. Instead, F* allows equational reasoning about functions within a logical theory. This allows us to recover some of the expressiveness lost by value dependency restrictions. As an example, consider the interface for an abstract data type of arrays (below, on the left), designed to ensure that all array accesses are within bounds, and some sample client code (on the right).

```
type nat = i:int{i ≥ 0}
type array :: ⋆⇒ ⋆
logic val Len : array a → nat
val anew: l:nat → init:a → x:array a{Len x=l}
val aget: x:array a → i:nat{i<Len x} → a
val aset: x:array a → i:nat{i<Len x} → a → unit
```

```
let rev (len:nat) (x:array a{Len x=len}) =
  let rec aux (i:nat{i ≤ len/2 ∧ len ≠ 0}) =
     let j = len − i − 1 in
     let tmp = aget x i in
     aset x i (aget x j); aset x j tmp;
     if i + 1 > len / 2 then () else aux (i + 1)
  in if len=0 then () else aux 0
```

The abstract type array a represents a mutable array containing a-typed values. We allocate an array using anew, providing a length and an initial value. The functions aget and aset read and write the ith cell in the array. The client program rev reverses the array x by swapping the contents of cells that are equidistant from the center of the array.

To ensure that clients only access array cells within bounds, we introduce an uninterpreted function Len:array a → nat. The **logic** qualifier preceding its declaration indicates that Len can only be used in the refinement logic, and has no operational semantics otherwise. It is illegal to call Len when evaluating a program—thus, rev takes two parameters, a len:nat value and the array x, where the refinement on x relates len to Len x in the logic. On the other hand, our interface may additionally provide an ordinary function **val** alength: x:array a → l:nat {Len x=l}. By making use of these "logical values" and by interpreting them in the logic with suitable axioms, we can simulate type-level reduction of expressions by equational rewriting of logic values.

The result type of anew records with a ghost refinement that the length of the new array x is l. The other two functions require that i:nat, the array index, be strictly less than the length of the array. Accordingly, we use a logic equipped with a theory of integer inequalities and arithmetic, i.e., the infix type constructors $(<)$::int ⇒ int ⇒ E, $(\leq)$::int ⇒ int ⇒ E, etc. are predicates in the refinement logic, with the usual interpretation as integer inequality.

In order to typecheck rev, we make use of F⋆'s standard prelude, which includes the following declarations for arithmetic primitives.

```
logic val (+) : int → int → int          val (+) : x:int → y:int → z:int{z = x + y}
logic val (−) : int → int → int          val (−) : x:int → y:int → z:int{z = x − y}
logic val (∗) : int → int → int          val (∗) : x:int → y:int → z:int{z = x ∗ y}
logic val (/) : int → int → int          val (/) : x:int → y:int{y ≠ 0} → z:int{z = x / y}
```

We have four interpreted arithmetic functions in the logic, and four corresponding primitive operators in F⋆, each primitive operator being specified through the use of the corresponding logic function. The duplication may seem somewhat redundant, but it is a one-time cost for primitive operators, it can be hidden under suitable syntactic sugar, and it can be adapted to match the theories implemented by Z3.

To typecheck aget x j within rev, for instance, the F⋆ typechecker must prove $j <$ Len x. Without any type-level reduction, the reasoning proceeds modulo theory by first showing $j = len - i - 1$ in the refinement logic; noting $0 \leq i + 1 \leq len$; and concluding $0 \leq j < len$.

2.5 Ghost refinements and affine-indexed types for state

The example above shows a weak, partial specification for arrays, capturing their size but not their mutable content, but F⋆ also has mechanisms to support stronger specifications and verify functional correctness. For instance, one can encapsulate effectful code within a monad, and write explicit stateful, pre- and post-conditions—this is the methodology of Nanevski *et al.* (2008); §7 discusses how a similar methodology can be applied to F⋆.

In this section, we illustrate the use of affine types, in combination with E-kinded types and logical values, to reason about stateful programs. In particular, we show how to program with *linear maps*, a data type proposed by Lahiri *et al.* (2011) to verify heap-manipulating programs. One innovation of F⋆ (which is a key enabler of this encoding) is that it permits indexing types with affine values, allowing us to state properties about affine values without consuming them. For space reasons, we do not show a client program using linear maps—a complete example is available in the F* distribution.

Linear maps are a data structure that equips a Floyd-Hoare logic (using a classical assertion logic) with a form of local reasoning in the style of separation logic. Rather than modeling the heap of a program as a single monolithic map H:heap from locations of type **ref** a to values of type a, the linear maps methodology advocates partitioning the heap H into several fragments $H_1, \ldots, H_n$ where the fragments have disjoint domains. Each H_i is a linear map, and the disjoint domain condition ensures that modifications to H_i leave all the other H_j unmodified. This allows formulating a kind of frame rule for programs that use linear maps. Since the assertion logic remains classical, linear map programs can be automatically verified using standard provers and SMT solvers.

The listing below shows a fragment of code that models a heap as a map from references of type **ref** a to values of type a. In addition to abstract types heap and **ref**, we provide two logical values Select and Update. We use the **assume** construct to provide axioms that interpret Select/Update in the theory of functional arrays, in the style of McCarthy (1962).

```
type heap :: ⋆
type ref :: ⋆⇒ ⋆
logic val Select : ref a → heap → a
logic val Update : ref a → a → heap → heap
assume ∀h x v. Select x (Update x v h) = v
assume ∀h x y v. not (x=y) ⟹ Select y (Update x v h) = Select y h
```

Heaps are total maps from references to values. To partition them into disjoint fragments, we need to keep track of the set of references in the domain of each fragment. For this, we provide another abstract type, locset, with a signature (below) that includes the set operations with their usual interpretation.

```
type locset
logic val Empty: locset
logic val Singleton: ref a → locset
logic val (∪): locset → locset → locset
logic val (\): locset → locset → locset
type (∈): ref a ⇒ locset ⇒ E
```

The type of linear maps, lin, is a record of a heap and a locset, and introduces the fourth base kind in F*: the kind A of affine types. To enforce the disjoint domains invariant on linear maps, Lahiri *et al.* require that linear maps be neither copied nor aliased. This directly corresponds to affinity in F*: values of affine type can be used *at most once*.

```
type lin :: A = {map:heap; domain:locset}
```

(We rely on the usual ML syntax for records, formally treated as data constructors.) We show below the types of four operations on linear maps. The first, newlin, allocates a new linear map with an empty domain. The read function reads a location x:**ref** a out of a map m1 (such that x is in the domain of m1), and returns the value y:a stored at x. Since m1 is affine, read threads m1 back to the caller as m2, with a refinement that states that it is unchanged. The write function is similar; in both cases the Select and Update predicates specify the appropriate post-conditions. A fourth function, transfer, allows moving a reference x from the domain of one linear map into another, while preserving the disjoint domains invariant.

```
val newlin: unit → m:lin{m.domain=Empty}
val read: x:ref a → m1:lin{x ∈ m1.domain} → (y:a ∗ m2:lin{m2=m1 && y=Select x m1.map})
val write: x:ref a → y:a → m1:lin{x ∈ m1.domain} → (u:unit ∗ m2:lin{m2.domain=m1.domain ∧
                                                                       m2.map=Update x y m1.map})
val transfer: m1:lin → m2:lin → x:ref a{x ∈ m1.domain}
          → (m1':lin ∗ m2':lin{m1'.map=m1.map ∧
                                m1'.domain=m1.domain \ Singleton x ∧
                                m2'.map=Update x (Select x m1.map) m2.map ∧
                                m2'.domain=m2.domain ∪ Singleton x})
```

While seemingly unremarkable, by refining affine values, the types above are a significant advance over prior languages with substructural and dependent types. In systems like Fine and Linear LF (Cervesato & Pfenning 2002), for instance, types are required to be free of affine (or linear) indices, i.e., type constructors of kind $\mathsf{t} \Rightarrow \mathsf{k}$, where $\mathsf{t}::A$ are forbidden. There are several reasons for this restriction in prior systems. Most prominently, expressing properties of affine values using concrete refinements requires constructing proof terms, hence consuming those affine resources. While there are ways to work around this restriction (Borgstrom *et al.* 2011), they involve relatively complex whole-program transformations.

A key innovation of F* is to use the E kind to freely state properties on affine values. Since E-kinded predicates have no runtime significance, indexing them with affine values does not consume them—in F*, kinds of the form $\mathsf{t} \Rightarrow E$ are permitted, even when $\mathsf{t}::A$. In our example, we use affine indexes on E-kinded types to state pre- and post-conditions using ghost refinements. When modeling linear maps programs, the dynamic log of assumptions is constant (unlike when modeling DOM programs and cryptography) so the metatheory of F* guarantees that refinement formulas in pre- and post-conditions are derivable from the axiomatization of linear maps alone.

We defer further discussion of affine indexed types until §5, where we use them with higher-rank E-kinded types to model concurrent, message passing programs.

2.6 Selective erasure using concrete and ghost refinements

Our overview of ghost refinements may lead the reader to believe that they are always to be preferred to refinements with concrete proof terms. This section finally illustrates that concrete proof terms are useful too, particularly when one is allowed to compute over these terms, to store them, and to communicate them over the network.

The example discussed here is an excerpt from a larger program that models a database of scientific experiments, where each record contains a proof term indicating the *provenance* of the experiment and its *validity*, according to some custom notion of validity. The full example brings together several elements, including the use of cryptography with a simple modal logic to authenticate experimental observations. For brevity, we focus on just one aspect, the selective erasure and reconstruction of proofs, which may be required both for efficiency and for confidentiality. This example is related to work by Guts *et al.* (2009), who show how to build cryptographic audit trails that can be verified by independent third parties. Also related is the work of Vaughan *et al.* (2008), who argue that logs of logical evidence could also build audit trails. However, neither consider the combination of mobile logical and cryptographic proofs, augmented with selective erasure and reconstruction.

Each experiment recorded in the database is given the type exp b, where b is a boolean, explained shortly. The record contains an optional primary key field xid:option int; a field r:expsetup that defines what ingredients were used in the experiment; and a concrete proof term, of type proof b (Valid r), that contains evidence recording the relationship of this experiment to others in the database. Intuitively, this proof term reflects the provenance of the experiment.

```
type expsetup = list {reagent:string; quantity:int}
type Valid :: expsetup ⇒ E
type exp (b:bool) = (xid:option int ∗ r:expsetup ∗ proof b (Valid r))
```

The type proof b t represents a value from a proof kernel defining a custom logic tailored to this specific application—another instance of logic parametricity in F*. We show a selection of the constructors from this kernel below.

```
let full, partial = true, false
type proof :: bool ⇒ E ⇒ P =
| AndIntro: ... | AndElim1 : ... | ...
| ChemicalVolcano: proof full (Valid[{reagent="(NH4)2Cr2O7"; ...}])
| Combine: r1:expsetup → r2:expsetup → r3:expsetup → b:bool
        → proof b (And (Union r1 r2 r3) (And (Valid r1) (Valid r2)))
        → proof b (Valid r3)
| Prune: r:expsetup{Valid r} → xid:int → proof partial (Valid r)
```

The interplay between ghost and concrete proofs is central in this example—it enables proof terms to be *selectively erased* and later *reconstructed*. This allows us to maintain compact, yet detailed and reliable provenance trails. The type proof full (Valid r) represents a fully explicated proof of Valid r, with no selective erasure applied. In contrast, values of type proof partial (Valid r) may have been partially erased—these values are not guaranteed to carry a complete provenance for the experiment setup r.

The constructors in the kernel include axioms for basic connectives and axioms like ChemicalVolcano which state the validity of some well-known experiments. Axioms like Combine allow new valid experiments to be constructed from other valid ones. The most interesting constructor is Prune, which allows a ghost refinement of the validity of an experiment (r:expsetup{Valid r}) to be traded for a concrete proof term for the validity. To allow proofs to be reconstructed, Prune takes an extra argument, xid:int, the primary key of a record in the database that holds the complete provenance for r.

We give below the typed interface to our database. The database content db is simply a list of experiments with full proofs. It supports operations to insert new experiments (returning a freshly generated key); to lookup using the primary keys; and, using lookupProof to look up just the provenance trail of a particular experiment setup, using a primary key for the experiment.

```
type db = list (exp full)
val insert: exp full → int
val lookup: xid → option (exp full)
val lookupProof: r:expsetup → xid:int → optionP (proof full (Valid r))
```

(Since proof full (Valid r) has kind P, we use a variant of the option type in the result of lookupProof, with a constructor optionP :: $P \Rightarrow \star$ instead of the standard option :: $\star \Rightarrow \star$.)

We implement a client-facing interface to the database that wraps the basic lookup and insert operations. On outbound request, we lookup an experiment by its primary key.

Rather than communicating a (potentially large) proof term with explicit provenance to the requestor, we erase the proof (using Prune) and send only a partial proof to the caller, recording the primary key xid in the proof term for later reconstruction—in our full implementation, rather than simply sending a Prune node, we send an authenticated proof term, signed under a key for the database, so that a requestor that trusts the database can still conclude that the returned experiment is indeed valid.

```
(∗ Erasing outbound proofs ∗)
assume ∀(b:bool) (r:expsetup) (pf:proof b (Valid r)). b=full ⟹ Valid r
let readExp xid : option (exp partial) =
  match lookup xid with
    | Some (xid, r, pf) → Some (xid, r, Prune r xid)
    | None → None
```

To apply the Prune constructor, we must prove that r has type r:expsetup{Valid r}. Although pf is full proof of Valid r, we cannot use pf directly to derive ghost refinement formulas. To connect concrete and ghost refinements, we introduce the assumption above. Given the soundness of the proof kernel, this assumption is admissible, and the type of Prune ensures that the database program never introduces partial proofs for experiments that do not have a valid provenance trail. Despite the fact that the Valid r type has no inhabitants, the introduction of this assumption does not lead to logical inconsistency. Formally, assumptions are simply recorded as effects in the log, and do not produce values that can be destructed, say, via pattern matching.

Conversely, on requests to insert new records in the database, we can reconstruct proofs. The function expand below traverses the structure of a proof tree and expands Prune nodes by looking them up in the database. The database maintains an invariant that each record has a full proof and thus a fully explicated provenance trail, ensured via type soundness.

```
(∗ Reconstructing proof terms on inbound requests ∗)
let rec expand (c:bool) (pf:proof c a ) : optionP (proof full a ) =
  if c=full then SomeP pf
  else match pf with
    | Prune r xid → lookupProof r xid
    | AndElim1 c1 pf → (match expand c1 pf with
                         | SomeP pf' → SomeP (AndElim1 full pf')
                         | _ → NoneP)
    | ...
(∗ Inserting a new record in the DB ∗)
let insertExp (r:expsetup) (c:bool) (pf: proof c (Valid r)) =
  match (expand c pf) with
    | SomeP pf' → Some (insert (None, r, pf'))
    | _ → None
```

The function expand is, in effect, a partial, effectful proof-search procedure. Despite the use of non-termination and effects, the type system guarantees that if this function terminates and returns SomeP pf, then pf is indeed a valid full proof in the P-fragment, F*'s logically consistent fragment of total functions.

3 Syntax and semantics of F*

This section presents the syntax and semantics of F*. We focus on five main themes: (1) the stratification into expressions, types, and kinds with the ability to describe functional dependences at each level; (2) the use of kinds to isolate sub-languages for proofs, computations, specifications, and affinity; (3) relating logical effects described using ghost refinements to propositions witnessed by proof terms; (4) logic parametricity, allowing us to plug-in proof kernels and automated decision procedures for the logics they define; and (5) the consistency of a core universe of propositions, via normalization, and the ability to program over its values, to support applications with mobile proofs and selective erasure.

3.1 Syntax

The syntax of F* is shown in Figure 1, starting with our meta-variable convention. We use α to range over type variables a and value variables x. We have two forms of value constructors D: we use C for data constructors (like None and Some) and L for term constructors in the logic (like **logic val** Select and **logic val** Update of §2.5). We also let τ range over both types t and values v. We use the notation $\bar{\iota}$ to stand for a finite sequence of elements $\iota_0, \ldots, \iota_{n-1}$, for any $n \geq 0$, and write $(\bar{\iota})_k$ for the sub-sequence $\iota_0, \ldots, \iota_{k-1}$.

Values v include variables x, memory locations ℓ, lambda abstractions over values and types, and fully applied polyadic data constructors applied to a sequence of values and types. The value v^ℓ is a technical device used to prove the soundness of affine typing—ℓ is an identifier drawn from a class of names distinct from value and type names.

We adopt a (partially) let-normalized view of the expression language e, in particular requiring function arguments (in $e\ v$) to always be values—this is convenient when using value-dependent types, since it ensures that expressions never escape into the level of types. Most of the constructs are standard, including value and type applications; let-bindings; n-ary pattern matching; operations to allocate, read and write references; and exception raising and handling. The only non-standard expression form is **assume** ϕ, which has the effect of adding a formula to the log and is explained in §3.3.

Types are ranged over by meta-variables t and ϕ—we use ϕ for types that stand for logical formulas. Types include variables a; constants T; dependent functions ranging over values whose domains may be values ($x{:}t \to t'$) or types ($\forall a{::}\kappa.t$); types applied to values ($t\ v$) and to types ($t\ t'$); type-level functions from values to types ($\lambda x{:}t.t'$, concretely written **fun** (x:t) $\rightarrow$t') and from types to types ($\Lambda a{::}k.t$, concretely written **fun** (a::k) $\rightarrow$t); ghost refinements $x{:}t\{\phi\}$; and, finally, coercions to affine types $¡t$. This modal operator $¡\cdot$ serves to qualify the type of a closure that captures an affine assumption; we include $¡t$ in the formalism to avoid duplicating the rules for function arrows, but concretely we write affine function types as x:t >> t$'$ and $\forall$a::k >> t instead of $¡(x{:}t \to t')$ and $¡(\forall a{::}\kappa.t)$.

Kinds κ include the four base kinds $\star$, P, A, and E—we distinguish the first three of these as *concrete kinds*, since they are the minimal kinds of types that are inhabited. As at the type level, we have kinds for dependent function spaces whose ranges are types and whose domains may be either values ($x{:}t \Rightarrow \kappa$) or types ($a{::}\kappa \Rightarrow \kappa'$). Stratifying the language into terms, types, and kinds allows us to place key restrictions (discussed below) that facilitate automated verification, and to compile efficiently to .NET. However, stratification does come at a cost—several pieces of technical machinery are replicated across the levels.

