Linear Types for Large-Scale Systems Verification

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Verifying large systems

◀ VeriBεtrKV
[Hance OSDI’20]

on-disk crash-safe KV-store

44K lines code+proof in Dafny

31K lines of generated C++

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performance focus

goal: scale verification techniques

Verifying large systems

VeriBεtrKV
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goal: scale verification techniques

success with Dafny, but

Challenges in SMT memory reasoning with dynamic frames (Dafny)

proof burden	developer effort
verification time	developer iteration time
diagnostics	

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proof burden — developer effort

verification time

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developer iteration time

compound at scale

Challenges in SMT memory reasoning with dynamic frames (Dafny)

proof burden — developer effort

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compound at scale

we measured them and set out to improve them

```
class Account {
  var balance: nat;
}


method Transfer(source: Account, dest: Account, amount: nat)
  requires source.balance >= amount

  ensures source.balance == old(source.balance) - amount
  ensures dest.balance == old(dest.balance) + amount
  modifies source, dest
{
  source.balance := source.balance - amount;
  dest.balance := dest.balance + amount;
}


method Main(acct: Account)
requires acct.balance >= 100
{
  Transfer(acct, acct, 100)
}
```

```
class Account {
  var balance: nat;
}


method Transfer(source: Account, dest: Account, amount: nat)
  requires source.balance >= amount

  ensures source.balance == old(source.balance) - amount
  ensures dest.balance == old(dest.balance) + amount    postcondition might not hold
  modifies source, dest
{
  source.balance := source.balance - amount;
  dest.balance := dest.balance + amount;
}


method Main(acct: Account)
requires acct.balance >= 100
{
  Transfer(acct, acct, 100)
}
```

```
class Account {
  var balance: nat;
}


method Transfer(source: Account, dest: Account, amount: nat)
  requires source.balance >= amount
  requires source != dest
  ensures source.balance == old(source.balance) - amount
  ensures dest.balance == old(dest.balance) + amount     postcondition might not hold
  modifies source, dest
{
  source.balance := source.balance - amount;
  dest.balance := dest.balance + amount;
}


method Main(acct: Account)
requires acct.balance >= 100
{
  Transfer(acct, acct, 100)
}
```

```
class Account {
  var balance: nat;
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method Transfer(source: Account, dest: Account, amount: nat)
  requires source.balance >= amount
  requires source != dest
  ensures source.balance == old(source.balance) - amount
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  modifies source, dest
{
  source.balance := source.balance - amount;
  dest.balance := dest.balance + amount;
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method Main(acct: Account)
requires acct.balance >= 100
{
  Transfer(acct, acct, 100)
}
```

a precondition might not hold

```
class Account {
  var balance: nat;
}


method Transfer(source: Account, dest: Account, amount: nat)
  requires source.balance >= amount

  ensures source.balance == old(source.balance) - amount
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  modifies source, dest
{
  source.balance := source.balance - amount;
  dest.balance := dest.balance + amount;
}


method Main(acct: Account)
requires acct.balance >= 100
{
  Transfer(acct, acct, 100)
}
```

postcondition might not hold

logic error or
missing framing condition?

Dynamic frames address potential aliasing

general, but costly

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general, but costly

- vague error messages

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- vague error messages
- framing invariants grow with system size
  - → more proof text

Dynamic frames address potential aliasing

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vague error messages

framing invariants grow with system size
→ more proof text

more difficult for the solver to discharge framing VCs
→ longer verification time

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aliasing isn’t the common case

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demonstrated by Rust’s success

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hypothesis: we can lower development effort by making the non-aliasing code cheaper to reason about

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▶ Linear type system

Linear Dafny

linear type system for SMT-based verification

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type system + SMT solver

extend expressivity of linear types leveraging the solver

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1. memory reasoning with linear types

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1. memory reasoning with linear types
2. regions to address non-linear data

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1. memory reasoning with linear types
2. regions to address non-linear data
3. quantitative and qualitative evaluation
   on a large system (VeriBεtrKV)