Signatures S are finite lists of logic value declarations and datatype definitions. A logic value declaration introduces a logical value constructor, $L : t$. The interpretation of this function symbol (if any) is provided by axioms introduced using **assume**. Each datatype

Meta-variables

α	$::=$	$a \mid x$	type and value variables
D	$::=$	$C \mid L$	data constructor and logic value
τ	$::=$	$v \mid t$	type or value
v	$::=$	$x \mid \ell \mid \lambda x{:}t.e \mid \Lambda a{::}\kappa.e \mid D\ \bar{\tau} \mid v^{\ell}$	values
e	$::=$	$v \mid e\ v \mid e\ t \mid$ **let** $x = e$ **in** $e' \mid$ **match** v **with** $\bar{p}$	expressions
	$\mid$	**ref** $t\ v \mid v_1 := v_2 \mid\ !v \mid$ **raise** $v \mid$ **try** e **with** $x.e \mid$ **assume** ϕ	
p	$::=$	"$\mid$" $C\ \bar{\alpha} \to e$	pattern branches
t, ϕ	$::=$	$a \mid T \mid x{:}t \to t' \mid \forall a{::}\kappa.t \mid t\ v \mid t\ t' \mid \lambda x{:}t.t' \mid \Lambda a{::}\kappa.t \mid x{:}t\{\phi\} \mid$ ¡t	types
c	$::=$	$\star \mid P \mid A$	concrete kinds
b	$::=$	$c \mid E$	base kinds
κ	$::=$	$b \mid x{:}t \Rightarrow \kappa \mid a{::}\kappa \Rightarrow \kappa'$	kinds
S	$::=$	$\cdot \mid L{:}t \mid T{::}\kappa\{\overline{C{:}t}\} \mid S, S'$	signatures
Γ	$::=$	$\cdot \mid \ell{:}t \mid x{:}t \mid a{::}\kappa \mid v_1 = v_2 \mid t_1 = t_2 \mid \Gamma, \Gamma'$	type environments
X	$::=$	$\cdot \mid \ell \mid \alpha \mid X, X'$	affine environments

Fig. 1. Syntax of F*

definition $T{::}\kappa\{\overline{C{:}t}\}$ introduces a type constructor T of kind κ and all its value constructors $C_1{:}t_1, \ldots, C_n{:}t_n$. For simplicity, we do not include mutually recursive types here, although they are supported by our implementation as well as in our Coq formalization. We do not need a fixpoint form in expressions since (as illustrated in §2.1) recursive datatypes allow us to encode recursive functions. To show that terms given P-kinded types are normalizing, a well-formedness condition on signatures imposes a positivity constraint on definitions for P-kinded types to ensure they are inductive. An additional constraint on signatures is that they must contain a declaration `unit`$::\star\{()$:`unit`$\}$ for the `unit` type and its one value (); the **ref** $:: \star \Rightarrow \star$ type constructor; and a definition of the datatype `exn` for exceptions.

Typing environments Γ track in-scope value variables (x with type t), type variables (α with kind κ), and equivalences between values ($v_1 = v_2$) and types ($t_1 = t_2$) introduced when checking **match** expressions. Additionally, Γ includes bindings for memory locations ℓ (which arise at runtime). We also show the syntax of affine environments X, a set of names, where X, X' denotes disjoint union.

3.2 The F* *type system*

We now present the F* type system, which takes the form of several mutually recursive judgments. The three main judgments defined well-formedness rules for kinds, kinding rules for types, and typing rules for values and expressions. In conjunction with these, we provide two subsumption judgments, one each for a sub-kinding and a sub-typing relation, as well as two conversion judgments, equating kinds and types (respectively) that are related by reduction or by equations in the environment. Finally, we have several auxiliary judgments for the well-formedness of signatures, environments, and runtime configurations.

Well-formedness of kinds. Figure 2 defines the judgment $S;\Gamma \vdash \kappa\ \ \mathrm{ok}(b)$, which states that κ is well-formed and is the kind of a constructor of b-kinded types. The rule (OK-b) is for

$$\boxed{S;\Gamma\vdash\kappa\ \text{ok}(b)}\qquad \text{OK-b}\ \frac{\vdash S;\Gamma\ \text{wf}}{S;\Gamma\vdash b\ \text{ok}(b)}$$

$$\text{OK-KK}\ \frac{S;\Gamma\vdash\kappa_1\ \text{ok}(b_1)\qquad b_2\in\{A,E\}\ \text{if}\ b_1=A\qquad S;\Gamma,a{::}\kappa_1\vdash\kappa_2\ \text{ok}(b_2)}{S;\Gamma\vdash a{::}\kappa_1\Rightarrow\kappa_2\ \text{ok}(b_2)}$$

$$\text{OK-TK}\ \frac{S;\Gamma\vdash t{::}b_1\qquad b_2=E\ \text{if}\ b_1=A\qquad S;\Gamma,x{:}t\vdash\kappa\ \text{ok}(b_2)}{S;\Gamma\vdash x{:}t\Rightarrow\kappa\ \text{ok}(b_2)}$$

$$\boxed{S;\Gamma\vdash t::\kappa}\qquad \text{K-}a\ \frac{\vdash S;\Gamma\ \text{wf}}{S;\Gamma\vdash a::\Gamma(a)}\qquad \text{K-T}\ \frac{\vdash S;\Gamma\ \text{wf}}{S;\Gamma\vdash T::S(T)}\qquad \text{K-A}\ \frac{S;\Gamma\vdash t::\star}{S;\Gamma\vdash {¡}t::A}$$

$$\text{K-}\!\rightarrow\ \frac{\begin{array}{c}S;\Gamma\vdash t::c\qquad S;\Gamma,x{:}t\vdash t'::c'\\ b=P\ \text{if}\ c'=P\ \text{and}\ b=\star\ \text{otherwise}\end{array}}{S;\Gamma\vdash x{:}t\rightarrow t'::b}\qquad \text{K-}\forall\ \frac{\begin{array}{c}S;\Gamma\vdash\kappa\ \text{ok}(b)\qquad S;\Gamma,a{::}\kappa\vdash t::c\\ b=P\ \text{if}\ c=P\ \text{and}\ b=\star\ \text{otherwise}\end{array}}{S;\Gamma\vdash\forall a{::}\kappa.t::b}$$

$$\text{K-}\phi\ \frac{S;\Gamma\vdash t::c\qquad S;\Gamma,x{:}t\vdash\phi::E}{S;\Gamma\vdash x{:}t\{\phi\}::c}\qquad \text{K-}\lambda\ \frac{S;\Gamma\vdash x{:}t\Rightarrow\kappa\ \text{ok}(b)\qquad S;\Gamma,x{:}t\vdash t'::\kappa}{S;\Gamma\vdash\lambda x{:}t.t'::x{:}t\Rightarrow\kappa}$$

$$\text{K-Tv}\ \frac{S;\Gamma\vdash t::x{:}t'\Rightarrow\kappa\qquad S;\Gamma;.\vdash^{\varepsilon}v:t'}{S;\Gamma\vdash t\ v::\kappa[v/x]}\qquad \text{K-}\Lambda\ \frac{S;\Gamma\vdash a{::}\kappa\Rightarrow\kappa'\ \text{ok}(b)\qquad S;\Gamma,a{::}\kappa\vdash t::\kappa'}{S;\Gamma\vdash\Lambda a{::}\kappa.t\ ::\ a{::}\kappa\Rightarrow\kappa'}$$

$$\text{K-tt}\ \frac{S;\Gamma\vdash t::a{::}\kappa\Rightarrow\kappa'\qquad S;\Gamma\vdash t'::\kappa}{S;\Gamma\vdash t\ t'\ ::\ \kappa'[t'/a]}\qquad \text{K-<:}\ \frac{S;\Gamma\vdash t{::}\kappa\qquad S;\Gamma\vdash\kappa<:\kappa'\qquad S;\Gamma\vdash\kappa'\ \text{ok}(b)}{S;\Gamma\vdash t::\kappa'}$$

$$\boxed{S;\Gamma\vdash\kappa_1<:\kappa_2}\qquad \text{SK-Refl}\ \frac{S;\Gamma\vdash\kappa\equiv\kappa'}{S;\Gamma\vdash\kappa<:\kappa'}\qquad \text{SK-Trans}\ \frac{S;\Gamma\vdash\kappa<:\kappa_1\qquad S;\Gamma\vdash\kappa_1<:\kappa'}{S;\Gamma\vdash\kappa<:\kappa'}$$

$$\text{SK-P-E}\ \frac{}{S;\Gamma\vdash P<:E}\qquad \text{SK-}\star\text{-E}\ \frac{}{S;\Gamma\vdash\star<:E}\qquad \text{SK-A-E}\ \frac{}{S;\Gamma\vdash A<:E}$$

$$\text{SK-TK}\ \frac{S;\Gamma\vdash t'<:t\qquad S;\Gamma,x{:}t'\vdash\kappa<:\kappa'}{S;\Gamma\vdash x{:}t\Rightarrow\kappa<:x{:}t'\Rightarrow\kappa'}\qquad \text{SK-KK}\ \frac{S;\Gamma\vdash\kappa_1'<:\kappa_1\qquad S;\Gamma,a{::}\kappa_1'\vdash\kappa_2<:\kappa_2'}{S;\Gamma\vdash a{::}\kappa_1\Rightarrow\kappa_2<:a{::}\kappa_1'\Rightarrow\kappa_2'}$$

$$\boxed{S;\Gamma\vdash\kappa\equiv\kappa'}\qquad \text{KE-Refl}\ \frac{}{S;\Gamma\vdash\kappa\equiv\kappa}\qquad \text{KE-Prod}\ \frac{S;\Gamma\vdash t\equiv t'\qquad S;\Gamma,x{:}t\vdash\kappa\equiv\kappa'}{S;\Gamma\vdash x{:}t\Rightarrow\kappa\equiv x{:}t'\Rightarrow\kappa'}$$

$$\text{KE-Sym}\ \frac{S;\Gamma\vdash\kappa'\equiv\kappa}{S;\Gamma\vdash\kappa\equiv\kappa'}\qquad \text{KE-ProdK}\ \frac{S;\Gamma\vdash\kappa_1\equiv\kappa_1'\qquad S;\Gamma,a{::}\kappa_1\vdash\kappa_2\equiv\kappa_2'}{S;\Gamma\vdash a{::}\kappa_1\Rightarrow\kappa_2\equiv a{::}\kappa_1'\Rightarrow\kappa_2'}$$

Fig. 2. Well-formedness of kinds, well-kinded types, sub-kinding, and kind conversion

base kinds. As in all other judgments, we require the leaves of a derivation to ensure that the environment is well-formed, using the judgment $\vdash S;\Gamma$ wf, discussed shortly. The rule (OK-TK) shows a key enhancement of F* over prior languages, e.g., Fine or Linear LF. Types can be constructed from affine values ($b_1=A$), so long as the type constructed is purely specificational ($b_2=E$). As illustrated in §2.5 and §5, this improves the expressiveness of affine typing significantly, enabling refinements on affine state. (OK-KK) is also an enhancement over Fine to allow dependences and to ensure that types parameterized by affine types are themselves affine. Although our formalism allows higher-kinds like $(\star\Rightarrow\star)\Rightarrow\star$, such kinds cannot easily be compiled to the type system of the .NET bytecode language and are currently rejected by our compiler if the target platform is .NET. However, F* programs can also be compiled to JavaScript (Fournet *et al.* 2013), with full type erasure, in which case this form of higher kinding is allowed.

Kinding of types. The judgment $S;\Gamma \vdash t :: \kappa$ (also in Figure 2) states that type t has kind κ. The rules (K-a) and (K-T) are straightforward. The rule (K-A) shows how the modal operator coerces the kind of a type. (K-$\rightarrow$) handles dependent function arrows, which (as seen in §2.1) can be used to represent both quantified formulas in the logic and term-level function abstractions; a function arrow is P-kinded if its range type is P-kinded. The rule for type functions (K-$\forall$) is similar. (K-ϕ) requires that formulas in ghost refinements be erasable (E-kinded). Formulas in ghost refinements are erased at runtime and refinements apply only to types given concrete kinds c (the first premise of (K-ϕ)), i.e., inhabitable types. Value-to-type functions are introduced either using (K-λ) or as type constructors T in the signature. They are eliminated using (K-Tv), which allows a type function t to be applied to a value v. Type-to-type functions are introduced using (K-Λ) and eliminated using (K-tt). Both elimination forms are dependent, i.e., the co-domain depends on the value or type argument. The rule (K-Tv) is worth closer study. Recall that we wish to allow affine values to be freely used at the type level, since specifications should not consume affine resources. For this reason, the values passed to type functions may use affine assumptions in the context Γ—the restrictions imposed by (OK-TK) ensure that such uses of affine assumptions at the type level cannot influence term-level reduction. The second premise of (K-Tv) uses the expression typing judgment, discussed shortly. This judgment has two modes ($m ::= \cdot \mid \varepsilon$) indicated on the turnstile. When the mode is ε (indicating that the term being typed occurs at the type-level, effectively as an index of an E-kinded type), affine assumptions in the context can be freely duplicated without resulting in their consumption. We discuss how this works shortly, in the context of the expression typing judgment.

Finally, Figure 2 shows a subsumption rule (K-<:) and the judgment $S;\Gamma \vdash \kappa <: \kappa'$. The latter is a reflexive and transitive relation, which treats all concrete kinds as a sub-kind of E, but otherwise unrelated to one another. This differs from an earlier formulation of the system presented by Swamy *et al.* (2011), which included $P <: \star$. While that is feasible, and allows more code re-use between $\star$ and P (e.g., we could simply re-use the option type for proofs, instead of a separate optionP type in §2.6), as discussed in §4.3, the current formulation enables a significantly cleaner proof of normalization for the P-fragment. Given our experience programming, to date, some 50,000 lines of code in F*, we concluded that the penalty we pay in terms of code duplication by forbidding $P <: \star$ is worthwhile for the improved metatheoretical development. Another difference is that we now include $A <: E$, an improvement over our prior work to promote re-use of specifications between affine and non-affine values.

The rest of the rules in the sub-kinding relation are homomorphic with respect to the sub-typing ($S;\Gamma \vdash t <: t'$, Figure 4, discussed shortly) and sub-kinding relations. Kind conversion, $S;\Gamma \vdash \kappa \equiv \kappa'$ is a straightforward equivalence relation. Technically, (K-<:) includes premises to ensure that sub-kinding preserves well-formedness of kinds. We conjecture that these premises can be eliminated in favor of lemmas establishing that sub-kinding never introduces ill-formed kinds. We have yet to prove it, so we include these premises to facilitate our formal proof of well-formedness of kinds produced by derivations.

Expression typing. Figure 3 defines the judgment $S;\Gamma;X \vdash^m e : t$, which states that expression e has type t, under signature S, environment Γ, and an affine environment X. A well-formedness condition on contexts requires that all variables in X be also bound in Γ. The context X represents a set of available affine assumptions, and usual context splitting rules apply to X when typing the sub-terms of an expression. (As in Fine, we choose not to split Γ itself, since this complicates well-formedness of contexts in the presence of dependent types.) Finally, as mentioned above, expression typing comes in two modes, indicated on the turnstile. We find it syntactically convenient to allow X to contain value names x, affine labels ℓ as well as type names a, although affinity restrictions do not apply to type names. We discuss each of the rules in detail, next.

Affinity. (T-XA) is typical of affine typing systems: to use an affine assumption x, we require x to be present in the affine environment X. (T-X) provides two alternatives to rule (T-XA): first, as usual, we can use non-affine assumptions without requiring them to be present in X. Second, when the mode is ε, we are typing a term at the level of types; since this does not consume the affine resource, we are free to use it even when X is empty. (T-Drop) provides weakening for the affine context. (T-Box) is for typing values that have been tagged with an affine label—we discuss it in detail after presenting the dynamic semantics.

Data and logic values. (T-D) types a constructor as a function application, by introducing a fresh variable x at the type of D in the context. The third premise ($t = T\ \_$) ensures that the constructor is fully applied, and the last premise ensures that if the constructor is a logic value, then it is used only at the type level since logic values have no operational interpretation.

Function abstraction and application. (T-Abs) and (T-TAbs) are standard rules for value- and type-abstractions, except that the introduced function type is tagged with the affine modality (using $Q(X, x{:}t \to t')$) if the function closure captures an affine assumption. This is achieved using the auxiliary function Q defined at the bottom of the figure. The corresponding elimination forms (T-App) and (T-TApp) are shown next. We split the affine context between the sub-expressions (if any), check each part, and then substitute the argument for the formal parameter in the result type. In the second premise of both rules, we use the auxiliary function $!t$ to strip an affine modality from t, if there is one.

Let-bindings. (T-Let) is a variation on the standard rules for let bindings that ensures that expressions with P-kinded types are total. Intuitively, for an expression e to reside in P, e must be free of non-P expressions, since those may diverge. Thus, the rule has a final premise to ensure that if the result type is in P, then the let-bound expression must also be in P. The third premise also serves to ensure that the let-bound variable does not escape its scope, and the first premise employs syntactic sugar (defined at the bottom of the figure) to compute the kind κ_1 of t_1. We can treat **let**-bound values **let** x = v **in** e simply as sugar for (λx:t. e) v, for some t. This allows non-P values to be let-bound in a P term, since the values are already reduced.

Exceptions and state. The stratification of F* into sub-languages makes it easy to provide primitive support for arbitrary effects. We illustrate this here using exceptions and mutable

$$\text{T-XA}\ \frac{\vdash S;\Gamma\ \text{wf} \qquad S;\Gamma \vdash \Gamma(x) :: A}{S;\Gamma;x \vdash x : \Gamma(x)} \qquad \text{T-X}\ \frac{\vdash S;\Gamma\ \text{wf} \qquad S;\Gamma \vdash \Gamma(x){::}b \qquad m = \varepsilon \text{ if } b = A}{S;\Gamma;. \vdash^m x : \Gamma(x)}$$

$$\text{T-Drop}\ \frac{S;\Gamma;X \vdash^m e : t}{S;\Gamma;X,X' \vdash^m e : t} \qquad \text{T-Box}\ \frac{S;\Gamma;X \setminus \ell \vdash^m v : t \qquad S;\Gamma \vdash t :: A \qquad \ell \in X \text{ or } m = \varepsilon}{S;\Gamma;X \vdash^m v^\ell : t}$$

$$\text{T-D}\ \frac{D{:}t_d \in S \qquad S;\Gamma,x{:}t_d;X \vdash^m x\ \bar{\tau} : t \qquad t = T\ \_ \qquad D = C \text{ or } m = \varepsilon}{S;\Gamma;X \vdash^m D\ \bar{\tau} : t}$$

$$\text{T-Abs}\ \frac{S;\Gamma \vdash t{::}c \qquad S;\Gamma,x{:}t;X,x \vdash^m e : t'}{S;\Gamma;X \vdash^m \lambda x{:}t.e : Q(X, x{:}t \to t')} \qquad \text{T-TAbs}\ \frac{S;\Gamma \vdash \kappa\ \text{ok}(b) \qquad S;\Gamma,a{::}k;X \vdash^m e : t}{S;\Gamma;X \vdash^m \Lambda a{::}\kappa.e : Q(X, \forall a{::}k.t)}$$

$$\text{T-App}\ \frac{\begin{array}{c} S;\Gamma;X_1 \vdash^m e : t_1 \\ !t_1 = x{:}t' \to t \qquad S;\Gamma;X_2 \vdash^m v : t' \end{array}}{S;\Gamma;X_1,X_2 \vdash^m e\ v : t[v/x]} \qquad \text{T-TApp}\ \frac{\begin{array}{c} S;\Gamma;X \vdash^m e : t_v \\ !t_v = \forall a{::}\kappa.t' \qquad S;\Gamma \vdash t :: \kappa \end{array}}{S;\Gamma;X \vdash^m e\ t : t'[t/a]}$$

$$\text{T-Let}\ \frac{S;\Gamma;X_1 \vdash^m e_1 : t_1(\kappa_1) \qquad S;\Gamma,x{:}t_1;X_2,x \vdash^m e_2 : t_2 \qquad S;\Gamma \vdash t_2 :: \kappa_2 \qquad \kappa_1 = P \text{ if } \kappa_2 = P}{S;\Gamma;X_1,X_2 \vdash^m \mathbf{let}\ x = e_1\ \mathbf{in}\ e_2 : t_2}$$

$$\text{T-Try}\ \frac{S;\Gamma;X_1 \vdash^m e_1 : t \qquad S;\Gamma,x{:}\mathsf{exn};X_2 \vdash^m e_2 : t \qquad S;\Gamma \vdash t :: \star}{S;\Gamma;X_1,X_2 \vdash^m \mathbf{try}\ e_1\ \mathbf{with}\ x.e_2 : t}$$

$$\text{T-Raise}\ \frac{S;\Gamma;X \vdash^m v : \mathsf{exn} \qquad S;\Gamma \vdash t :: \star}{S;\Gamma;X \vdash^m \mathbf{raise}\ v : t} \qquad \text{T-Rd}\ \frac{S;\Gamma;X \vdash^m v : \mathbf{ref}\ t}{S;\Gamma;X \vdash^m\ !\ v : t}$$

$$\text{T-Ref}\ \frac{S;\Gamma;X \vdash^m v : t \qquad S;\Gamma \vdash t :: \star}{S;\Gamma;X \vdash^m \mathbf{ref}\ t\ v : \mathbf{ref}\ t} \qquad \text{T-Wr}\ \frac{S;\Gamma;X_1 \vdash^m v_1 : \mathbf{ref}\ t \qquad S;\Gamma;X_2 \vdash^m v_2 : t}{S;\Gamma;X_1,X_2 \vdash^m v_1 := v_2 : \mathsf{unit}}$$

$$\text{T-Match}\ \frac{\begin{array}{c} S;\Gamma;X_1 \vdash^m v : t_v(\kappa_v) \qquad S;\Gamma \vdash t :: \kappa_b \qquad \kappa_v = P \text{ if } \kappa_b = P \qquad \text{exhaustive}(S, t_v, \bar{p}) \\ \forall\, C\bar{\alpha} \to e \in \bar{p}.\ \exists \Gamma', t_p, \bar{\tau}, \Gamma_{eq}. \left(\begin{array}{l} \text{dom}(\Gamma') = \bar{\alpha} \quad S;\Gamma';\bar{\alpha} \vdash^m C\ \bar{\alpha} : t_p \quad t_p\ {}_{\bar{\alpha}}{\bowtie}_{\bar{\tau}}\ t_v : \Gamma_{eq} \\ S;\Gamma,\Gamma',\Gamma_{eq}, v = C\ \bar{\alpha};X_2,\bar{\alpha} \vdash^m e : t \end{array} \right) \end{array}}{S;\Gamma;X_1,X_2 \vdash^m \mathbf{match}\ v\ \mathbf{with}\ \bar{p} : t}$$

$$\text{T-V}\ \frac{S;\Gamma;X \vdash^m v : t \qquad S;\Gamma \vdash t :: c \qquad S;\Gamma,x{:}t,x = v \models \phi}{S;\Gamma;X \vdash^m v : x{:}t\{\phi\}} \qquad \text{T-Ax}\ \frac{S;\Gamma \vdash \phi :: E}{S;\Gamma;\cdot \vdash^m \mathbf{assume}\ \phi : \_{:}\mathsf{unit}\{\phi\}}$$

$$\text{T-Sub}\ \frac{S;\Gamma;X \vdash^m e : t' \qquad S;\Gamma \vdash t' <: t \qquad S;\Gamma \vdash t :: \kappa}{S;\Gamma;X \vdash^m e : t}$$

$$\text{where} \left\{ \begin{array}{lll} S;\Gamma;X \vdash^m e : t(\kappa) & \triangleq & S;\Gamma;X \vdash^m e : t \ \wedge\ S;\Gamma \vdash t{::}\kappa \\[1ex] t\ {}_{\cdot}{\bowtie}_{\cdot}\ t : \cdot & \dfrac{\alpha \in FV(t) \qquad t[\tau/\alpha]\ {}_{\bar{\alpha}}{\bowtie}_{\bar{\tau}}\ t' : \Gamma}{t\ {}_{\alpha,\bar{\alpha}}{\bowtie}_{\tau,\bar{\tau}}\ t' : \alpha = \tau, \Gamma} & \dfrac{\alpha \notin FV(t) \qquad t\ {}_{\bar{\alpha}}{\bowtie}_{\bar{\tau}}\ t' : \Gamma}{t\ {}_{\alpha,\bar{\alpha}}{\bowtie}_{\tau,\bar{\tau}}\ t' : \Gamma} \\[1ex] \text{constructors}(S, T\ \bar{\tau}) & \triangleq & \{C_i \mid T{::}\kappa\{\overline{C{:}t}\} \in S \ \wedge\ \exists \bar{\tau}, \Gamma', \bar{\tau}', \Gamma_{eq}.\, \text{dom}\,\Gamma' = \bar{\alpha} \\ & & \qquad \wedge\ S;\Gamma';\cdot \vdash C_i\bar{\alpha} : t \ \wedge\ t\ {}_{\bar{\alpha}}{\bowtie}_{\bar{\tau}'}\ T\ \bar{\tau} : \Gamma_{eq}\} \\ \text{exhaustive}(S, t, \bar{p}) & \triangleq & \text{constructors}(S, t) = \{C \mid C\bar{\alpha} \to e \in \bar{p}\} \\ Q(\cdot, t) & = & t \\ Q(X, t) & = & \text{¡}t \\ !\text{¡}t & = & t \\ !t & = & t \ \text{ otherwise} \end{array} \right.$$

Fig. 3. Well-typed expressions: $S;\Gamma;X \vdash^m e : t$

state—adding other effects is similarly straightforward. The rules from (T-Try) to (T-Wr) are mostly standard; they restrict the use of these constructs to the $\star$-fragment and split the affine contexts between any sub-expressions. The one technical device worth noting is that reference allocation **ref** $t\ v$ takes an explicit type for its value. This simplifies our dynamic semantics and soundness proof, while this type can usually be inferred in practice.

Pattern matching. The next rule, (T-Match), is expectedly the most complex. First, as in (T-Let), we place restrictions on cross-universe elimination to ensure the consistency of the P-fragment. The first premise derives the type of the scrutinee as $t_v{::}\kappa_v$; the second premise derives the kind of t (the type of the branches) as κ_b; and the third premise disallows discriminating values that reside in $\star$ or A when constructing P-kinded expressions in the branches. We describe the exhaustiveness check in the fourth premise shortly. The remaining premises are quantified for each pattern-guarded branch $C\bar{\alpha} \to e$ in $\bar{p}$. For each such branch, we first type the pattern $C\bar{\alpha}$ in a context Γ' that contains only the pattern-bound variables, giving it the type t_p. We then unify the type of the pattern t_p with the type of the scrutinee t_v, given the equations in Γ_{eq}, using the auxiliary judgment $t_p\ {}_{\bar{\alpha}}\!\bowtie_{\bar{\tau}}\ t_v : \Gamma_{eq}$, which ensures that $t_p[\bar{\tau}/\bar{\alpha}] = t_v$ and Γ_{eq} contains equations of the form $\alpha_i = \tau_i$ for those α_i that are free in t_p. The final premise checks the branch body e in a context including the pattern-bound variables, extended with the equations in Γ_{eq} as well as one additional equation between the scrutinee and the pattern. As we will see, these equations are used in $S;\Gamma \vdash t \equiv t'$ to allow typing derivations to freely refine both type and value indices within types. Note also that the affine context is split between the scrutinee and the branches.

The exhaustiveness check (defined at the bottom of the figure) is somewhat subtle. At a high level, exhaustive$(S,t,\bar{p})$ ensures that, for every constructor of the scrutinee type t, there exists at least one pattern in $\bar{p}$ that matches it. The auxiliary function constructors(S,t) computes the set of potential constructors of t, where t must be an application $T\,\bar{\tau}$ of some type constructor T in the signature S. The set of constructors $T\,\bar{\tau}$ is a subset of all the declared constructors $\bar{C}$ of T, namely those whose types (when fully applied) are unifiable with $T\,\bar{\tau}$. Exhaustiveness then demands that the set of these constructors be equal to the set of constructors in the pattern-guarded branches.

The constraints on cross-universe elimination in (T-Let) and (T-Match) are similar to those imposed by Aura on its Prop universe. However, there are several important differences. First, Aura (like Coq) insists on Prop terms being computationally irrelevant, so its match rule forbids cross-universe elimination—Prop terms cannot be eliminated to construct values in Type. We explicitly wish to program over proofs, so F* permits P-to-$\star$ elimination. Next, Aura (unlike F*) does not allow the branches of a match expression to use equality assumptions between the pattern and the scrutinized term. This excludes programming on proof terms, as illustrated in §2.6, which makes essential use of GADT-style programming patterns. (T-Match) also compares favorably with the corresponding rule in Coq. Unlike F*'s call-by-value reductions, Coq supports strong reductions (e.g., reducing terms in a branch without first matching the scrutinee against the pattern), making it difficult to support the automatic refinement of terms in a branch based on the pattern. Providing better support for dependent pattern matching in Coq is an active topic of research, with recent advances reported by Sozeau (2010). F* supports dependent pattern matching with equations natively.

Using (T-Match), we can write and check the following code, providing no branches when destructing the Empty type.

```
type Empty :: P
let contra (ϕ::P) (ff:Empty) : ϕ = match ff with
```

When programming in the $\star$ or A fragment, we often discharge infeasible cases using code that resembles the following snippet (writing type abstractions and applications explicitly here, for clarity):

```
type exn = ... | Impos : exn
type Nat = Z : Nat | S : Nat → Nat
let unreachable (a::⋆) (u:unit{False}) : a = raise Impos
let decr (n:Nat{n ≠ Z}) = match n with Z → unreachable Nat () | S m → m
```

Writing a similar program in the P fragment is only slightly harder, as shown below. Since we cannot raise exceptions in the P fragment, we must work explicitly with inequality proofs to discard the unreachable case.

```
type Seq :: P ⇒ P = Nil : ∀a. Seq a | Cons : ∀a. a → Seq a → Seq a
type Not ϕ = ∀(a::P). ϕ → a
let head (a::P) (s:Seq a) (pf:Not (s=Nil a)) : a = match n with
    | Nil _ → pf a (refl s)
    | Cons _ hd _ → hd
```

Ghost refinements. The rules (T-V), (T-Ax), and the subsumption rule (T-Sub) introduce ghost refinement types. (T-Ax) introduces a unit refined with the assumed formula ϕ; in the refinement, _ stands for a fresh variable. No logical evidence is produced for ϕ. To justify this rule, the dynamic semantics of this expression adds the formula to the dynamic log $\mathscr{A}$. (T-V) allows value v to be refined with the formula ϕ when ϕ is derivable: $S;\Gamma' \models \phi$. The context Γ' includes bindings $x{:}t, x = v$ which allow the derivability relation to use information about v; however, for kind-correctness, since the type in the conclusion has to be well-formed in the context Γ, we require that the kinding of the introduced formula does not rely on the introduced equality.

Subsumption. The judgment $S;\Gamma \vdash t_1 <: t_2$ in Figure 4 shows a reflexive and transitive fully structural subtyping relation on types. The main interesting rules are (ST-Left), which allows a ghost refinement to be dropped on a type, and (ST-Right) which introduces a ghost refinement type. Ghost refinements have no impact on the representation of values, so they admit full structural subtyping, as illustrated by rules like (ST-Prod) which allow co- and contravariant subtyping on functions. In contrast, concrete refinements (i.e., the dependent pairs of Coq, Fine, F*, etc.) do not enjoy structural subtyping, although, via a systematic translation to insert coercions (called *derefinement*), the Fine language provided a weaker, non-structural subtyping relation on concrete refinements.

Subtyping also includes type conversion $S;\Gamma \vdash t_1 \equiv t_2$. This equivalence relation, discussed briefly in conjunction with (T-Match), converts types using equations that appear in the context, and is available everywhere within the structure of types.

Logic parametricity. The rules (TE-V) and (ST-Right) yield logic parametricity for F*. Both those rules have premises that use a judgment $S;\Gamma \models \phi$, a logic derivability relation that can be "plugged in" to the type system, as long as the relation meets a few important admissibility constraints, which we enumerate below.

$$\boxed{S;\Gamma \vdash t <: t'} \quad \text{ST-Refl}\,\frac{S;\Gamma \vdash t \equiv t'}{S;\Gamma \vdash t <: t'} \quad \text{ST-Trans}\,\frac{S;\Gamma \vdash t <: t_1 \qquad S;\Gamma \vdash t_1 <: t'}{S;\Gamma \vdash t <: t'}$$

$$\text{ST-Prod}\,\frac{S;\Gamma \vdash t_1' <: t_1 \qquad S;\Gamma, x{:}t_1' \vdash t_2 <: t_2'}{S;\Gamma \vdash x{:}t_1 \to t_2 <: x{:}t_1' \to t_2'} \quad \text{ST-ProdK}\,\frac{S;\Gamma \vdash \kappa' <: \kappa \qquad S;\Gamma, a{::}\kappa' \vdash t <: t'}{S;\Gamma \vdash \forall a{::}\kappa.t <: \forall a{::}\kappa'.t'}$$

$$\text{ST-Left}\,\frac{S;\Gamma \vdash t <: t'}{S;\Gamma \vdash x{:}t\{\phi\} <: t'} \quad \text{ST-Right}\,\frac{S;\Gamma \vdash t <: t' \qquad S;\Gamma, x{:}t \models \phi'}{S;\Gamma \vdash t <: x{:}t'\{\phi'\}} \quad \text{ST-Afn}\,\frac{S;\Gamma \vdash t <: t'}{S;\Gamma \vdash \text{¡}t <: \text{¡}t'}$$

$$\boxed{S;\Gamma \vdash t \equiv t'} \quad \text{TE-Refl}\,\frac{}{S;\Gamma \vdash t \equiv t} \quad \text{TE-Sym}\,\frac{S;\Gamma \vdash t_2 \equiv t_1}{S;\Gamma \vdash t_1 \equiv t_2} \quad \text{TE-Afn}\,\frac{S;\Gamma \vdash t \equiv t'}{S;\Gamma \vdash \text{¡}t \equiv \text{¡}t'}$$

$$\text{TE-TApp}\,\frac{S;\Gamma \vdash t_1 \equiv t_1' \qquad S;\Gamma \vdash t_2 \equiv t_2'}{S;\Gamma \vdash t_1\ t_2 \equiv t_1'\ t_2'} \quad \text{TE-Prod}\,\frac{S;\Gamma \vdash t_1 \equiv t_1' \qquad S;\Gamma, x{:}t_1 \vdash t_2 \equiv t_2'}{S;\Gamma \vdash x{:}t_1 \to t_2 \equiv x{:}t_1' \to t_2'}$$

$$\text{TE-ProdK}\,\frac{S;\Gamma \vdash \kappa \equiv \kappa' \qquad S;\Gamma, a{::}\kappa \vdash t \equiv t'}{S;\Gamma \vdash \forall a{::}\kappa{::}t. \equiv \forall a{::}\kappa'{::}t'.} \quad \text{TE-Ref}\,\frac{S;\Gamma \vdash t \equiv t' \qquad S;\Gamma, x{:}t \vdash \phi \equiv \phi'}{S;\Gamma \vdash x{:}t\{\phi\} \equiv x{:}t'\{\phi'\}}$$

$$\text{TE-Lam}\,\frac{S;\Gamma \vdash t_1 \equiv t_1' \qquad S;\Gamma, x{:}t_1 \vdash t_2 \equiv t_2'}{S;\Gamma \vdash \lambda x{:}t_1.t_2 \equiv \lambda x{:}t_1'.t_2'} \quad \text{TE-}\beta\,\frac{}{S;\Gamma \vdash (\lambda x{:}t.t')\ v \equiv t'[v/x]}$$

$$\text{TE-T}\beta\,\frac{}{S;\Gamma \vdash (\Lambda a{::}\kappa.t)\ t' \equiv t[t'/a]} \quad \text{TE-T}\,\frac{t = t' \in \Gamma}{S;\Gamma \vdash t \equiv t'} \quad \text{TE-V}\,\frac{S;\Gamma \vdash t \equiv t' \qquad S;\Gamma \models v = v'}{S;\Gamma \vdash t\ v \equiv t'\ v'}$$

Fig. 4. Subtyping and type-conversion

Definition 1 (Admissibility of entailment relation)**.** *The relation $S;\Gamma \models \phi$ is admissible if and only if it is*

(1) *At least the identity on refined assumptions: for all S,Γ,x,t,ϕ, such that $\vdash S;\Gamma,x{:}(x:t\{\phi\})$ wf, we have $S;\Gamma,x{:}(x:t\{\phi\}) \models \phi$.*
(2) *Compatible with type equivalence: for all S,Γ,ϕ,ϕ' such that $\vdash S;\Gamma$ wf and $S;\Gamma \vdash \phi \equiv \phi'$, if x is fresh, then $S;\Gamma,x{:}(x{:}\mathit{unit}\{\phi\}) \models \phi'$.*
(3) *Closed under value substitution: for all $S,\Gamma,x{:}t,\Gamma'$ such that $\vdash S;\Gamma,x{:}t,\Gamma'$ wf, we have $S;\Gamma,x:t,\Gamma' \models \phi \Rightarrow \forall v.S;\Gamma;\cdot \vdash v:t \Rightarrow S;\Gamma,\Gamma'[v/x] \models \phi[v/x]$.*
(4) *Closed under type substitution: for all $S,\Gamma,a{::}\kappa,\Gamma'$ such that $\vdash S;\Gamma,a{:::}\kappa,\Gamma';\cdot$ ok, we have $S;\Gamma,a{::}\kappa,\Gamma' \models \phi \Rightarrow \forall t.S;\Gamma \vdash t :: \kappa \Rightarrow S;\Gamma,\Gamma'[t/a] \models \phi[t/a]$.*
(5) *Closed under weakening: for all $S,\Gamma_1,\Gamma,\Gamma_2$ such that $\vdash S;\Gamma_1,\Gamma_2$ wf and $S;\Gamma_1,\Gamma,\Gamma_2$ wf, we have $S;\Gamma_1,\Gamma_2 \models \phi \Rightarrow S;\Gamma_1,\Gamma,\Gamma_2 \models \phi$.*
(6) *Closed under elimination of derivable value equality: for all S,Γ,v,v',Γ' such that $\vdash S;\Gamma,v=v',\Gamma';\cdot$ ok and $S;\Gamma \vdash v \equiv v'$, we have $S;\Gamma,v=v',\Gamma' \models \phi \Rightarrow S;\Gamma,\Gamma' \models \phi$.*
(7) *Closed under elimination of derivable type equality: for all S,Γ,t,t',Γ' such that $\vdash S;\Gamma,t=t',\Gamma';\cdot$ ok and $S;\Gamma \vdash t \equiv t'$, we have $S;\Gamma,t=t',\Gamma' \models \phi \Rightarrow S;\Gamma,\Gamma' \models \phi$.*
(8) *Entailing only well-kinded formulas: for all S,Γ,ϕ such that $\vdash S;\Gamma$ wf, if $S;\Gamma \models \phi$ then $S;\Gamma \vdash \phi{::}E$.*