Variable usages

		duplicate	compiled
dafny	ordinary	yes	yes
	ghost	yes	

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		duplicate	compiled
dafny	ordinary	yes	yes
	ghost	yes	
linear dafny	shared	yes*	yes
	linear		yes

linear usage

```
linear datatype Account = Account(balance: nat)

method Transfer(linear source: Account, linear dest: Account, amount: nat)
returns (linear source': Account, linear dest': Account)
  requires source.balance >= amount
  ensures source'.balance == source.balance - amount
  ensures dest'.balance == dest.balance + amount
{
  source’ := source;
  dest’ := dest;
  var new_source_balance := source’.balance - amount;
  var new_dest_balance := dest’.balance + amount;
  AccountSetBalance(inout source’, new_source_balance);
  AccountSetBalance(inout dest’, new_dest_balance);
}

method AccountSetBalance(linear inout a: Account, balance: nat)
ensures a.balance == balance
{
  inout a.balance := balance;
}
```

in-place update

linear usage

```
linear datatype Account = Account(balance: nat)

method Transfer(linear source: Account, linear dest: Account, amount: nat)
returns (linear source': Account, linear dest': Account)
  requires source.balance >= amount
  ensures source'.balance == source.balance - amount
  ensures dest'.balance == dest.balance + amount
{
  source’ := source;
  dest’ := dest;
  var new_source_balance := source’.balance - amount;
  var new_dest_balance := dest’.balance + amount;
  AccountSetBalance(inout source’, new_source_balance);
  AccountSetBalance(inout dest’, new_dest_balance);
}
```

shared usage

```
linear datatype Account = Account(balance: nat)

method Transfer(linear source: Account, linear dest: Account, amount: nat)
returns (linear source': Account, linear dest': Account)
  requires source.balance >= amount
  ensures source'.balance == source.balance - amount
  ensures dest'.balance == dest.balance + amount
{
  source’ := source;
  dest’ := dest;
  var new_source_balance := (
                                  borrow source’
    source’.balance - amount;
                                  end of borrow source’
  );
  var new_dest_balance := dest’.balance + amount;
  AccountSetBalance(inout source’, new_source_balance);
  AccountSetBalance(inout source’, new_dest_balance);
}
```

Evaluation

improvement in proof burden at scale
verification time
diagnostics

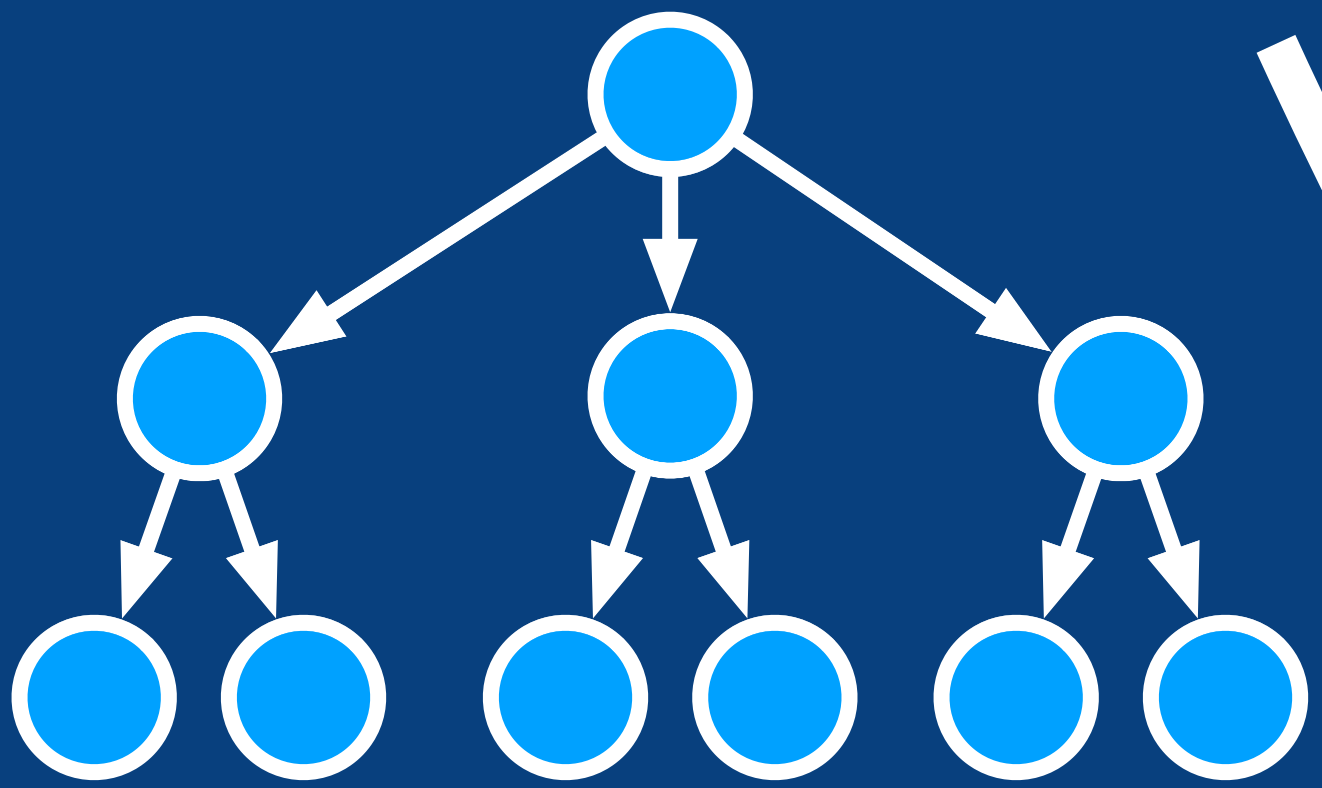
VeribetrKV — 24K lines code+proof
of imperative code