Pragmatically, we often plug in a decision procedure for first order logic with additional theories, as implemented by the Z3 theorem prover—the ability to use structural rules (e.g., weakening) in the logic, enabled by our restrictions on affine indices in types, makes

$$\boxed{\vdash S;\Gamma;X\ \ \mathrm{wf}} \quad \frac{\vdash S;\Gamma;X\ \mathrm{wf} \qquad \alpha \notin X}{\vdash S;\Gamma;X,\alpha\ \mathrm{wf}} \quad \frac{\vdash S;\Gamma;X\ \mathrm{wf} \qquad \ell \notin X}{\vdash S;\Gamma;X,\ell\ \ \mathrm{wf}} \quad \frac{\vdash S;\Gamma\ \mathrm{wf}}{\vdash S;\Gamma;\cdot\ \ \mathrm{wf}}$$

$$\boxed{\vdash S;\Gamma\ \ \mathrm{wf}} \quad \frac{S;\Gamma \vdash t :: c \qquad \vdash S;\Gamma\ \ \mathrm{wf} \qquad x \notin \Gamma}{\vdash S;\Gamma,x{:}t\ \ \mathrm{wf}} \quad \frac{S;\Gamma \vdash \kappa\ \mathrm{ok}(b) \qquad \vdash S;\Gamma\ \ \mathrm{wf} \qquad a \notin \Gamma}{\vdash S;\Gamma,a{::}\kappa\ \ \mathrm{wf}}$$

$$\frac{\forall i.S;\Gamma \vdash v_i : t \qquad \vdash S;\Gamma\ \ \mathrm{wf}}{\vdash S;\Gamma,v_1 = v_2\ \ \mathrm{wf}} \quad \frac{\forall i.S;\Gamma \vdash t_i :: k \qquad \vdash S;\Gamma\ \ \mathrm{wf}}{\vdash S;\Gamma,t_1 = t_2\ \ \mathrm{wf}} \quad \frac{\mathsf{exn}{::}\star\{\overline{C{:}t}\} \in S \qquad \vdash S\ \mathrm{wf}}{\vdash S;\cdot\ \ \mathrm{wf}}$$

$$\boxed{\vdash S\ \mathrm{wf}} \quad \frac{}{\vdash \mathsf{unit}{::}\star\{() : \mathsf{unit}\}, \mathbf{ref} :: \star \Rightarrow \star\{\}\ \mathrm{wf}}$$

$$\frac{\vdash S\ \mathrm{wf} \qquad \{T,\overline{D}\} \cap FV(S) = \emptyset \qquad S \vdash T{::}\kappa\{\overline{D{:}t}\}\ \mathrm{ok}}{\vdash S,T{::}\kappa\{\overline{D{:}t}\}\ \mathrm{wf}} \quad \frac{\vdash S\ \mathrm{wf} \qquad L \notin FV(S) \qquad S;\cdot \vdash t :: \star}{\vdash S,L{:}t\ \mathrm{wf}}$$

$$\boxed{S \vdash T{::}\kappa\{\overline{C{:}t}\}\ \mathrm{ok}} \quad \text{T-Ok0}\frac{S \vdash \kappa\ \mathrm{ok}(b)}{S \vdash T{::}\kappa\{\}\ \mathrm{ok}} \quad \text{T-OkN}\frac{S \vdash T{::}\kappa\{D_0{:}t_0\}\ \mathrm{ok} \qquad S \vdash T{::}\kappa\{\overline{D{:}t}\}\ \mathrm{ok}}{S \vdash T{::}\kappa\{D_0{:}t_0,\overline{D{:}t}\}\ \mathrm{ok}}$$

$$\text{T-Ok1}\frac{S;\cdot \vdash \kappa\ \mathrm{ok}(c) \qquad \mathrm{dom}(\Gamma) = \bar{\alpha} \qquad S,T{::}\kappa\{\};\Gamma;\cdot \vdash C\ \bar{\alpha} : T\ \bar{\tau}(c) \qquad S;\cdot \vdash apos(c,T,\Gamma)}{S \vdash T{::}\kappa\{C{:}t\}\ \mathrm{ok}}$$

$$\boxed{S;\Gamma \vdash apos(c,T,\Gamma')} \quad \text{APos-0}\frac{}{S;\Gamma \vdash apos(c,T,\cdot)} \quad \text{APos-T}\frac{S;\Gamma,a{::}\kappa \vdash apos(c,T,\Gamma')}{S;\Gamma \vdash apos(c,T,(a{::}\kappa,\Gamma'))}$$

$$\text{APos-XP}\frac{t = \Gamma_t \to t' \qquad \forall 0 \le i < |\Gamma_t|\,.T \notin FTC(\Gamma_t[i]) \qquad S;\Gamma,x{:}t \vdash apos(P,T,\Gamma')}{S;\Gamma \vdash apos(P,T,(x{:}t,\Gamma'))}$$

$$\text{APos-XA}\frac{S;\Gamma \vdash t :: c' \qquad c \neq P \qquad c' = A \Rightarrow c = A \qquad S;\Gamma,x{:}t \vdash apos(c,T,\Gamma')}{S;\Gamma \vdash apos(c,T,(x{:}t,\Gamma'))}$$

Fig. 5. Well-formed signatures, environments and runtime states

it easy to support automation. Formally, we also exploit logic parametricity to provide an embedding of a formal core of F7 into F*, plugging its entailment relation (which, unlike F*, includes the basic first-order connectives and equality, each satisfying their usual introduction and elimination forms).

Note that inconsistent logics (such that $\models$ False is derivable) are also admissible. In this case, ghost refinement proofs are clearly meaningless, but the P-fragment is unaffected.

Well-formedness of environments. Finally, Figure 5 defines well-formed environments. The first judgment, $\vdash S;\Gamma;X$ wf, is straightforward—it requires the names in X to be distinct, and for $\vdash S;\Gamma$ to be derivable. The latter holds when Γ binds distinct value names x at concrete types, distinct well-kinded type names, well-typed equations, and finally, when S is well-formed. The latter holds, when S binds at least unit, **ref**, and exn and has distinct $\star$-kinded logic value constructors.

Additionally, we have constraints on the well-formedness of datatypes T defined in S, according to the judgment $S \vdash T{::}\kappa\{\overline{C{:}t}\}$ ok. The main rule in the judgment is (T-Ok1), which requires the constructor to be well-typed, to have a concrete kind, and to construct a value whose type is an instance of type T. We also require the constructor to respect affinity restrictions and positivity constraints depending on the kind c of types constructed by T.

This is captured by the last judgment $S;\Gamma \vdash apos(c,T,\Gamma')$. Its main rules, (APos-XP) and (APos-XA), ensure (1) that constructors with affine arguments construct affine results—this is unrelated to totality of P-functions; (2) a positivity constraint on inductive P-kinded types. We use a relatively simple version of positivity that excludes the constructed type T in negative position in any argument of D. (The auxiliary function FTC computes the free type constructors in a type; we omit its standard definition.)

3.3 Dynamic semantics: logical effects and affine names

The dynamic semantics of F*, shown in Figure 6, is a small-step reduction relation for a call-by-value language. The semantics is given in the style of Felleisen & Hieb (1992) using evaluation contexts E and exception frames F. It has the form $(\mathscr{A};e) \rightarrow_S (\mathscr{A}';e')$ where the signature S is unvarying, and a runtime configuration is a pair of a runtime state $\mathscr{A}$ and an expression e. The state $\mathscr{A}$ maintains a set of facts introduced by the dynamic assumption of ghost refinements and a map from reference locations to values. Additionally, $\mathscr{A}$ records affine names in two variants, ℓ or $\hat{\ell}$, which we use to track the usage of affinely typed values. The most interesting part of this relation is the way it maintains a non-decreasing set of logical facts ϕ and names ℓ for affine values in the state $\mathscr{A}$. As mentioned in §2.2, the set of facts in $\mathscr{A}$ is used in the definition of ghost refinement derivability. Facts are added to the log using the **assume** ϕ form, reduced by rule (E-Log).

Foreshadowing our safety condition for ghost refinements (Corollary 1), we show that, when a well-typed program $e : x{:}t\{\phi\}$ reduces to a value, that is $(\cdot;e) \rightarrow_s^* (\mathscr{A};v)$, its refinement formula ϕ is derivable from the signature and all the accumulated logical effects: $S;\mathsf{Facts}(\mathscr{A}) \models \phi[v/x]$. This is in contrast to our soundness result for proof expressions that reside in the P-fragment, for which we obtain a more traditional logical consistency property. In a distributed program, the log is an idealized global view of the logical state of all participants. Ghost refinements accompanied by cryptographic evidence (in the form of digital signatures) enable speaking about this distributed state.

The state $\mathscr{A}$ also tracks affine values. We aim to show that well-typed programs destruct affine values at most once. For this purpose, we instrument the dynamic semantics to tag an affine value v with a fresh name when it is introduced, recording the name in the log (E-Newℓ). Names held in the log come in two variants: names ℓ are "live", while names $\hat{\ell}$ are "dead"—the auxiliary functions $\mathsf{live}(\cdot)$ and $\mathsf{dead}(\cdot)$ collect these names from the state. To introduce a new name, (E-Newℓ) checks if a value has an affine type by reifying the runtime state $\mathscr{A}$ into a typing environment (using $\mathscr{A} \Longrightarrow \Gamma;X$, where environments Γ are generalized to additionally contain bindings for locations ℓ) and typing the value. When v appears in a destructor position—the context E in (E-Kill), which includes the function position of a β redex, and the scrutinee position of a match—reduction requires the name ℓ to be "live" in the log, kills the name in $\mathscr{A}$, and then proceeds. This instrumentation serves as our specification of the use-at-most-once property.

At the bottom of the figure we show the rules for typing a runtime state $\mathscr{A}$. This is straightforward, requiring the names in $\mathscr{A}$ to be distinct, for the values stored in reference cells to be well-typed, and for all logged formulas to be E-kinded.

$$
\begin{array}{lcll}
\mathscr{A} & ::= & \cdot \mid \phi \mid \ell \mid \hat{\ell} \mid (\ell \mapsto_t v) \mid \mathscr{A}, \mathscr{A}' & \text{runtime state} \\
F[\bullet] & ::= & \bullet \mid F\ v \mid F\ t \mid \mathbf{let}\ x = F\ \mathbf{in}\ e & \text{exception frame} \\
E[\bullet] & ::= & \bullet \mid E\ v \mid E\ t \mid \mathbf{let}\ x = E\ \mathbf{in}\ e \mid \mathbf{try}\ E\ \mathbf{with}\ x.e & \text{evaluation context}
\end{array}
$$

$$
\text{E-Ctx}\ \frac{(\mathscr{A}, e) \rightarrow_S (\mathscr{A}', e') \qquad e \neq \mathbf{raise}\ \_}{(\mathscr{A}, E[e]) \rightarrow_S (\mathscr{A}', E[e'])}
\qquad
\text{E-Kill}\ \frac{}{(\mathscr{A}_1, \ell, \mathscr{A}_2; E[v^{\ell}]) \rightarrow_S (\mathscr{A}_1, \hat{\ell}, \mathscr{A}_2; E[v])}
$$

$$
\text{E-Err}\ \frac{}{(\mathscr{A}; F[\mathbf{raise}\ v]) \rightarrow_S (\mathscr{A}, \mathbf{raise}\ v)}
\qquad
\text{E-Hdl}\ \frac{}{(\mathscr{A}; \mathbf{try}(F[\mathbf{raise}\ v])\ \mathbf{with}\ x.e) \rightarrow_S (\mathscr{A}; e[v/x])}
$$

$$
\text{E-Log}\ \frac{}{(\mathscr{A}; \mathbf{assume}\ \phi) \rightarrow_S (\mathscr{A}, \phi; ())}
\qquad
\text{E-Let}\ \frac{}{(\mathscr{A}; \mathbf{let}\ x = v\ \mathbf{in}\ e) \rightarrow_S (\mathscr{A}; e[v/x])}
$$

$$
\text{E-Beta}\ \frac{}{(\mathscr{A}; (\lambda x{:}t.e)\ v) \rightarrow_S (\mathscr{A}; e[v/x])}
\qquad
\text{E-TBeta}\ \frac{}{(\mathscr{A}; (\Lambda\alpha{::}\kappa.e)\ t) \rightarrow_S (\mathscr{A}; e[t/\alpha])}
$$

$$
\text{E-M}\ \frac{\forall (C'\ \bar{\tau}' \rightarrow e') \in \bar{p}. C' \neq C}{(\mathscr{A}; \mathbf{match}\ C\ \bar{\tau}\ \mathbf{with}\ \bar{p}\ \mid C\ \bar{\alpha} \rightarrow e\ \mid \bar{p}') \rightarrow_S (\mathscr{A}; e[\bar{\tau}/\bar{\alpha}])}
\qquad
\text{E-Rd}\ \frac{\ell \mapsto_t v \in \mathscr{A}}{(\mathscr{A}; !\ell) \rightarrow_S (\mathscr{A}; v)}
$$

$$
\text{E-Wr}\ \frac{\mathscr{A}' = \mathscr{A}[\ell \mapsto_t v]}{(\mathscr{A}; \ell := v) \rightarrow_S (\mathscr{A}'; ())}
\qquad
\text{E-Ref}\ \frac{\ell \not\in \mathsf{Names}(\mathscr{A})}{(\mathscr{A}; \mathbf{ref}\ t\ v) \rightarrow_S (\mathscr{A}, \ell \mapsto_t v; \ell)}
$$

$$
\text{E-New}\ell\ \frac{\mathscr{A} \Longrightarrow \Gamma; X \qquad S;\Gamma;X \vdash v : t \qquad S;\Gamma \vdash t :: A \qquad \ell \not\in \mathsf{Names}(\mathscr{A})}{(\mathscr{A}; v) \rightarrow_S (\mathscr{A}, \ell; v^{\ell})}
$$

$$
\text{where}\quad
\begin{array}{lcllcl}
\mathsf{live}(\mathscr{A}, \ell \mapsto \_) & = & \mathsf{live}(\mathscr{A}), \ell & \mathsf{dead}(\mathscr{A}, \ell) & = & \mathsf{dead}(\mathscr{A}) \\
\mathsf{live}(\mathscr{A}, \ell) & = & \mathsf{live}(\mathscr{A}), \ell & \mathsf{dead}(\mathscr{A}, \hat{\ell}) & = & \mathsf{dead}(\mathscr{A}), \hat{\ell} \\
\mathsf{live}(\mathscr{A}, \hat{\ell}) & = & \mathsf{live}(\mathscr{A}) & \mathsf{dead}(\mathscr{A}, \phi) & = & \mathsf{dead}(\mathscr{A}) \\
\mathsf{live}(\mathscr{A}, \phi) & = & \mathsf{live}(\mathscr{A}) & \mathsf{Names}(\mathscr{A}) & = & \mathsf{live}(\mathscr{A}), \mathsf{dead}(\mathscr{A})
\end{array}
$$

$$
\boxed{\mathscr{A} \Longrightarrow \Gamma; X}
\qquad
\frac{}{\cdot \Longrightarrow \cdot; \cdot}
\qquad
\frac{\mathscr{A} \Longrightarrow \Gamma; X \qquad \text{fresh } x}{(\mathscr{A}, \phi) \Longrightarrow \Gamma, x{:}\mathsf{unit}\{\phi\}; X}
$$

$$
\frac{\mathscr{A} \Longrightarrow \Gamma; X}{(\mathscr{A}, \ell \mapsto_t v) \Longrightarrow \Gamma, \ell{:}\mathbf{ref}\ t; X}
\qquad
\frac{\mathscr{A} \Longrightarrow \Gamma; X}{(\mathscr{A}, \ell) \Longrightarrow \Gamma; X, \ell}
\qquad
\frac{\mathscr{A} \Longrightarrow \Gamma; X}{(\mathscr{A}, \hat{\ell}) \Longrightarrow \Gamma; X}
$$

$$
\boxed{S;\Gamma \vdash \mathscr{A}\ \text{wf}}
\qquad
\frac{}{S;\Gamma \vdash \cdot\ \ \text{wf}}
\qquad
\frac{\ell{:}\mathbf{ref}\ t \in \Gamma \qquad S;\Gamma;\cdot \vdash v : t}{S;\Gamma \vdash \mathscr{A}, \ell \mapsto_t v}
\qquad
\frac{S;\Gamma \vdash \mathscr{A}\ \text{wf} \qquad S;\Gamma \vdash \phi :: E}{S;\Gamma \vdash \mathscr{A}, \phi\ \ \text{wf}}
$$

$$
\frac{S;\Gamma \vdash \mathscr{A}\ \text{wf} \qquad \ell, \hat{\ell} \not\in \mathscr{A}}{S;\Gamma \vdash \mathscr{A}, \ell\ \ \text{wf}}
\qquad
\frac{S;\Gamma \vdash \mathscr{A}\ \text{wf} \qquad \ell, \hat{\ell} \not\in \mathscr{A}}{S;\Gamma \vdash \mathscr{A}, \hat{\ell}\ \ \text{wf}}
$$

Fig. 6. Dynamic semantics of F*: $(\mathscr{A}; e) \rightarrow_S (\mathscr{A}'; e')$

One may wonder if our instrumentation strategy is a sufficiently precise characterization of the use-at-most-once property. After all, the following reduction sequence may cause the initially tagged value $(\lambda \mathsf{x}.\mathsf{x})^{\ell}$ to appear in a redex more than once without getting stuck.

$$
\begin{array}{ll}
 & ((\mathscr{A}, \ell); \mathbf{let}\ \mathsf{f} = (\lambda \mathsf{x}.\mathsf{x})^{\ell}\ \mathbf{in}\ (\mathsf{f}\ 1, \mathsf{f}\ 2)) \\
\text{(E-Kill)} & \rightarrow (\mathscr{A}; \mathbf{let}\ \mathsf{f} = \lambda \mathsf{x}.\mathsf{x}\ \mathbf{in}\ (\mathsf{f}\ 1, \mathsf{f}\ 2)) \\
\text{(E-Let)} & \rightarrow (\mathscr{A}; ((\lambda \mathsf{x}.\mathsf{x})\ 1, (\lambda \mathsf{x}.\mathsf{x})\ 2)) \\
\text{(E-Beta)} & \rightarrow (\mathscr{A}; (1, (\lambda \mathsf{x}.\mathsf{x})\ 2)) \\
\text{(E-Beta)} & \rightarrow (\mathscr{A}; (1, 2))
\end{array}
$$

However, our dynamic semantics is non-deterministic with respect to the application of rule (E-Kill). Thus, the following reduction sequence is also valid, and in this case yields a stuck configuration.

$$
\begin{array}{ll}
 & ((\mathscr{A},\ell);\ \mathbf{let}\ \mathsf{f} = (\lambda \mathsf{x}.\mathsf{x})^{\ell}\ \mathbf{in}\ (\mathsf{f}\ 1,\ \mathsf{f}\ 2)) \\
\text{(E-Let)} & \rightarrow ((\mathscr{A},\ell);\ ((\lambda \mathsf{x}.\mathsf{x})^{\ell}\ 1,\ (\lambda \mathsf{x}.\mathsf{x})^{\ell}\ 2)) \\
\text{(E-Kill)} & \rightarrow (\mathscr{A};\ ((\lambda \mathsf{x}.\mathsf{x})\ 1,\ (\lambda \mathsf{x}.\mathsf{x})^{\ell}\ 2)) \\
\text{(E-Beta)} & \rightarrow (\mathscr{A};\ (1,\ (\lambda \mathsf{x}.\mathsf{x})^{\ell}\ 2)) \not\rightarrow
\end{array}
$$

Theorem 1 proves that any reduct of a well-typed configuration is well-typed, thus accounting for the non-determinism in the application of (E-Kill), and excluding the code above. Although it is possible to make (E-Kill) deterministic (e.g., by introducing priorities between the reduction rules), the added complexity seems a poor trade-off.

This completes our presentation of the static and dynamic semantics of F*. Next, we develop its metatheory proving type soundness, normalization of the *P*-fragment, and discussing an embedding of RCF in F*.

4 Metatheory of F*

This section provides our main theorems for F*. The proofs of its metatheory were initially conducted by hand; as we reached completion of the hand proofs, we started a formalization of F* in the Coq proof assistant, using the SSREFLECT extension of Gonthier *et al.* (2011). We now have a mechanized proof of type soundness for the whole language defined in §3. In the process, we found a few oversights in our pencil and paper proofs, which we have since corrected.

Our formalization in Coq is noteworthy in several ways. First, it is the first time the SSREFLECT package has been used to carry out a large development in programming language metatheory. We started out attempting to use the Coq code generator OTT of Sewell *et al.* (2010) to help reduce the gap between the formal and informal descriptions of our type system; although this did help in the maintenance of the two versions of the type system, we found that with the many different kinds of variables in F*, the code produced by OTT resulted in a very large, yet incomplete set of lemmas.

Following this experience, we developed a new framework for metatheory using SSREFLECT, and applied it to F*—a particularly challenging test case, since it involves many kinds of names and binders, with subtle differences across the levels of terms, types and kinds. The type system has many rules. Furthermore, its central judgments are all mutually recursive. Despite these complications, we are happy to note that our framework has allowed us to develop short, largely automated proofs: the final development consists of 1 KLOC for the framework, 2.5 KLOC for the F* definition, and 4 KLOC for its metatheory. Our experience is encouraging initial progress towards a general framework, based on the reflection pattern and the theory of the pure lambda calculus, dedicated to the study of type systems.

4.1 Type soundness via preservation and progress

Our first theorem is a type soundness result, stated in terms of standard progress and preservation—we refer to the formal development for the intermediate lemmas. In addition to well-typed programs not getting stuck, this result ensures that affinely typed values are destructed at most once, and can thus be soundly implemented using destructive reads and mutation. The theorem relies on the auxiliary judgment $\mathscr{A} \Longrightarrow \Gamma;X$ of Figure 6, which obtains a context $\Gamma;X$ from the dynamic log, where Γ and X collect the logical assumptions and the live names of $\mathscr{A}$, respectively.

Theorem 1 (Type soundness)**.**
For all S, $\mathscr{A}$, Γ, X, e, and t such that $S \vdash \mathscr{A} \Longrightarrow \Gamma;X$, and $S;\Gamma;X \vdash e : t$, we have:
Preservation*: for all $\mathscr{A}'$, e' such that $(\mathscr{A},e) \rightarrow_S (\mathscr{A}',e')$, there exist Γ', X' such that $S \vdash \mathscr{A}' \Longrightarrow \Gamma';X'$, and $S;\Gamma';X' \vdash e' : t$.*
Progress*: either e is a value, or there exist $\mathscr{A}'$, e' such that $(\mathscr{A},e) \rightarrow_S (\mathscr{A}',e')$.*

From type soundness, we obtain our main safety property for ghost refinements: their formulas are derivable from the logical effects accumulated in the log.

Corollary 1 (Safety for ghost refinements)**.** *For all S, $\mathscr{A}$, Γ, X, e, ϕ, t, $\mathscr{A}'$, Γ', and v such that $\vdash S$ ok, $S \vdash \mathscr{A} \Longrightarrow \Gamma;X$, $S;\Gamma;X \vdash e : x{:}t\{\phi\}$, and $(\mathscr{A};e) \rightarrow_S^* (\mathscr{A}';v)$, there exists Γ' such that $S \vdash \mathscr{A}' \Longrightarrow \Gamma';\_$ and $S;\Gamma' \models \phi[v/x]$.*

4.2 Embedding RCF in F*

We show that F* subsumes F7 (one of its predecessors), by providing an embedding of RCF (the formal calculus behind F7) within F*. This embedding allows us to carry over large prior developments in F7 to F*, while maintaining the main formal results. In Section 6, we discuss a preliminary implementation of an “F7 mode” that allows F7 programs to be typechecked in F*.

More formally, we give an embedding into F* of a core fragment of RCF without Public/Tainted kinds, without concurrency, and with restrictions on the use of RCF’s isorecursive types. This fragment of RCF is used, for instance, by Fournet *et al.* (2011) for modeling ideal cryptography. We refer to the technical report for the definition of RCF and its embedding, which mostly accounts for syntactic differences between the two languages. In the statement below, A is an RCF configuration; E is an RCF context; and $A \rightarrow A'$ is a single step of reduction in RCF. The notation $[\![\cdot]\!]$ means translation. The judgment $E \vdash \diamond$ means that E is well-formed. The translation is over the structure of RCF typing derivations. The theorem states, roughly, that well-typed RCF terms translate to well-typed F* terms, and that the translation is a simulation, i.e., reduction steps in RCF correspond to reductions in F*.

Theorem 2 (Well-typed translation of RCF)**.** *Given $E \vdash [\![A]\!] = (\mathscr{A};e)$, $\vdash [\![E]\!] = S;\Gamma$, and $E \vdash \diamond$, we have $S;\Gamma;. \vdash e : t$ where $E \vdash [\![T]\!] = t$. Additionally $A \rightarrow A'$ if and only if $(\mathscr{A};e) \rightarrow_S (\mathscr{A}';e')$ and $E \vdash [\![A']\!] = (\mathscr{A}';e')$.*

4.3 Normalization for the P-fragment

One significant difference between our version of F* and the version of Swamy *et al.* (2011) is in the normalization proof for its P-fragment. Our initial proof involved translating P-terms in F* to CiC (The Coq Development Team 2010), and proving this translation a simulation. Relying on strong normalization results for CiC (Barthe *et al.* 2006), we concluded that P-terms in F* were also strongly normalizing. This indirect proof was, however, not without difficulties. In particular, the implicit type conversion relation of F*, from any equations in context, were represented in the translation to CiC through the use of dependent pattern matching with explicit coercions. Completing the proof in this style involved cumbersome book-keeping. Additionally, in order for the proof to go through, we required a non-standard side condition on the rule (T-TApp) for type applications. We discuss this side condition next, illustrating it on an example. Recall that, in our previous formulation, we had the additional sub-kinding rule $P <: \star$, and consider the following program:

```
type False :: P
let badid : ∀a::⋆. unit → a = fun (a::⋆) () → raise Error in
badid False : unit → False
```

We define first a P-kinded type False with no constructors, then a polymorphic function of type ∀a::⋆. unit → a that simply raises an exception. Since the co-domain of badid is a $\star$-kinded type, the function is free to have effects like exceptions or divergence. However, if we are not careful, the rule $P <: \star$ let us instantiate badid to False and obtain a term of type unit → False. Since this function has a P-kinded co-domain, we expect it to be total, but clearly it is not. To exclude such problematic instantiation, our earlier system includes the following variation on rule (T-TApp):

$$\text{T-TApp-Old}\frac{\begin{array}{ccc} S;\Gamma;X \vdash^m e : t_v & !t_v = \forall\alpha{::}\kappa.t' & S;\Gamma \vdash t :: \kappa \\ S;\Gamma \vdash t'[t/\alpha] \equiv t'' & S;\Gamma \vdash t'' :: P \implies & S;\Gamma \vdash t_v :: P \end{array}}{S;\Gamma;X \vdash^m e\ t : t'[t/\alpha]}$$

The third and fourth premises of (T-TApp-Old) ensured that if, after instantiating a to t in t', we obtain a type t'' in P, then t' must have been in P initially. The side condition excludes the problematic example listed above, since the initial type ∀a::⋆. unit → a has kind $\star$ and after instantiation it has kind P. The side condition also accounts for examples in which t' could have more than one kind, e.g., kind $\star$ then kind P after type conversion to t''.

While this side condition is sufficient to establish the soundness of the P-fragment while tolerating $P <: \star$, we find this restriction on type application cumbersome. More fundamentally, this style of side condition prevented us from easily developing a direct, domain-theoretic proof of normalization for the P-fragment. Thus, as discussed earlier, we revised our kind hierarchy to disallow $P <: \star$ and simplify (T-TApp-Old) to (T-TApp). In the remainder of this section, we present our new proof of normalization, stated below:

Theorem 3 (Normalization). *If $S \vdash \mathscr{A} \implies \Gamma;X,\ \vdash S;\Gamma;X$ wf, and $S;\Gamma;X \vdash^m e : t :: P$, then $(\mathscr{A}, e)$ must reduce to $(\mathscr{A}', v)$ for some $\mathscr{A}'$, v.*

The proof is in three parts. First, we define a new reduction relation on expressions that captures, at the P level, the one defined in §3.3. We then show, using the now standard technique of *reducibility candidates*, that this reduction relation is normalizing on well-typed expressions of the P fragment. We conclude by transferring the normalization property to the dynamic semantics of F*.

Weaker reductions Our new reduction relation is defined by pruning from the dynamic semantics of F* all the rules not related to the P-level. The main benefit is the removal of all the rules depending on the log $\mathscr{A}$, which matter only at the $\star$ and A levels, leading to a simpler relation that still captures the dynamic semantics at the P level.

Definition 2 (P-level dynamic semantics)**.** *Figure 6, where only the rules E-Ctx, E-Let, E-Beta, E-TBeta and E-M are kept, defines the* P-level dynamic semantics *of* F*.

Since this semantics does not involve $\mathscr{A}$, we write $e \rightarrow_S e'$, or simply $e \rightarrow e'$ when S is clear from the context, if e reduces to e' at the P-level. The relation $\rightarrow$ is non-branching, hence confluent. Moreover, from type soundness, we obtain the subject reduction property:

Lemma 2 (Subject reduction)**.** *If* $S;\Gamma;X \vdash^m e : t$ *and* $e \rightarrow_S e'$, *then* $S;\Gamma;X \vdash^m e' : t$.

Proof. From Theorem 1, since $\rightarrow_S$ does not create any new label, it is sufficient to take $\mathscr{A}' = \mathscr{A}$ and $\Gamma' = \Gamma$. □

By definition, P-level reduction only contracts redexes at the P-level, hence providing a good simulation of the F* dynamic semantics for P-level terms:

Lemma 3 (P-level dynamic semantics simulation)**.** *If* $S;\Gamma;X \vdash^m e : t$, $S;\Gamma \vdash t :: P$, *and* $(\mathscr{A}, e) \rightarrow_S (\mathscr{A}', e')$, *then* $e \rightarrow_S e'$.

For the sake of the normalization proof, we also define a reduction relation at type level capturing the contraction of type level β-redexes.

Definition 3 (Type level reduction)**.** *The type level reduction, written* $\cdot \rightarrow \cdot$, *is the smallest compatible (i.e. context-closed) relation such that* $(\Lambda a{::}\kappa.t)\ u \rightarrow t[u/a]$ *and* $(\lambda x{:}t.u)\ v \rightarrow u[v/x]$.

This type level reduction definition is routine, and it can easily be shown that it is confluent (Barendregt *et al.* 1992). Moreover, as a consequence of type soundness, we know that type level judgment is stable by substitution, and we thus obtain a subject reduction property:

Lemma 4 (Type level subjection reduction)**.** *If* $S;\Gamma \vdash t :: \kappa$ *and* $t \rightarrow u$, *then* $S;\Gamma \vdash u :: \kappa$.

We now move to the proof of Theorem 3. We follow the *reducibility candidates* methodology of Girard that amounts to

- interpreting kinds by sets of sets of terms—the so-called reducibility candidates; and
- interpreting well-kinded types t by sets that (1) belong to the previously defined set of reducibility candidates for their corresponding kind, and (2) contain all the expressions that can be equipped with the type t.

Hence, if $S;\Gamma;X \vdash e : t(\kappa)$, we obtain that $e \in [\![t]\!]_\xi \in \mathscr{R}_\kappa$ where $[\![t]\!]_\xi$ is the interpretation of the type t (for a given well-formed valuation ξ, a notion to define later) and $\mathscr{R}_\kappa$ is the set of reducibility candidates for the kind κ. The set $\mathscr{R}_P$ will be defined such that it only contains sets of normalizing (at P-level) expressions, implying that e is a P-level normalizing term as soon as it can be equipped with a P-level type.

Normalization of P-level reduction For the entire section, we assume given a fixed, well-formed, inductive signature S. We write **SN** for the set of expressions that normalize at P-level, and **NT** for neutral expressions, defined below:

Definition 4 (Neutral terms)**.** *An expression is* neutral *when it is neither an abstraction ($\lambda x{:}t.e$), nor a type abstraction ($\Lambda a{::}\kappa.e$), nor an applied constructor ($C\ \overline{\tau}$).*

The sets of values, expressions, types and kinds are respectively denoted by Λ_v, Λ_e, Λ_t and Λ_κ. We write $\mathscr{X}^{\mathrm{t}}$ and $\mathscr{X}^{\mathrm{e}}$ for the set of type variables and value variables. We are ready to define our notion of *reducibility candidates*:

Definition 5 (Reducibility candidates)**.** *Let $\preceq$ be the smallest (partial) order such that*

$$\begin{array}{ll} P \preceq E \quad \star \preceq E \quad A \preceq E & \\ x{:}t \Rightarrow \kappa \ \preceq\ x{:}t' \Rightarrow \kappa' & \textit{whenever } \kappa \preceq \kappa' \\ \alpha{:}\kappa_1 \Rightarrow \kappa_2 \ \preceq\ \alpha{:}\kappa_1' \Rightarrow \kappa_2' & \textit{whenever } \kappa_1' \preceq \kappa_1 \textit{ and } \kappa_2 \preceq \kappa_2' \end{array}$$

Let $\sim$ be the equivalence relation induced by $\preceq$. We define the sets $\mathscr{R}_\kappa$ of the interpretations of types of kind κ, by induction on the structure of κ and by case on the head symbol:

- *$\mathscr{R}_P$ is the set of all the subsets R of Λ_e such that*

$$\begin{array}{ll} \textit{(CR1)} & R \subseteq \mathbf{SN} \\ \textit{(CR2)} & \textit{if } e \in R, \textit{ then } e' \in R \textit{ whenever } e \to e' \\ \textit{(CR3)} & \textit{for any } e \in \mathbf{NT}, \textit{ if } e' \in R \textit{ whenever } e \to e', \textit{ then } e \in R \end{array}$$

- *$\mathscr{R}_b = \{\Lambda_e\}$ for $b \in \{\star, A\}$.*
- *$\mathscr{R}_E = \wp(\Lambda_e)$.*
- *$\mathscr{R}_{x:t\Rightarrow\kappa}$ is the set of functions from $\{\emptyset\}$ to $\mathscr{R}_{\kappa'}$ for all $\kappa' \preceq \kappa$.*
- *$\mathscr{R}_{\alpha::\kappa_1\Rightarrow\kappa_2}$ is the set of functions in $\mathscr{R}_{\kappa_1'} \to \mathscr{R}_{\kappa_2'}$ for all κ_1', κ_2' such that $\kappa_1 \preceq \kappa_1'$ and $\kappa_2' \preceq \kappa_2$.*

It is immediate that $\kappa \sim \kappa'$ (resp. $\kappa \preceq \kappa'$) implies $\mathscr{R}_\kappa = \mathscr{R}_{\kappa'}$ (resp. $\mathscr{R}_\kappa \subseteq \mathscr{R}_{\kappa'}$). Hence:

Lemma 5 (Candidate (in)variance)**.** *If $\Gamma \vdash \kappa \equiv \kappa'$ (resp. $\Gamma \vdash \kappa <: \kappa'$), then $\mathscr{R}_\kappa = \mathscr{R}_{\kappa'}$ (resp. $\mathscr{R}_\kappa \subseteq \mathscr{R}_{\kappa'}$).*

The interpretation of inductive types in the P fragment will be defined as the smallest fixpoint of a given operator over $\mathscr{R}_\kappa$ that we equip with a structure of a complete lattice:

Definition 6 (Lattice structure of $\mathscr{R}_\kappa$)**.** *We equip $\mathscr{R}_\kappa$ with a structure of complete lattice $(\mathscr{R}_\kappa, \leq_\kappa, \top_\kappa, \mathrm{lub}_\kappa)$ by induction on κ, where $\leq_\kappa$ (resp. $\top_\kappa$, $\mathrm{lub}_\kappa(\mathbf{R})$) stands for the ordering over $\mathscr{R}_\kappa$ (resp. the top element of $\mathscr{R}_\kappa$, the supremum of $\mathbf{R} \in \wp(\mathscr{R}_\kappa)$).*

- *$\leq_P = \subseteq$, $\top_P = \mathbf{SN}$ and for any $\mathbf{T}$, $\mathrm{lub}_P(\mathbf{T}) = \mathbf{SN}$.*
- *If $c \in \{\star, A\}$, then $\leq_c = \subseteq$, $\top_c = \Lambda_e$, and for any $\mathbf{T}$, $\mathrm{lub}_c(\mathbf{T}) = \Lambda_e$.*
- *$\leq_E = \subseteq$, $\top_E = \Lambda_e$ and for any $\mathbf{T}$, $\mathrm{lub}_E(\mathbf{T}) = \Lambda_e$.*
- *Let $R_1 : \{\emptyset\} \to \mathscr{R}_{\kappa_1}$, $R_2 : \{\emptyset\} \to \mathscr{R}_{\kappa_2} \in \mathscr{R}_{x:t\Rightarrow\kappa}$. Then, $R_1 \leq_{x:t\Rightarrow\kappa} R_2$ if $\kappa_1 \preceq \kappa_2$ and $R_1(\emptyset) \leq_{\kappa_2} R_2(\emptyset)$. Moreover, $\top_{x:t\Rightarrow\kappa} = \emptyset \mapsto \top_\kappa$ and $\mathrm{lub}_{x:t\Rightarrow\kappa}(\mathbf{R}) = \emptyset \mapsto \mathrm{lub}_\kappa\{R(\emptyset) \mid R \in \mathbf{R}\}$.*
- *Let $R_1 : \mathscr{R}_{\kappa_1'} \to \mathscr{R}_{\kappa_2'}$, $R_2 : \mathscr{R}_{\kappa_1''} \to \mathscr{R}_{\kappa_2''} \in \mathscr{R}_{\alpha::\kappa_1\Rightarrow\kappa_2}$. Then $R_1 \leq_{\alpha:\kappa_1\Rightarrow\kappa_2} R_2$ if $\kappa_1'' \preceq \kappa_1'$, $\kappa_2' \preceq \kappa_2''$, and for any $x \in \mathscr{R}_{\kappa_1''}$, $R_1(x) \leq_{\kappa_2''} R_2(x)$. Moreover, $\top_{a::\kappa_1\Rightarrow\kappa_2} = S \mapsto \top_{\kappa_2}$ and $\mathrm{lub}_{a::\kappa_1\Rightarrow\kappa_2}(\mathbf{R}) = S \mapsto \mathrm{lub}_{\kappa_2}(\{R(S) \mid R \in \mathbf{R}\})$.*

We now move to the definition of the interpretation schema:

Definition 7 (Interpretation). *Let $\mathscr{R} = \bigcup_{\kappa \in \Lambda_\kappa} \mathscr{R}_\kappa$. A candidate assignment is any finite map from $\mathscr{X}^{\mathrm{t}}$ to $\mathscr{R}$. We inductively define the interpretation of a well-kinded t w.r.t a candidate assignment ξ, written $[\![t]\!]_\xi$. If $\Gamma \vdash t :: b$ but not $\Gamma \vdash t :: P$, then $[\![t]\!]_\xi = \Lambda_e$. Otherwise:*

$$
\begin{array}{ll}
[\![a]\!]_\xi & = \xi(a) \\
[\![T]\!]_\xi & = \mathscr{I}_T \\
[\![x{:}t \to u]\!]_\xi & = \{e \in \Lambda_e \mid \forall v \in [\![t]\!]_\xi \cap \Lambda_v, (e\ v) \in [\![u]\!]_\xi\} \\
[\![\forall a{::}\kappa.u]\!]_\xi & = \{e \in \Lambda_e \mid \forall t \in \Lambda_t, \forall S \in \mathscr{R}_\kappa, (e\ t) \in [\![u]\!]_{\xi_a^S}\} \\
[\![t\ v]\!]_\xi & = [\![t]\!]_\xi(\emptyset) \\
[\![t\ u]\!]_\xi & = [\![t]\!]_\xi([\![u]\!]_\xi) \\
[\![\lambda x{:}t.u]\!]_\xi & = \emptyset \mapsto [\![u]\!]_\xi \\
[\![\Lambda a{::}\kappa.u]\!]_\xi & = S \in \mathscr{R}_\kappa \mapsto [\![u]\!]_{\xi_a^S} \\
[\![x{:}t\{\phi\}]\!]_\xi & = [\![t]\!]_\xi
\end{array}
$$

where ξ_a^S stands for the interpretation augmented by the binding $a \mapsto S$.

The interpretation of inductive types $\mathscr{I}_T$ is defined in a standard way, using an introduction based methodology (Mendler 1987; Dybjer 2000). For instance, $\mathscr{I}_{\mathbf{nat}} = F^\infty(\emptyset)$ where $F(X) = \{e \in \mathbf{SN} \mid e \to^* \mathbf{0}\} \cup \{e \in \mathbf{SN} \mid e \to^* \mathbf{S}\ e' \text{ with } e' \in X\}$. As usual, the lattice structure of the $\mathscr{R}_\kappa$ and the strict positivity of inductive types at P level assure the well-formedness of the definition of the map $\mathscr{I}$.