proven equivalent to high-level spec
via state-machine refinement

Conversion To Linear Dafny

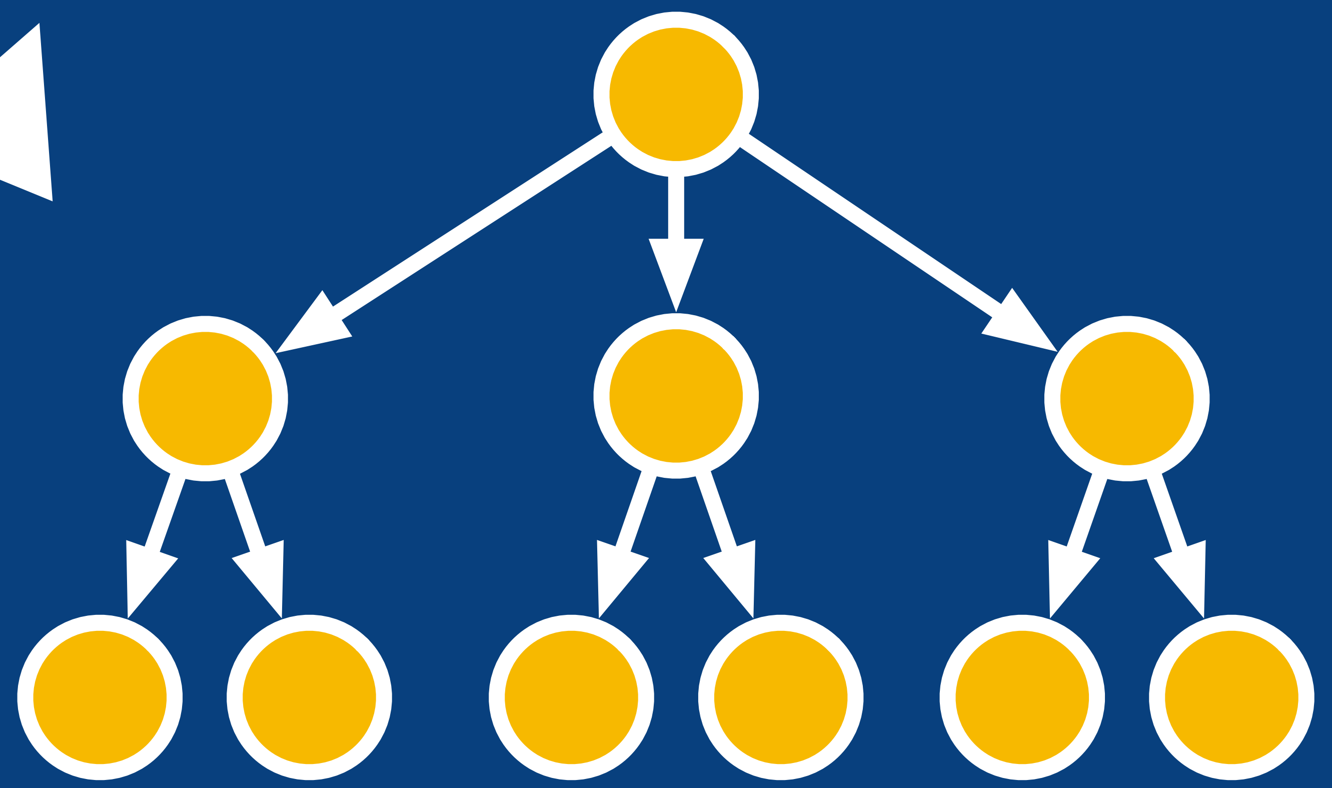
Dynamic frames

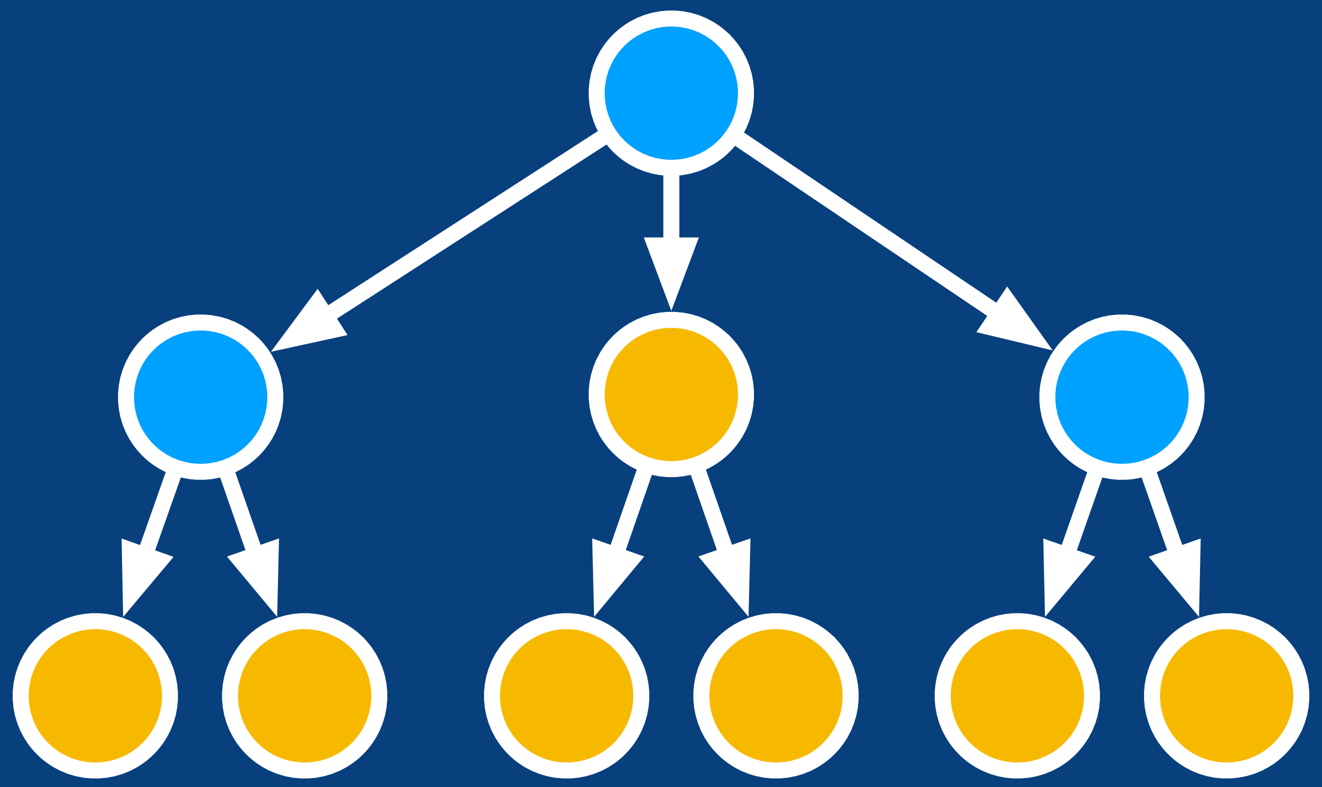
VeribetrKV-DF



Linear types

VeribetrKV-LT





linear data inside non-linear data

🟦 nonlinear component

🟨 linear component

Dynamic frames

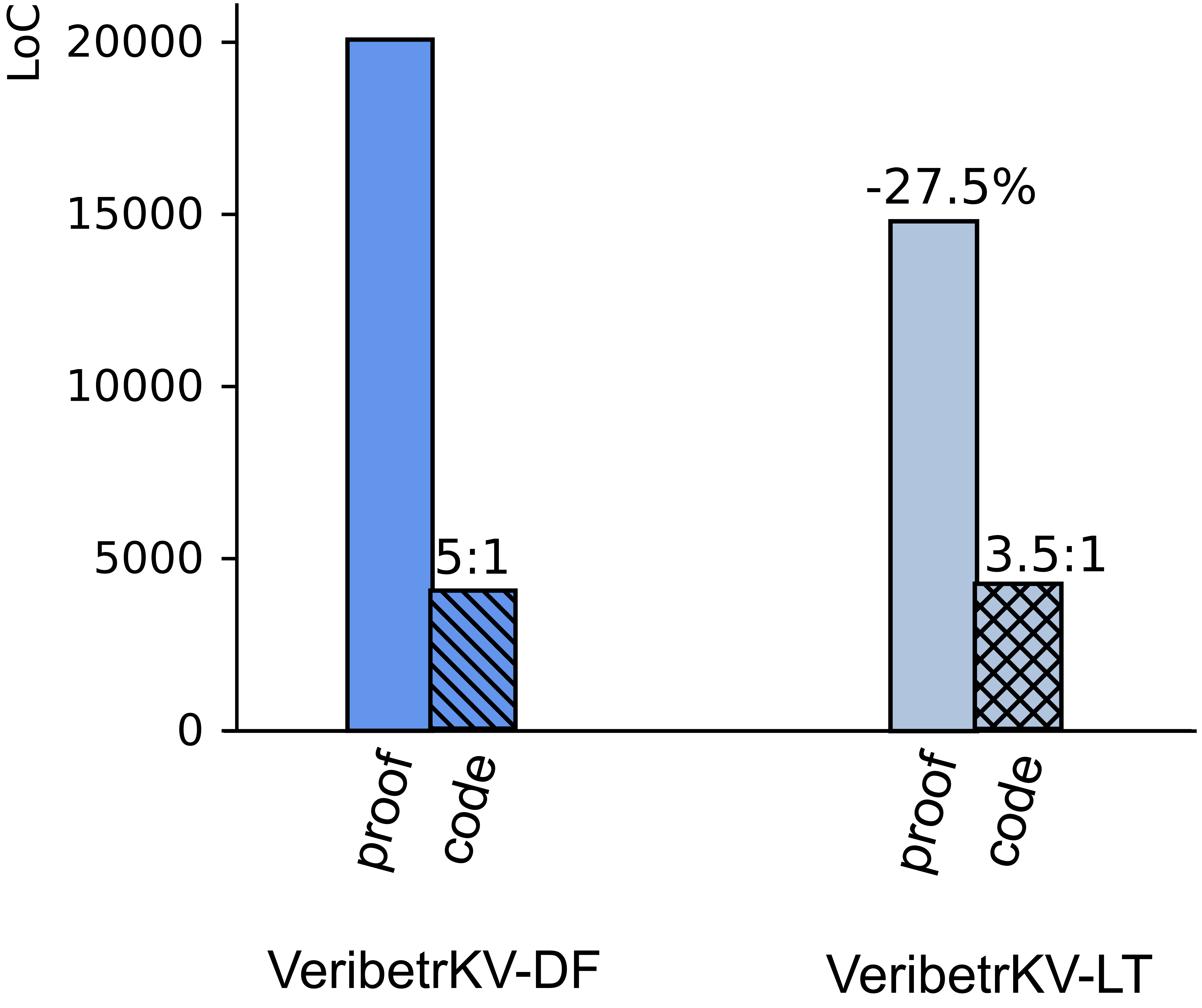