A candidate assignment ξ validates an environment Γ (or is a Γ-assignment*), written $\xi \vDash \Gamma$ if, for any variable $a \in \mathrm{dom}(\Gamma) \cap \mathscr{X}^{\mathrm{t}}$, we have $\xi(a) \in \mathscr{R}_{\Gamma(a)}$ and, for any equation $a = t \in \Gamma$, we have $\xi(a) = [\![t]\!]_\xi$. Note that we do not consider the case $t_1 = t_2 \in \Gamma$. Indeed, it is straightforward to prove that the sequence of type-level equations of an environment Γ s.t. $S;\Gamma;X \vdash^m e : t$ (for some S, X, e and t) is of the form $a_1 = t_1, \cdots, a_n = t_n$ where all the a_i's are pairwise disjoint and the set of free type-level variables of any t_i is contained in $\{a_1, \cdots, a_{i-1}\}$. As such, from now on, it is safe to consider only environments of that form.*

We are now left to prove that if $\Gamma;S;X \vdash^m e : t :: \kappa$, then $e \in [\![t]\!]_\xi \in \mathscr{R}_\kappa$ for any pair ξ validating Γ.

Lemma 6 (Well-formedness of interpretation). *If $S;\Gamma \vdash t :: \kappa$, then $[\![t]\!]_\xi \in \mathscr{R}_\kappa$ for any candidate assignment ξ validating Γ.*

Proof. By induction on $S;\Gamma \vdash t :: \kappa$. If $S;\Gamma \vdash t :: b$ but not $S;\Gamma \vdash t :: P$, then $[\![t]\!]_\xi^\kappa = \Lambda_e \in \{\Lambda_e\} = \mathscr{R}_b$. Otherwise, we do a case analysis on the last rule used:

- If $S;\Gamma \vdash a :: \Gamma(a)$, then $[\![a]\!]_\xi = \xi(a) \in \mathscr{R}_{\Gamma(a)}$ by assumption on ξ.
- If $S;\Gamma \vdash T :: S(T)$, then $[\![T]\!]_\xi = \mathscr{I}_T \in \mathscr{R}_{S(T)}$ by assumption on $\mathscr{I}$.
- Assume that $S;\Gamma \vdash \forall a{::}\kappa.t :: P$ is derived using the rule K-$\forall$ from i) $S;\Gamma \vdash \kappa\ \mathrm{ok}(P)$, and ii) $S;\Gamma; a :: \kappa \vdash t :: P$. Let $R = \{e \in \Lambda_e \mid \forall u \in \Lambda_t, \forall S \in \mathscr{R}_\kappa, (e\ u) \in [\![t]\!]_{\xi_a^S}\}$. We have to prove that $R \in \mathscr{R}_P$:
  — **(CR1)** Let $e \in R$. For any $u \in \Lambda_t$, $S \in \mathscr{R}_\kappa$, we have $e\ u \in [\![t]\!]_{\xi_a^S}$. By application of the induction hypothesis on ii), $[\![t]\!]_{\xi_a^S} \in \mathscr{R}_P \supseteq \mathbf{SN}$. Taking $u = x$, we obtain $e\ x \in \mathbf{SN}$, hence $e \in \mathbf{SN}$.
  — **(CR2)** Let $e \in R$ and e' such that $e \to e'$. Let $u \in \Lambda_t$ and $S \in \mathscr{R}_\kappa$. Then, $e\ u \in [\![t]\!]_{\xi_a^S}$. By induction hypothesis, $[\![t]\!]_{\xi_a^S} \in \mathscr{R}_P$, and is thus stable by reduction (prop-

erty (CR3)). Since u is normal (by syntactical restriction, it is a value), $e\ u \to e'\ u$ and $e'\ u \in [\![t]\!]_{\xi_a^S}$. Hence, $e' \in R$.

— **(CR3)** Let $e \in \mathbf{NT}$. Assume that $e' \in R$ whenever $e \to e'$. Let $u \in \Lambda_t$ and $S \in \mathscr{R}_\kappa$. We have to show that $e\ u \in [\![t]\!]_{\xi_a^S}$. By induction hypothesis, $[\![t]\!]_{\xi_a^S} \in \mathscr{R}_P$. Hence, noting that $e\ u$ is neutral, by (CR3), $e\ u \in [\![t]\!]_{\xi_a^S}$ if the reduced of $e\ u$ is in $[\![t]\!]_{\xi_a^S}$. Since e is neutral, $e\ u$ can only reduce to a term of the form $e'\ u$. By assumption, $e' \in R$, hence the result.

- Assume that $S;\Gamma \vdash \Lambda a{::}\kappa.t :: a{::}\kappa \Rightarrow \kappa'$ is derived using the rule K-Λ from i) $S;\Gamma \vdash a{::}\kappa \Rightarrow \kappa'\ \mathrm{ok}(b)$, and ii) $S;\Gamma, a :: \kappa \vdash t :: \kappa'$. We have to prove that $R = [\![\Lambda a{::}\kappa.t]\!]_\xi \in \mathscr{R}_{a::\kappa \Rightarrow \kappa'}$. Let $S \in \Lambda_t \mathscr{R}_\kappa$. Then, $R(S) = [\![u]\!]_{\xi_a^S}$. By induction hypothesis on ii), $R(S) \in \mathscr{R}_{\kappa'}$.
- Assume that $S;\Gamma \vdash t\ t' :: \kappa'[t'/a]$ using rule K-tt from i) $S;\Gamma \vdash t :: a{::}\kappa \Rightarrow \kappa'$, and ii) $S;\Gamma \vdash t' :: \kappa$. We have to prover that $R = [\![t\ t']\!]_\xi = [\![t]\!]_\xi([\![t']\!]_\xi) \in \mathscr{R}_{\kappa'[t'/a]}$. By application of the induction hypothesis, $[\![t]\!]_\xi \in \mathscr{R}_{a::\kappa \Rightarrow \kappa'}$ and $[\![t']\!]_\xi \in \mathscr{R}_\kappa$. Hence, by definition of $\mathscr{R}_{a::\kappa \Rightarrow \kappa'}$, $R \in \mathscr{R}_{\kappa'} = \mathscr{R}_{\kappa'[t'/a]}$.
- The cases K-$\to$, K-λ and K-tv are similar to the K-$\forall$, K-Λ and K-tt cases.
- In the K-<: case, the result follows by direct application on the induction hypothesis, using Lemma 5.
- In the K-ϕ case, the result follows by direct application of the induction hypothesis, noting that $[\![x{:}t\{\phi\}]\!]_\xi = [\![t]\!]_\xi$. □

Lemma 7 ((In)variance of interpretation)**.** *If $S;\Gamma \vdash t_1 <: t_2$ (resp. $S;\Gamma \vdash t_1 \equiv t_2$), then $[\![t_1]\!]_\xi \subseteq [\![t_2]\!]_\xi$ (resp. $[\![t_1]\!]_\xi = [\![t_2]\!]_\xi$) for any assignment $\xi \models \Gamma$.*

Proof. By induction on $S;\Gamma \vdash t_1 <: t_2$. □

Definition 8. *A* substitution θ *is any finite mapping from $\mathscr{X}^{\mathrm{e}} \cup \mathscr{X}^{\mathrm{t}}$ to $\Lambda_v \cup \Lambda_t$ such that for any $x \in \mathscr{X}^{\mathrm{e}}$ (resp. $a \in \mathscr{X}^{\mathrm{t}}$), $x\theta \in \Lambda_v$ (resp. $a\theta \in \Lambda_t$). A* type substitution θ *is any substitution such that* $\mathrm{dom}(\theta) \subseteq \mathscr{X}^{\mathrm{t}}$.

For any well-formed environment Γ, Γ-assignment ξ, and substitution θ, we say that the pair (ξ,θ) validates Γ *if for any $x \in \mathrm{dom}(\Gamma) \cap \mathscr{X}^{\mathrm{e}}$, we have $x\theta \in [\![\Gamma(x)]\!]_\xi$.*

Lemma 8 (Candidate substitution)**.** *Assume that $S;\Gamma \vdash^m t :: \kappa$. Let θ be a type substitution and Δ s.t. for any $a \in \mathrm{dom}(\Gamma)$, $S;\Delta \vdash^m a\theta :: (\Gamma(a))\theta$. Then, for any Δ-assignment ξ_Δ, $[\![t\theta]\!]_{\xi_\Delta} = [\![t]\!]_{\xi_\Gamma}$ with $\xi_\Gamma = \{a \mapsto [\![a\theta]\!]_{\xi_\Delta} \mid a \in \mathrm{dom}(\Delta)\}$.*

Proof. By induction on t, noting that $\mathscr{R}_{\kappa\theta} = \mathscr{R}_\kappa$ for any substitution θ. □

Lemma 9 (Correctness of interpretation)**.** *If $S;\Gamma;X \vdash^m e : t$, then $e\theta \in [\![t]\!]_\xi$ for any pair (ξ,θ) validating Γ.*

Proof. By induction on $S;\Gamma;X \vdash^m e : t$. By type correctness, there exists a concrete kind c such that $\Gamma \vdash t :: c$. Hence, $[\![t]\!]_\xi \in \mathscr{R}_c$. If $c \neq P$, then $\mathscr{R}_c = \{\Lambda_e\}$. Thus, $[\![t]\!]_\xi = \Lambda_e$ and the result easily follows. If $c = P$, we do a case analysis on the last rule used:

- If $S;\Gamma;. \vdash x : \Gamma(x)$ with $\Gamma \vdash \Gamma(x) :: P$, then $x\theta \in [\![\Gamma(x)]\!]_\xi$ by assumption. Hence, θ being at type level, $x\theta = x \in \mathbf{SN} \subseteq [\![\Gamma(x)]\!]_\xi$.

- Assume that $S;\Gamma;X \vdash^m \lambda x{:}t.e : x{:}t \to t'$ is derived using T-Abs from $S;\Gamma \vdash t :: c$, and $S;\Gamma,x:t;X,x \vdash^m e : t'$ with $S;\Gamma \vdash x{:}t \to t' :: P$. We have to prove that $(\lambda x{:}t\theta.e\theta) \in [\![x{:}t \to t']\!]_\xi$. Unfolding definition, this amounts to show that $(\lambda x{:}t\theta.e\theta)\ v \in [\![t']\!]_\xi$ for any $v \in [\![t]\!]_\xi \cap \Lambda_v$. By inversion of $S;\Gamma \vdash x{:}t \to t' :: P$, we have $S;\Gamma \vdash t' :: P$. Hence, $[\![t']\!]_{\xi^S_a} \in \mathscr{R}_P$. By condition (CR3), it suffices to show that $(e\theta)[v/x] = (e\theta^v_x) \in [\![t']\!]_\xi$. Since (ξ,θ^v_x) validates $\Gamma,x:t$, we can apply the induction hypothesis on ii) and conclude.
- Assume that $S;\Gamma;X \vdash^m \Lambda a{::}\kappa.e : \forall a{::}\kappa.t$ is derived using T-Tabs from i) $S;\Gamma \vdash \kappa$ ok(b), and ii) $S;\Gamma,\alpha :: \kappa;X \vdash^m e : t$, with iii) $S;\Gamma \vdash \forall a{::}\kappa.t :: P$. We have to prove that $\Lambda a{::}\kappa\theta.e\theta \in [\![\forall a{::}\kappa.t]\!]_\xi$, i.e. that $(\Lambda a{::}\kappa\theta.e\theta)\ t_\kappa \in [\![t]\!]_{\xi^S_a}$ for any $t_\kappa \in \Lambda_t$ and $S \in \mathscr{R}_\kappa$. By inversion of iii), we have $S;\Gamma \vdash t :: P$. Hence, $[\![t]\!]_{\xi^S_a} \in \mathscr{R}_P$. By condition (CR3), it suffices to show that $(e\theta)[t_\kappa/a] = (e\theta^{t_\kappa}_a) \in [\![t]\!]_{\xi^S_a}$. Since $(\xi^S_a,\theta^{t_\kappa}_a)$ validates $\Gamma,a :: \kappa$, we can apply the induction hypothesis on ii) and conclude.
- Assume that $S;\Gamma;X_1,X_2 \vdash^m e\ v : t[v/x]$ is derived using T-App from i) $!t_1 = x{:}t' \to t$, ii) $S;\Gamma;X_1 \vdash^m e : t_1$, and iii) $S;\Gamma;X_2 \vdash^m v : t'$, with iv) $S;\Gamma \vdash t[v/x] :: P$. We have to prove that $(e\theta\ v\theta) \in [\![t[v/x]]\!]_\xi = [\![t]\!]_\xi$. By inversion of iv), $S;\Gamma \vdash x{:}t' \to t :: P$. Hence, $x{:}t' \to t$ cannot be typed under the affine constructor ¡ and $t_1 = x{:}t' \to t$. By application of the induction hypothesis on ii) and iii), we have $e\theta \in [\![x{:}t' \to t]\!]_\xi$. and $v\theta \in [\![t']\!]_\xi$. Hence, $(e\theta\ v\theta) \in [\![t]\!]_\xi$ by definition of $[\![x{:}t' \to t]\!]_\xi$.
- Assume that $S;\Gamma;X \vdash^m e\ t : t'[t/a]$ is derived using T-TApp from i) $!t_v = \forall a{::}\kappa.t'$, ii) $S;\Gamma;X \vdash^m e : t_v$, and iii) $S;\Gamma \vdash^m t :: \kappa$, with iv) $S;\Gamma \vdash t'[t/a] :: P$. Using a similar reasoning, we obtain that $(e\theta\ t\theta) \in [\![t']\!]_{\xi'}$ with $\xi' = \xi\{x \mapsto [\![t\theta]\!]_\xi\}$. By candidate substitution, $[\![t']\!]_{\xi'} = [\![t'[t/a]]\!]_\xi$, hence the result.
- For the T-match case, we detail the **nat** case. Let $e =$ **match** v **with** $\mathbf{0} \to e_0 \mid \mathbf{S}\ x \to e_S$. Assume that $S;\Gamma;X_1,X_2 \vdash^m e : t$ from i) $S;\Gamma;X_1 \vdash v : \mathbf{nat} :: P$, ii) $S;\Gamma,v=\mathbf{0};X_2 \vdash e_0 : t$, iii) $S;\Gamma,x:\mathbf{nat},v = \mathbf{S}\ x;X_2 \vdash e_S : t$, and iv) $S;\Gamma \vdash t :: P$. By induction hypothesis on iv), we have $[\![t]\!]_\xi \in \mathscr{R}_P$. Hence, by (CR3), it suffices to show that $e' \in [\![t]\!]_\xi$ whenever $e\theta \to e'$. By induction hypothesis on i), $v\theta \in [\![\mathbf{nat}]\!]_\xi = \mathscr{I}_{\mathbf{nat}}$. Since $v\theta$ is a value, $v\theta \in \mathscr{I}_{\mathbf{nat}}$ implies that $v\theta = \mathbf{0}$ or $v\theta = \mathbf{S}\ v'$ for some $v' \in \mathscr{I}_{\mathbf{nat}} = [\![\mathbf{nat}]\!]_\xi$.

  — If $v\theta = \mathbf{0}$, then $e\theta \to e_0\theta \in [\![t]\!]_\xi$ by induction hypothesis on ii).
  — If $v\theta = \mathbf{S}\ v'$ with $v' \in [\![\mathbf{nat}]\!]_\xi$, then $e\theta \to (e_S\theta)[v'/x] = e_S\theta^{v'}_x$. Since, $v' \in [\![\mathbf{nat}]\!]_\xi$, we have that the pair $(\xi,\theta^{v'}_x)$ validates $\Gamma,x:\mathbf{nat}$. By the induction hypothesis on iii), we obtain $e_S\theta^{v'}_x \in [\![t]\!]_\xi$.

- The case T-Sub directly follows from the invariance of interpretation by subtyping.
- The cases T-Drop, T-V are done by direct application on the induction hypothesis.
- All other cases implies $c \neq P$. □

Lemma 10 (Normalization of the P-level reduction)**.**
If $S;\Gamma;X \vdash^m e : t$ with $S;\Gamma \vdash t :: P$, then $e \in SN$.

Proof. Let $\xi(\Gamma)$ be defined by:

$$\begin{array}{ll}
\xi(\varepsilon) & = \varepsilon \\
\xi(\Gamma, x{:}t) & = \xi(\Gamma) \\
\xi(\Gamma, a{::}\kappa) & = \xi(\Gamma)_a^{\top\kappa} \\
\xi(\Gamma, v_1 = v_2) & = \xi(\Gamma) \\
\xi(\Gamma, a = t) & = \xi(\Gamma)_a^{[\![t]\!]_{\xi(\Gamma)}}
\end{array}$$

It is immediate that $(\xi(\Gamma), \varepsilon)$ validates the environment Γ, and by Lemma 9, $e \in [\![t]\!]_{\xi(\Gamma)}$. By Lemma 6, $[\![t]\!]_{\xi(\Gamma)} \in \mathscr{R}_P$. By condition (CR1), $[\![t]\!]_{\xi(\Gamma)} \subseteq \mathbf{SN}$. Hence, $e \in \mathbf{SN}$. $\square$

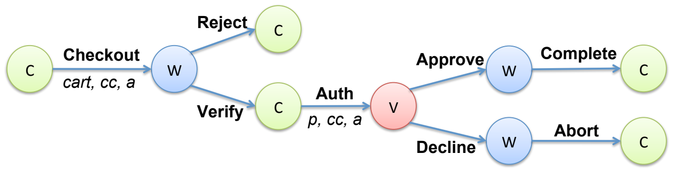
Theorem 3 is obtained as a direct corollary of Lemma 10.

5 Security applications in F*

We outline two larger security applications written and verified in F*, showing how its design enables compact yet precise specifications that can be verified by typechecking.

5.1 Multi-party sessions

Multi-party sessions (Honda *et al.* 2008; Bhargavan *et al.* 2009; Deniélou & Yoshida 2011) offer a powerful method to structure and build distributed message-based applications when their message flow is fixed beforehand. Consider a 3-party session between a customer (c), a website (w), and a credit-card verifier (v), with the message flow below:



The customer initiates a Checkout session for buying some items (*cart*), billed to her credit card *cc* for the total amount *a*. The web site then either rejects the transaction outright, or asks for credit card verification. The customer is redirected to a verification server and provides a password (p) to authorize payment of a on her credit card *cc*. The verifier then either confirms or declines payment to the web site, who completes or aborts the session accordingly.

Intuitively, such a session specifies a global contract between component programs in a distributed application. Every program promises to play one role of the session and, in return, it expects the others to correctly play their roles. For instance, w promises not to charge more than a, and not to abort the transaction if the payment is approved: c can rest assured that if she receives an Abort message, her credit card has not been charged.

A variety of type systems have been proposed to verify that a program complies with a session role; each of those type systems is tailored to a specific set of session primitives and programming language features. Instead, we encode multi-party sessions as F* types. By standard F* typing, we can verify that a program correctly plays a session role. Following Bhargavan *et al.* (2009), even if some programs deviate from their role at run-time (because they have been taken over by an attacker, for example), we show how the rest of the application can protect itself by using a custom cryptographic protocol. Other related work on session types focuses on enforcing session compliance in the absence of malicious adversaries. Honda *et al.* (2008) develop special-purpose type systems for multi-party asynchronous sessions. They do not consider security or source code verification. Also related is work by Kiselyov *et al.* (2010), who add type functions to Haskell and show how these can be used to program simple two-party sessions.

5.2 A session API in F*

We define a generic session API for distributed applications to enforce a multi-party session discipline. We start with a simplified version of our API, then build up to showing our model of more complex features.

To begin with, we ignore the values (*cart*, *cc*, *a*, *p*) passed in the session and aim to control the sequence of messages a session participant can send and receive. Using affine types, we can define a type for a *role process*, **type** role0::$E \Rightarrow A$, where the parameter of the role is a type describing an automaton. The types used to define these automata are purely specificational—they are given E-kind. A value of a role process type is a handle that gives a program the capability to enact the automaton. We show two simple automata types provided by our API, and a function that consumes and returns a role handle.

```
type Send0 :: m::⋆ ⇒ k::(m ⇒ E) ⇒ E
type Done :: E
val send: msg:m → role0 (Send0 m k) → role0 (k msg)
```

The Send0 automaton is indexed by two types—the first, a type m of the message to be sent by the process; the second, a type k representing a *continuation process*, where the process is dependent on the value of type m sent in the first state. Done represents a finished automaton. Using these automata, we can define the following role process type that represents a program that first sends an integer x, then an integer y greater than x, and then concludes. Recall that in concrete syntax, we write **fun** (x:t) ⇒ t' for a type-level function $\lambda x{:}t.t'$; **fun** _ ⇒ t' ignores its type argument.

```
role0 (Send0 int (fun (x:int) ⇒ Send0 (y:int{y > x}) (fun _ ⇒ Done)))
```

Our full API generalizes the automata types above with the notion of a global distributed store for session values; each participant maintains a local view of the store and we ensure, by typing, that these views are consistent. We show below the extended analogs of role0, Send0, and also automata types for receiving a message and for choice-points in the session graph. The type of a role process (role) is parametrized by a store value (of type st); automata types (Send, Recv) are indexed by binary predicates d on st values that define the allowed changes to the store during the next step. The function send allows a client to send a message m and update the store from s0 to s1 given that the current role process is a Send and that the stores satisfy the predicate d attached to Send—client programs calling send have to prove d s0 s1 for some specific instantiation of d, and our type checker uses Z3 to assist with the proof of such ghost refinement properties.

```
type role:: st::⋆ ⇒ E ⇒ st ⇒ A
type Send:: m::⋆ ⇒ st::⋆ ⇒ m ⇒ (st ⇒ st ⇒ E) ⇒ k::(m ⇒ E) ⇒ E
type Recv:: m::⋆ ⇒ st::⋆ ⇒ m ⇒ (st ⇒ st ⇒ E) ⇒ k::(m ⇒ E) ⇒ E
type Choice:: l::E ⇒ r::E ⇒ E
val send: msg:m → s0:st → s1:st{d s0 s1} → role st (Send m st msg d k) s0 → role st (k m) s1
```

The code below shows how we can use this session API to model the website role (*w*) in the example session of §5.1. The type msg defines the set of messages and the type store is the type of the distributed store (including, for this example, the names of each participant in the session, their view of the contents of the shopping cart, etc.) The process automaton involves an alternation of message send and receive, and this type uses two store update predicates (of kind store ⇒ store ⇒ E): Update_id_c_v_cart_cc_a allows initial assignments from the customer to id, c, v, cart, cc, and a; then Unchanged disallows any changes. For clarity, we omit inferrable type arguments writing, for example, role instead of role msg store, Recv instead of Recv msg store etc.

```
type msg = Checkout | Reject | Verify | Auth | Approve | (...)
type store = {id:nat; c:prin; w:prin; v:prin; cart:string; (...) }
type proc_w =
  Recv Checkout Update_id_c_v_cart_cc_a (fun _ ⇒ Choice
    (Send Reject Unchanged (fun _ ⇒ Done)
    (Send Verify Unchanged (fun _ ⇒ Choice
      (Recv Approve Unchanged (fun _ ⇒ Send Complete Unchanged (fun _ ⇒ Done)))
      (Recv Decline Unchanged (fun _ ⇒ Send Abort Unchanged (fun _ ⇒ Done))))))
```

Type soundness ensures that a well-typed program is guaranteed to comply with its declared role process. For example, a program that joins a session in role *w* obtains a role handle of type role proc_w init_store_w. It may then call the receive function (the counterpart of send, not shown here) to receive a Checkout message but cannot call send; subsequently, it may call send with either a Reject or a Verify message, but not both.

In earlier work, Bhargavan *et al.* (2009) show how to encode multi-party sessions as refinement types in F7. However, since the F7 type system does not support generic predicate-indexed types, such as Send above, they encode the session using verbose, session-specific logical formulas rather than types. Our use of higher-order kinds yields session specifications that are, in general, one-third the size of the corresponding F7 specifications. Moreover, F7 lacks affine types, and they have to prove by hand, with the help of an awkward continuation-passing style encoding, that their applications use role handles linearly.

5.3 Custom cryptographic protocols for session consistency

Distributed applications typically run in an untrusted environment, where the network and one or more of the session participants may be under the control of malicious adversaries. In this scenario, cryptographic mechanisms, such as digital signatures, can be used to ensure that all honest session participants have consistent states. For example, when the client *c* receives an Abort message from the website *w*, it may demand that this message include a valid signature proving that card verifier *v* sent a "Declined" message, to prevent a malicious *w* from double-crossing *c*.

Bhargavan *et al.* (2009) show how to systematically use cryptographic evidence as proof of session compliance. They compile multi-party sessions to efficient custom cryptographic protocols that exchange and check a minimal number of digital signatures to ensure global session consistency. Their compiled protocols use session types and cryptography in the style of F7: without higher-order kinds, affinity, or predicate-indexed types.

We implement secure multi-party sessions in F* using protocol libraries adapted from those of Bhargavan *et al.*, but instead using the crypto library of §2.3 and the sessions API shown above. In our example session, the Abort message from w to c carries two digital signatures, one from w and one from v, each signature authenticating the last message sent by the corresponding principal and the values in its store at that time. On receiving the Abort message, c verifies these signatures and checks that they conform to the session type: in particular, that the signature from v says that v sent a Decline message and not an Approve. The resulting type for the recv_Abort function (a specialization of the generic receive function in our API) is as follows:

```
type Aborted:: w:prin ⇒ st_w:store ⇒ E
type Declined:: v:prin ⇒ st_v:store ⇒ E
val recv_Abort:
  st_c:store → role (RecvCompleteOrAbort) st_c →
  (st_c':store ∗ role Done st_c'){
    Unchanged st_c st_c' ∧
    Says st_c.w (∃ st_w. Aborted st_c.w st_w ∧ Unchanged st_w st_c') ∧
    Says st_c.v (∃ st_v. Declined st_c.v st_v ∧ Unchanged st_v st_c')}
```

The function takes the current store st_c at c and a role handle for c that must be in the state after c has sent Auth. The function returns an (unchanged) store st_c' and a new (completed) role handle. The E-kinded predicates Aborted and Declined represent the session states at the other roles. For example, Declined p st means that the principal p, playing role v previously sent a Decline when it had a store st. Hence, the post-condition says that the principals st_c.w and st_c.v (playing w, v) claim to be in the states Aborted st_c.w st_w and Declined st_c.v st_v where the stores st_w and st_v are the same as c's store st_c'. So if v is honest, then even if w is malicious, it cannot cause c to accept an Abort unless v sent a Decline. Note that the post-condition is a ghost refinement that is proved here using a combination of cryptographic evidence and F* typechecking.

5.4 Encoding advanced session constructs in F*

The automata types shown above are adequate to represent a wide variety of static sessions that do not use delegation or parallelism. Adding constructors for recursive sessions is straightforward. We now show how to extend our API to capture a limited form of parallelism, inspired by the dynamic multi-role session types of Deniélou & Yoshida (2011).

Distributed applications often run several instances of the same role in parallel, for scalability. For example, a web site may run several copies of a web server all connected to the same backend database. Or, a client may fork several processes that may communicate with a server in parallel, in an arbitrary order. To verify such applications we extend our sessions API with three new automata types: Fork, Join, and Await.

The Fork automaton (given below) enables a role to fork multiple instances of a child role, transfer control to them, and then wait for them to complete. These child role processes may either execute sequentially (in any order), or in parallel. Each child process is given a unique principal name which it can use when communicating with its parent or with other roles. The Join automaton enables the child role to transfer control back to the parent; and Await represents a parent role process waiting for its children to complete. We illustrate Fork and its use in an application below, where we elide the store for simplicity (and so use role0 instead of role).

```
type Fork :: ps:list prin ⇒ parentProc::E
          ⇒ childProc::(role0 (Await ps parentProc) ⇒ prin ⇒ E ) ⇒ E
let go ps : role0 Done =
  let client = startClient ps in
  let client, children = fork ps client in
  let children =
    map (fun (q, child) →
          let child = send0 Request child in
          let Response, child = receive0 child in
          (q, child)) children in
  join ps client children
```

The function go forks a number of children (indexed by a given list of principals ps). Each child sends a Request message, then receives a Response message and then joins its parent (p). Here, the variable client is a role handle that has an automaton type of the form Fork ps Done ChildRole, where the automaton ChildRole sends a Request, receives a Response and then Joins its parent. Since role handles have an affine type, the code here passes client in and out of every session operation. The variable children is given an affine list type, which guarantees that the different child processes cannot interfere with each other; in other words each Response can be accurately correlated with its corresponding Request.

5.5 Privacy-friendly smart metering

As another security application, we consider a privacy protocol. Utility providers are deploying smart meters for billing customers for their use of electricity, gas, etc. These meters provide frequent readings (up to every minute) so that variable rates and billing policies may be applied for each time period, depending on contracts between utilities and customers. However, many customers are reluctant to disclose such detailed readings, as they leak information about their private life: ideally, the utility providers should get the aggregate fee once a month, not the series of individual readings.

Rial & Danezis (2010) develop privacy-friendly zero-knowledge cryptographic protocols for smart metering. We implement and verify their simpler, ‘fast protocol’, which applies to linear policies: for some given series of readings $\vec{x}$ and rates $\vec{p}$, the monthly fee is the scalar product $z = \vec{x}.\vec{p}$. Skimming over most cryptographic details, the protocol goes as follows: at the end of the month, the customer collects readings $\vec{x}$ from the meter and rates $\vec{p}$ from the utility provider, and it builds cryptographic evidence that he owes z without disclosing any extra information on $\vec{x}$. The protocol relies on homomorphic commitments (Pedersen 1992): instead of signing the readings $\vec{x}$, the meter signs blinded commitments $\vec{c}$ to those readings, and also gives their corresponding openings $\vec{r}$ to the customer; the customer computes $z = \vec{x}.\vec{p}$ and $r = \vec{r}.\vec{p}$, then sends z, r, and the signed commitments $\vec{c}$ to the utility provider. For each reading x_i and opening r_i, the commitment is $c_i = g^{x_i}h^{r_i}$ in some large multiplicative group. The opening r_i is sampled uniformly at random, so x_i and c_i are statistically independent and, as long as r_i is secret, the scheme is ‘perfectly hiding’: the commitments do not leak any information about the readings. The utility provider verifies the meter's signature, computes $c = \prod_{n=1..N} c_i^{p_i}$, and checks that $c = g^f h^r$. Inasmuch as the customer cannot effectively compute any other opening that would pass this check, the scheme is 'computationally binding'.

Our F⋆ implementation includes a new library supporting Pedersen commitments. We rely on the .NET BigInt library for multiplications and modular exponentiations on 2048-bit integers and use ghost refinements on Commit to keep track of committed values. We give below the types of functions for building and verifying commitments, and a computational assumption stating that a commitment can be opened to at most one value. In addition, our library supports vectors of commitments and their operations, with refinements that state, for instance, that Commit x0 r0 c0 and Commit x1 r1 c1 imply Commit (x1+x0) (r0+r1) (c0∗c1).

We finally briefly present the code of the utility function verify_payment, which performs the verification steps explained above: (1) calls verify_meter_signature to confirm the existence of genuine readings xs for the received commitments, line 7; (2) calls scalarExp in Commitment, to compute $\prod_{n=1..N} c_i^{p_i}$ with (ghost) post-condition ∃xs,x,r. Readings xs && ScalarProduct xs ps x && Commit x r c; (3) calls verify on the result and the received x and r. In conjunction with the injectivity assumption on line 4, this suffices to prove the post-condition on line 10 that expresses our security goal: if b is true, then indeed $z = \vec{x}.\vec{p}$ for the readings $\vec{x}$ issued by the meter.

```
1  type Commit:: num ⇒ num ⇒ exp ⇒ P
2  val commit: x:num → (r:num ∗ c:exp{ Commit x r c })
3  val verify: x:num → r:num → c:exp → b:bool{ b=true ⇒ Commit x r c }
4  assume ∀c x0 x1 r0 r1. Commit x0 r0 c && Commit x1 r1 c ⇒ x0 = x1
5  (...)
6  val verify_meter_signature: cs:vec → dsig → b:bool
7  { b=true ⇒ (∃(xs:vec),(rs:vec). Readings xs && Commits xs rs cs)}
8  val verify_payment:
9     ps:vec → cs:vec → s: dsig → x: num → r: num → b: bool
10    { b=true ⇒ (∃ (xs:vec).Readings xs && ScalarProduct xs ps x)}
11 let verify_payment ps cs s x r =
12    let b = verify_meter_signature cs s in if b = true then
13    let c = scalarExp Readings cs ps in verify x r
14    else false
```

Backes *et al.* (2008) also verify authentication properties of zero-knowledge protocols, but they extend F7 with special-purpose types that represent zero-knowledge proofs. Instead, our types use the generic higher-order kinds available in F⋆ (but not in F7).

6 Implementation and experimental evaluation

This section describes the implementation of our prototype F⋆ compiler and its experimental evaluation on a variety of programs (about 20,000 lines of code) selected from the F⋆ developments mentioned in the Introduction.

Typechecking. The F⋆ compiler consists of about 35,000 lines of F# code and is still under active development. It is based on the type-preserving compiler for Fine (Swamy *et al.* 2010; Chen *et al.* 2010). It takes as input a partially annotated F⋆ program and desugars it into a core syntax that closely follows the syntax of Section 3. Then, it applies a heuristic, bidirectional type inference algorithm while asking logical queries of Z3. In order for this process to succeed, the user generally interacts with the typechecker in several rounds. A failed verification attempt causes the typechecker to report a source location requiring the application of a type conversion relation that was unable to be proven (e.g., a `x:int` was provided where a `nat` was expected, and Z3 was unable to prove $x \geq 0$). When this happens, the user typically begins to add assertions at that program point to deduce which facts the theorem prover is able to derive, and which are as yet underivable. Sometimes, the added assertions provide useful lemmas for the theorem prover to discharge the main proof obligation; other times, failed assertions suggest missing or incorrect annotations which the user then rectifies. With some practice, this process can be reasonably quick, although improving the user interaction is substantial future work. For example, following work on verification debuggers for tools like Boogie (Goues *et al.* 2011) and Why3 (Filliâtre & Paskevich 2013), we hope to provide users with more structured information about failed verification attempts using counterexample models from the theorem prover.

Once the source program has been checked, a fully annotated program is passed to a second, *core* typechecker. The core typechecker is itself implemented in F* and is certified to correctly implement the type system of Section 3 (Strub *et al.* 2012), i.e., programs accepted by the core typechecker are proven to be type correct in the formal semantics of F*. Section 7 provides more information on the core typechecker.

Compilation. Typechecked source programs are finally compiled to RDCIL, an extension of DCIL (Chen *et al.* 2010), which is in turn an extension of a functional core of CIL, the .NET bytecode language. DCIL is the target language of Fine, and extends CIL with type-level functions and value parameters (in addition to type parameters) in class declarations, to model value-dependent types in the source language. Building on DCIL, RDCIL also supports ghost refinements, which capture the translation of ghost refinements in F*. RDCIL programs are also checked for refinement type safety using Z3, providing confidence in our compiler.

Interoperability. For backwards compatibility, the additional type constructs in RDCIL are encoded as custom attributes. Thus, RDCIL binaries can run on stock .NET virtual machines, can access libraries of other .NET languages (e.g., C# and F#), and can be called from those languages. Of course, interoperating with non-refinement type-safe languages must be done with care. Informally, we follow a discipline where other .NET languages interact with F* programs only via a simply typed interface.

Reducing the size of generated bytecode. In comparison with Fine and DCIL, the addition of ghost refinement types to F* and RDCIL leads to a marked improvement in the size of compiled programs, Concrete refinements in Fine and DCIL are represented as pairs of a value and proof term, where, in some cases, proof terms increase the code size by 50x. The F* compiler addresses this difficulty by relying on the RDCIL typechecker to reconstruct proofs by refinement type checking, rather than relying on explicit proofs. As a result, RDCIL programs contain far fewer proofs compared to DCIL, and the overhead of proofs and types is only 60% for our benchmarks. The F* compiler also reduces the size of generated bytecode (ignoring proofs and custom attributes for types), because higher-order dependent kinds allow a more concise translation of polymorphic types and higher-order code. Combining the two factors, the F* compiler produces binaries an order of magnitude smaller than those produced by Fine, as much as a 45x improvement.

	F* code size		Fine code size		Attr+/	Attr-/	Attr+/	Attr-/
Benchmark	Attr+	Attr-	Proof+	Proof-	Proof+	Proof+	Attr-	Proof-
Authac	15 K	12 K	30 K	20 K	0.50	0.4	1.3	0.6
Iflow	27 K	18 K	840 K	30 K	0.03	0.02	1.5	0.6
Automaton	28 K	15 K	40 K	20 K	0.70	0.38	1.9	0.8
HealthWeb	76 K	48 K	2.1 M	80 K	0.04	0.02	1.6	0.6
Lookout	147 K	81 K	1.8 M	120 K	0.08	0.05	1.8	0.7
ConfRM	72 K	51 K	3.3 M	110 K	0.02	0.02	1.4	0.5
Total	365 K	225 K	8.1 M	380 K	0.05	0.03	1.6	0.6
ProofLib	7 M	5 M	51 M	51 M	0.14	0.1	1.4	0.1

Fig. 7. Code size (in bytes)

6.1 Benchmarks and measurements

Code size. We compile the Fine benchmarks of Chen *et al.* (2010) with the F* compiler, treating all refinement types as ghost refinements. This way, no proofs are extracted. Figure 7 shows the names of the benchmarks (column Benchmark), the F* code size (in bytes) with and without custom attributes for the additional types (Attr+ and Attr- respectively), and Fine size (in bytes) with and without proofs reported in (Chen *et al.* 2010) (Proof+ and Proof- respectively). The Fine numbers reflect only proof overhead, not attributes.

Because of no proofs, the code size overhead is simply the custom attributes for encoding more expressive types than the CIL types. Column "Attr+/Attr-" shows that RDCIL code with those custom attributes is about 1.3x–1.9x of the code without the custom attributes, with an average 60% overhead for the custom attributes. Our current implementation simply uses compressed strings of pretty-printing types as custom attributes. A smarter encoding may further reduce the size overhead.

The RDCIL code is about an order of magnitude smaller than the DCIL code for the Fine benchmarks. Column "Attr+/Proof+" shows that the RDCIL code (with custom attributes) is about 3%–70% of the DCIL code (with proofs), with an average of 5%—a 20x improvement. Column "Attr-/Proof+" shows that the RDCIL code (without custom attributes) is about 2%–38% of the DCIL code (with proofs), with an average of 3%—indicating a 30x improvement in this configuration, although the accurate breakdown is hard to obtain because Fine numbers do not include custom attributes. Benchmarks with fewer proofs, such as Authac and Automaton, show less reduction. Column "Attr-/Proof-" shows that the pure code size of RDCIL is about 10% to 80% of that of DCIL, with an average of 60%—a 40% reduction due to a more expressive type language. Prooflib is purely refinement-free code. The 10x reduction in code size is entirely due to dependent higher kinds.