VeribetrKV-DF <> VeribetrKV-LT

Linear types

Proof burden

lines of proof

proof:code ratio



Dynamic frames

VeribetrKV-DF

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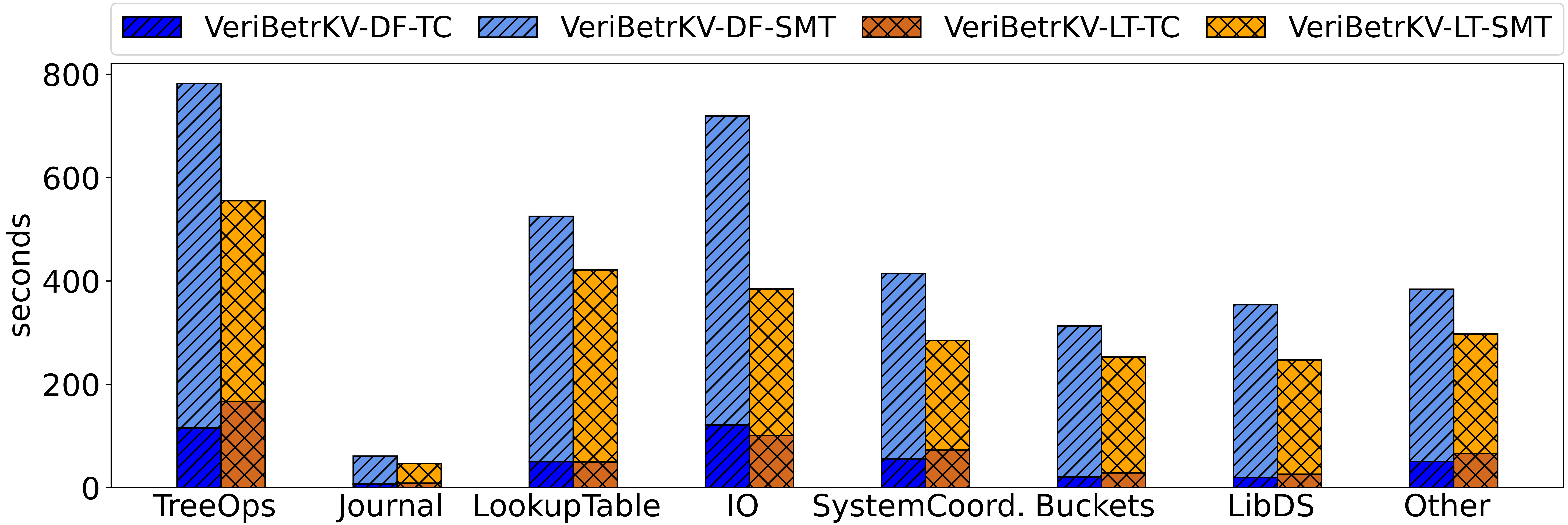
Linear types

VeribetrKV-LT

Verification time proxy for developer iteration time

Type checking (TC), and SMT solving