Compilation and typechecking times. Figure 8 shows the time taken to typecheck and compile the Fine benchmarks as well as several new F* programs we develop ourselves. For each program, it shows number of lines of source code (LOC), source parsing and checking time (SrcChk, in seconds), compilation of F* to RDCIL time (Trans), target checking time (TgtChk), and the number of queries made to Z3 by the source checker (SrcQry) and target checker (TgtQry). All measurements were performed on a 2.67 GHz two-core Intel Core i7 CPU running Windows 7.

Benchmark	LOC	SrcChk (S)	Trans (S)	TgtChk (S)	SrcQry	TgtQry
Authac	37	0.2	0.1	0.2	1	1
Iflow	119	0.8	0.4	0.5	25	18
Automaton	117	0.3	0.2	0.3	5	4
HealthWeb	330	2.3	1.9	1.1	33	10
Lookout	502	2.4	2.4	1.9	29	33
ConfRM	704	2.7	2.5	1.8	63	21
Prooflib	10,694	20.8	258.3	14.7	0	0
HealthwebEnh	766	8.0	8.5	5.8	156	83
HigherOrderIter	150	1.0	3.5	1.6	13	13
HigherOrderFoldr	108	2.3	5.8	0.9	10	6
Permission	251	4.1	4.3	5.5	29	29
Iflow_state	204	0.8	0.6	0.8	7	14
Provenance	221	1.6	1.5	0.8	22	17
Browser exts	785	3.1	3.3	3.8	89	55
DynSessions	211	0.7	0.5	0.2	0	0

Fig. 8. Compilation and typechecking times

HealthwebEnh is a cloud application managing an electronic medical record database, interacting with code written in ASP.NET, C#, and F#. It is about twice as big as the Fine HealthWeb benchmark, and is deployable on Microsoft Windows Azure. HigherOrderIter and HigherOrderFoldr implement higher-order functions that iterate over lists. Permission implements a stateful API of collections and iterators that guarantee that the collection underlying an iterator is never modified while an iteration is in progress. Iflow_state provides an information-flow tracking library for stateful programs. Provenance is a larger version of the curated database in §2.6. Browser exts is a suite of 17 browser extensions, verified for authorization and information flow properties. DynSessions is the example of §5, including fork/join parallelism.

The F* compilation and typechecking is reasonably efficient and quite comparable to that of the Fine compiler. Fine and F* source typechecking times are roughly equivalent. F* translation is faster than Fine because there are fewer proofs to translate. Conversely, typechecking RDCIL code with refinement types is slower than checking DCIL proofs, but in view of the many advantages of F*, such as smaller bytecode and more expressive types, we find this trade-off worthwhile. Some of the new F* examples (e.g.,HealthWebEnh) rely heavily on Z3 to automatically discharge (hundreds of) proofs during typechecking. It would be rather arduous to write so many proofs interactively.

Verifying cryptographic applications. Finally, Figure 9 reports source code verification results for several cryptographic protocol examples, many of which were previously developed for F7, and are now verified by F*. The first three examples make more than a thousand queries in total to Z3. Handling these queries contributes to a large chunk of the source checking time.

CryptoLib is a large F7 library implementing symbolic cryptography, which is used in all subsequent applications. KeyManager is a key management application. AuthRPC implements an authenticated RPC protocol. SessionLib is the generic API for multi-party

Example	LOC	SrcChk (S)	SrcQry
CryptoLib	1,530	50.5	426
KeyManager	608	55.6	287
AuthRPC	232	67.9	335
SessionLib	32	0.4	0
Commit	126	1.5	28
Forward	131	1.3	22
Metering	111	0.6	3

Fig. 9. Source code verification of cryptographic applications

sessions (§5), used to securely implement a two-party session Commit and a three-party session Forward. Metering is a privacy-friendly zero-knowledge cryptographic protocol for smart metering (Rial & Danezis 2010).

7 Further work

We have compared F* to Fine, F7, Aura, Coq, Agda, and discussed other related work in detail throughout this paper. Another language worth discussing is Trellys (Kimmell *et al.* 2012). Like F*, Trellys aims to isolate a safe proof language to express properties about effectful computations. However, the means by which these ends are achieved are rather different. For example, rather than resort to a kind system to isolate a normalizing sub-language, Trellys relies on a judgmental notion of values combined with constructs that allow discriminating on potentially divergent expressions within the proof language. This yields an interesting new proof methodology, although the design of Trellys remains preliminary. (As far as we are aware, the soundness proof of Trellys is as yet incomplete.) Also, Trellys considers only divergence as an effect, whereas F* incorporates many other primitive effects—our stratified presentation combined with the kind system makes it relatively easy to handle these features in the metatheory.

In the remainder of this section, we briefly review further work based on F* in a variety of contexts, complementing the results in this paper.

Self-certification. Strub *et al.* (2012) propose a general technique called *self-certification* that allows a typechecker for a suitably expressive language to be certified for correctness, and illustrate it using F*. Self-certification involved implementing a core typechecker for F* in approximately 5,500 lines of F* code, while using all the conveniences F* provides for the compiler-writer (e.g., partiality, effects, implicit conversions, proof automation, libraries). This core typechecker is given a specification (in F*) strong enough to ensure that it computes valid typing derivations. Running the core typechecker on itself yields a typing derivation for the core typechecker, which is exported to Coq as a type-derivation certificate. By typechecking this derivation (in Coq) and applying the F* metatheory (also mechanized in Coq; see §4), Strub et al. formally conclude that the typechecker is correct. Once certified in this manner, the F* typechecker is emancipated from Coq, i.e., programs accepted by the core typechecker are guaranteed to be formally well-typed in Coq, without having to run Coq itself.

Monadic $F^\star$**.** Schlesinger & Swamy (2012) define a monadic dialect of $F^\star$ based on a monad of predicate transformers that they call the *Dijkstra state monad*. This monad provides $F^\star$ with a customizable type inference algorithm, or, equivalently, a weakest pre-condition calculus. Their methodology involves a liberal use of higher-order logic, but, when specifications are structured in their prescribed style, the resulting higher-order verification conditions can be normalized and encoded in a first-order theory, e.g., in the logic provided by an automated solver like Z3. They use monadic $F^\star$ to verify a number of programs, ranging from small classic combinators to web applications and security protocols. We emphasize, however, that the core $F^\star$ calculus remains unchanged, justifying the design choices made in this paper. As such, programmers in $F^\star$ have several complementary ways of verifying effectful programs, e.g., the linear maps of §2 for state, the session types of §5 for IO, and, also monadic $F^\star$ which can be used to precisely model a range of monadic effects including exceptions, state, IO, reactivity, etc.

Verifying JavaScript programs. Swamy *et al.* (2013) apply monadic $F^\star$ to the problem of verifying JavaScript programs. Using a new refinement of the type dyn (§2.1), they show how JavaScript programs translated to $F^\star$ (via a standard translation provided by Guha *et al.* (2010)) can be given precise specifications and verified in a modular manner using monadic $F^\star$'s verification condition (VC) generator combined with its encoding of higher-order VCs in Z3. In evaluating this approach, Swamy et al. develop JSVerify, a library of JavaScript runtime primitives (e.g., operations to allocate objects, to implement JavaScript's calling convention, etc.), in all some 1,500 lines of fully verified, heavily higher-order and stateful code. In addition, they show how a collection of web-browser extensions authored in JavaScript can be translated to monadic $F^\star$ and verified there for a variety of safety properties.

Translating $F^\star$ ***to JavaScript.*** Many tools allow programmers to develop applications in high-level languages and deploy them in web browsers via compilation to JavaScript. While practical and widely used, these compilers are ad hoc. No guarantee is provided on their correctness for whole programs, nor their security for programs executed within arbitrary JavaScript contexts. Fournet *et al.* (2013) present a compiler from (a subset of) $F^\star$ (including higher-order functions, references and exceptions) down to JavaScript, while preserving all source program properties. The main contribution of their work includes a new applicative bisimulation for $F^\star$ (yielding a powerful coinductive technique for proving equivalences on $F^\star$ programs), and they show how to use this bisimulation to prove that the translation from $F^\star$ to JavaScript is fully abstract. Providing further evidence for the suitability and expressiveness of $F^\star$ for practical program verification tasks, Fournet et al. use monadic $F^\star$ and the mechanically verified JSVerify library to facilitate the proof of full abstraction, e.g., they use the types of monadic $F^\star$ to show that the translation from $F^\star$ to JavaScript is types preserving and to maintain a heap shape invariant. The translation to JavaScript, in conjunction with the type-preserving translation to .NET mentioned in this paper, allows $F^\star$ programs to be deployed in a wide variety of settings while obtaining formal assurances of the security of the deployed code.

Relational $F^\star$**.** The applicative bisimulation of Fournet et al. provides a manual proof technique for program equivalence in $F^\star$. In order to mechanically check proofs of program equivalence, and other relations between multiple programs or multiple executions of a single program (i.e., *hyperproperties* (Clarkson & Schneider 2010)), Barthe *et al.* (2012) present a probabilistic, relational variant of F* called RF*. They prove the soundness of this language using a denotational semantics for RF*, in contrast to the operational formalization used in this paper. Through careful language design, they adapt the monadic F* typechecker to generate both classic and relational verification conditions, and to automatically discharge their proofs using Z3. Thus, they are able to benefit from the existing features of F*, including, for example, its abstraction facilities that support modular reasoning about program fragments. They evaluate RF* experimentally by programming a series of cryptographic constructions and protocols, and by verifying their security properties, ranging from information flow to unlinkability, integrity, and privacy.

***A DSL with an authorization logic in* F*.** To facilitate the easy construction and deployment of authorization protocols, Jeannin *et al.* (2013) develop DKAL*, a domain specific language that embeds the DKAL authorization logic (Gurevich & Neeman 2008) within F*. Protocol and policy designers can use DKAL*'s authorization logic for expressing distributed trust relationships, and its small rule-based programming language to describe the message sequence of a protocol. Importantly, many low-level details of the protocol (e.g., marshaling formats, management of state consistency etc.) are left abstract in DKAL*, but sufficient details must be provided in order for the protocol to be executable. Jeannin et al. formalize the semantics of DKAL*, giving it both an operational semantics and a type system. They also present an interpreter for DKAL*, programmed and mechanically verified in F* for correctness and security.

In summary, in addition to the experimental evaluation in this paper, the aforementioned efforts have used F* for building and verifying a wide variety of programs, ranging from typecheckers and compilers to distributed programs and cryptographic constructions. As we continue to gain experience with F*, its core system presented in this paper has remained mostly unchanged. The most significant changes since our original presentation (Swamy *et al.* 2011) have been the revised kind hierarchy (motivated primarily to streamline our metatheoretic development) and the addition of other effects (such as exceptions, required to embed JavaScript). Thus, we conclude that the value-dependent types provided by F* identifies a sweet spot in the wide design space of dependently typed programming languages—the language is expressive enough for a variety of practical and theoretical programming tasks, incorporating complex language features like effects, while enjoying a formal and relatively simple metatheory.

Acknowledgements: We thank the editors of JFP, the chair of ICFP 2011, and all the anonymous reviewers at both venues for their help in improving this work.

References

Augustsson, L. (1998). Cayenne - a language with dependent types. *In International Conference on Functional Programming*.

Avijit, K., Datta, A., & Harper, R. (2010). Distributed programming with distributed authorization. *In Types in Language Design and Implementation*.

Backes, M., Hritcu, C., & Maffei, M. (2008). Type-checking zero-knowledge. *In Computer and Communications Security*.

Barendregt, H., Abramsky, S., Gabbay, D. M., Maibaum, T. S. E., & Barendregt, H. P. (1992). Lambda Calculi with Types. *Handbook of Logic in Computer Science*. Oxford University Press.

Barthe, G., Grégoire, B., & Pastawski, F. (2006). CIC$\hat{}$: Type-based termination of recursive definitions in the calculus of inductive constructions. *In Logic for Programming, Artificial Intelligence, and Reasoning*.

Barthe, G., Fournet, C., Gregoire, B., Strub, P.-Y., Swamy, N., & Beguelin, S. Z. (2012). *Probabilistic relational verification for cryptographic implementations*. Tech. rept. MSR-TR-2012-37. Microsoft Research.

Bengtson, J., Bhargavan, K., Fournet, C., Gordon, A. D., & Maffeis, S. (2008). Refinement types for secure implementations. *In Computer Security Foundations Symposium*.

Bertot, Y., & Castéran, P. (2004). *Coq'art: Interactive theorem proving and program development.* Springer Verlag.

Bhargavan, K., Fournet, C., & Gordon, A. D. (2010). Modular verification of security protocol code by typing. *In Principles of Programming Languages*.

Bhargavan, K., Corin, R., Dénielou, P.-M., Fournet, C., & Leifer, J. (2009). Cryptographic protocol synthesis and verification for multiparty sessions. *In Computer Security Foundations Symposium*.

Borgstrom, J., Chen, J., & Swamy, N. 2011 (Jan.). Verifying stateful programs with substructural state and hoare types. *In Programming Languages meets Program Verification*.

Cervesato, I., & Pfenning, F. (2002). A linear logical framework. *Information and Computation*, **179**(1).

Chapin, P. C., Skalka, C., & Wang, X. S. (2008). Authorization in trust management: Features and foundations. *ACM Computing Surveys*, **40**.

Chen, J., Chugh, R., & Swamy, N. (2010). Type-preserving compilation of end-to-end verification of security enforcement. *In Programming Language Design and Implementation*.

Clarkson, M., & Schneider, F. (2010). Hyperproperties. *Journal of Computer Security*, **18**(6).

de Moura, L., & Bjørner, N. (2008). Z3: An efficient SMT solver. *In Tools and Algorithms for the Construction and Analysis of Systems*.

Deniélou, P.-M., & Yoshida, N. (2011). Dynamic multirole session types. *In Principles of Programming Languages*.

Dybjer, P. (2000). A general formulation of simultaneous inductive-recursive definitions in type theory. *Journal of Symbolic Logic*, **65**(2).

Felleisen, M., & Hieb, R. (1992). The revised report on the syntactic theories of sequential control and state. *Theoretical Computer Science*, **103**(2).

Filliâtre, J.-C., & Paskevich, A. (2013). Why3 - where programs meet provers. *In European Symposium on Programming*.

Fournet, C., Gordon, A. D., & Maffeis, S. (2007). A type discipline for authorization policies in distributed systems. *In Computer Security Foundations Symposium*.

Fournet, C., Kohlweiss, M., & Strub, P.-Y. (2011). Modular code-based cryptographic verification. *In Computer and Communications Security*.

Fournet, C., Swamy, N., Chen, J., Dagand, P.-É., Strub, P.-Y., & Livshits, B. (2013). Fully abstract compilation to JavaScript. *In Principles of Programming Languages*.

Girard, J.-Y. (1972). *Interprétation fonctionelle et élimination des coupures de l'arithmétique d'ordre supérieur*. Ph.D. thesis, Université Paris VI I.

Gonthier, G., Mahboubi, A., & Tassi, E. (2011). *A Small Scale Reflection Extension for the Coq system*. Research Report RR-6455. INRIA.

Gordon, A. D., & Jeffrey, A. (2003). Authenticity by typing for security protocols. *Journal of Computer Security*, **11**(4).

Goues, C. L., Leino, K. R. M., & Moskal, M. (2011). The Boogie verification debugger (tool paper). *In Software Engineering and Formal Methods*.

Guha, A., Saftoiu, C., & Krishnamurthi, S. (2010). The essence of JavaScript. *In European Conference on Object-Oriented Programming*.

Guha, A., Fredrikson, M., Livshits, B., & Swamy, N. (2011). Verified security for browser extensions. *In Security and Privacy*.

Gurevich, Y., & Neeman, I. (2008). DKAL: Distributed-Knowledge Authorization Language. *In Computer Security Foundations Symposium*.

Guts, N., Fournet, C., & Nardelli, F. Z. (2009). Reliable evidence: Auditability by typing. *In European Symposium on Research in Computer Security*.

Honda, K., Yoshida, N., & Carbone, M. (2008). Multiparty asynchronous session types. *In Principles of Programming Languages*.

Jeannin, J.-B., de Caso, G., Chen, J., Gurevich, Y., Naldurg, P., & Swamy, N. (2013). DKAL*: Constructing Executable Specifications of Authorization Protocols. *In Engineering Secure Software and Systems*.

Jia, L., & Zdancewic, S. (2009). Encoding information flow in Aura. *In Programming Languages and Analysis for Security*.

Jia, L., Vaughan, J., Mazurak, K., Zhao, J., Zarko, L., Schorr, J., & Zdancewic, S. (2008). Aura: A programming language for authorization and audit. *In International Conference on Functional Programming*.

Kimmell, G., Stump, A., Eades, III, H. D., Fu, P., Sheard, T., Weirich, S., Casinghino, C., Sjöberg, V., Collins, N., & Ahn, K. Y. (2012). Equational reasoning about programs with general recursion and call-by-value semantics. *In Programming Languages meets Program Verification*.

Kiselyov, O., Peyton-Jones, S., & Shan, C.-C. (2010). *Fun with type functions*. Preprint, Microsoft Research.

Lahiri, S. K., Qadeer, S., & Walker, D. (2011). Linear maps. *In Programming Languages meets Program Verification*.

McCarthy, J. (1962). Towards a mathematical science of computation. *In IFIP Congress*.

Mendler, N. P. (1987). *Inductive definition in type theory*. Ph.D. thesis, Cornell University, United States.

Nanevski, A., Morrisett, G., Shinnar, A., Govereau, P., & Birkedal, L. (2008). Ynot: dependent types for imperative programs. *In International Conference on Functional Programming*.

Norell, U. (2007). *Towards a practical programming language based on dependent type theory.* Ph.D. thesis, Chalmers Institute of Technology.

Pedersen, T. P. (1992). Non-interactive and information-theoretic secure verifiable secret sharing. *In Advances in Cryptology*.

Rial, A., & Danezis, G. (2010). *Privacy-friendly smart metering*. Tech. rept. Microsoft Research.

Schlesinger, C., & Swamy, N. (2012). *Verification condition generation with the Dijkstra state monad*. Tech. rept. Microsoft Research.

Sewell, P., Zappa Nardelli, F., Owens, S., Peskine, G., Ridge, T., Sarkar, S., & Strnisa, R. (2010). Ott: Effective tool support for the working semanticist. *Journal of Functional Programming*, **20**(1).

Sozeau, M. (2007). Subset coercions in Coq. *In Types for Proofs and Programs*.

Sozeau, M. (2010). Equations: A dependent pattern-matching compiler. *In Interactive Theorem Proving*.

Strub, P.-Y., Swamy, N., Fournet, C., & Chen, J. (2012). Self-certification: bootstrapping certified typecheckers in F* with Coq. *In Principles of Programming Languages*.

Stump, A., Deters, M., Petcher, A., Schiller, T., & Simpson, T. (2008). Verified programming in Guru. *In Programming Languages meets Program Verification*.

Swamy, N., Corcoran, B. J., & Hicks, M. (2008). Fable: A language for enforcing user-defined security policies. *In Security and Privacy*.

Swamy, N., Chen, J., & Chugh, R. (2010). Enforcing stateful authorization and information flow policies in Fine. *In European Symposium on Programming*.

Swamy, N., Chen, J., Fournet, C., Strub, P.-Y., Bhargavan, K., & Yang, J. (2011). Secure distributed programming with value-dependent types. *In International Conference on Functional Programming*.

Swamy, N., Weinberger, J., Schlesinger, C., Chen, J., & Livshits, B. (2013). Verifying higher-order programs with the Dijkstra monad. *In Programming Languages Design and Implementation*.

The Coq Development Team. (2010). *Chapter 4: Calculus of Inductive Constructions*. Tech. rept. INRIA.

Vaughan, J. A., Jia, L., Mazurak, K., & Zdancewic, S. (2008). Evidence-based audit. *In Computer Security Foundations Symposium*.

Volpano, D., Smith, G., & Irvine, C. (1996). A sound type system for secure flow analysis. *Journal of Computer Security*, **4**(3).