Dynamic frames

VeribetrKV-DF

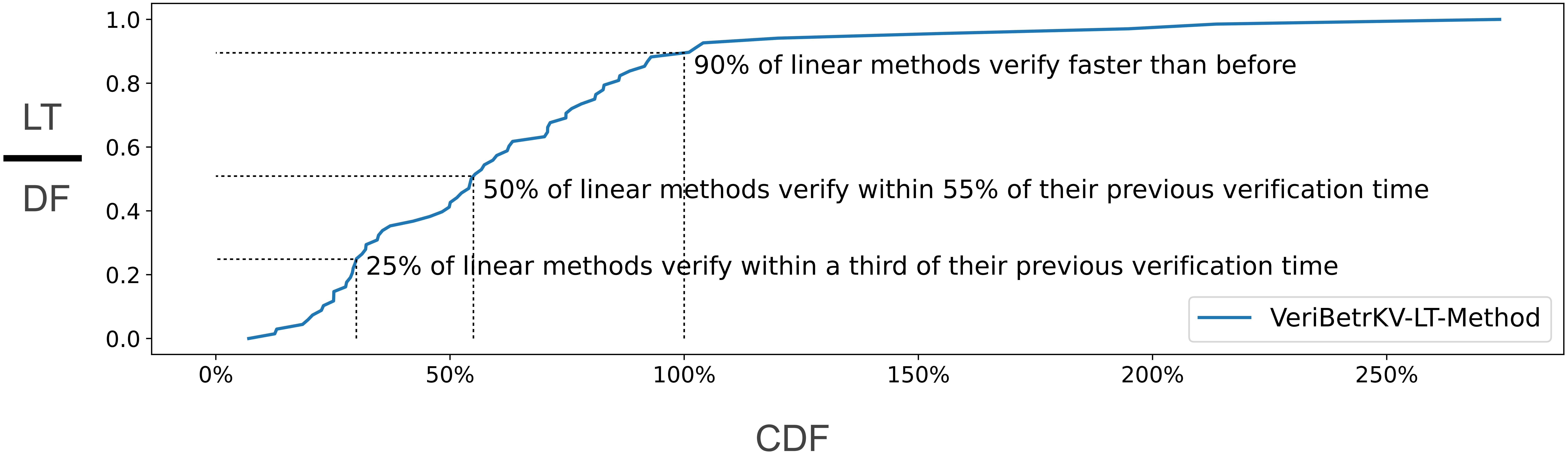
<>

Linear types

VeribetrKV-LT

Verification time improvement

for functions ≥ 5sec



90% of linear methods verify faster than before

50% of linear methods verify within 55% of their previous verification time

25% of linear methods verify within a third of their previous verification time

Linear Dafny

+ immutable+mutable borrowing

+ non-linear inside linear and viceversa

linear type system + SMT-based verification

→ lower developer effort

→ faster developer iteration time

evaluation likely underestimates potential benefits

incremental conversion enabled evaluation

→ improved diagnostics

SMT-based (semi-automated) verification at scale