The Lean standard library

Markus Himmel, Lean FRO

Lean’s “five pillars”

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- Formal mathematics

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- Software and hardware verification

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- Formal mathematics
- Software and hardware verification
- (Verified) software development
- AI research for mathematics and code synthesis
- New math and computer science education methodologies

What’s in the Lean distribution?

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- The language (parser, elaborator, kernel, compiler, runtime, …)

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- The metaprogramming framework
- **The standard library**

What is the standard library?

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It’s what makes Lean into a verification platform.

It is a public API.

What is/will be in the standard library?

1. Core types and operations
    a. Basic types
    b. Numeric types, including floating point numbers
    c. Containers
    d. Strings and formatting
2. Language constructs
3. Libraries
4. Operating system abstractions

What is/will be in the standard library?

1. Core types and operations
2. Language constructs
    a. Ranges and iterators
    b. Comparison, ordering, hashing and related type classes
    c. Basic monad infrastructure
3. Libraries
4. Operating system abstractions

What is/will be in the standard library?

1. Core types and operations
2. Language constructs
3. Libraries
    a. Random numbers
    b. Dates and times
4. Operating system abstractions

What is/will be in the standard library?

1. Core types and operations
2. Language constructs
3. Libraries
4. Operating system abstractions
    a. Concurrency and parallelism primitives
    b. Asynchronous I/O
    c. FFI helpers
    d. Environment, file system, processes
    e. Locales

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All Lean users!

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- Programmers

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  - Lean developers
  - Library authors
- Mathlib users
- Software and hardware verification users
- Individuals evaluating Lean for use

Goals of the standard library

Goals of the standard library

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Useful for real applications

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High-quality and polished: comprehensive, consistent, systematic, optimized, verified, testable, tested, documented, interconnected, stable, comprehensible, visible, benchmarked, …

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Excellent **out-of-the-box experience** for software development and software verification

Setting a high bar

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End goal: make formal verification **economical** and commonplace

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Challenge: things don’t just need to be possible, but **easy and productive**

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Need:

- No missing material

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Need:

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Need a principled approach to quality!

Tooling

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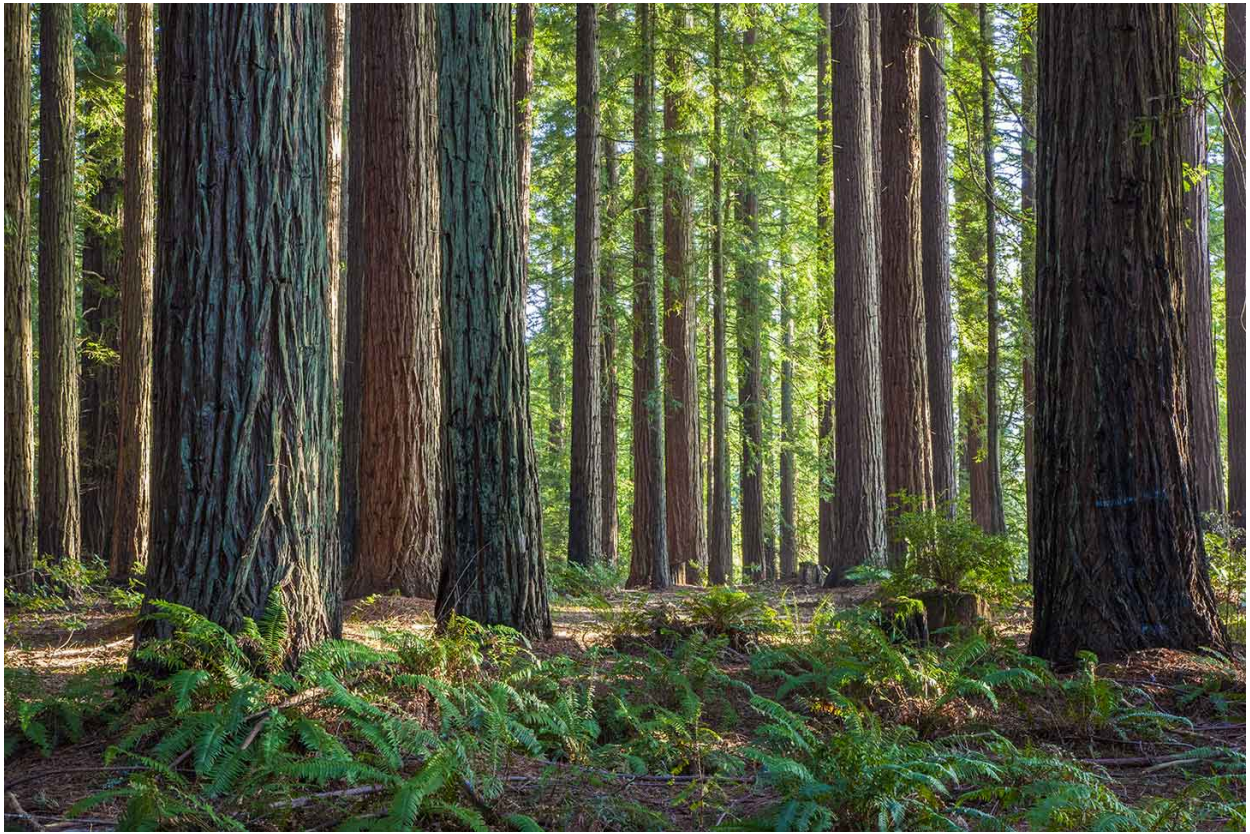
There are gaps!



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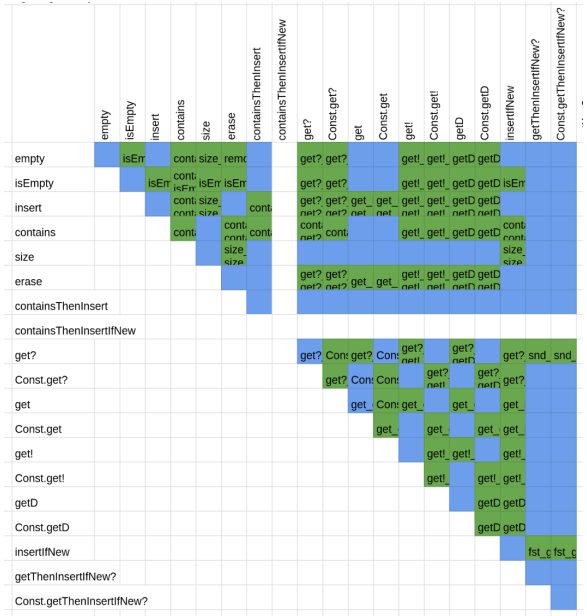
- Quality assurance will always have a **manual** component
- Not all rules can be fully formalized, and many rules will have **exceptions**
- Global **consistency** of the library is desirable
- To understand where we are, we need to be able to **visualize and track** the state of the library

Early experiments

Early experiments



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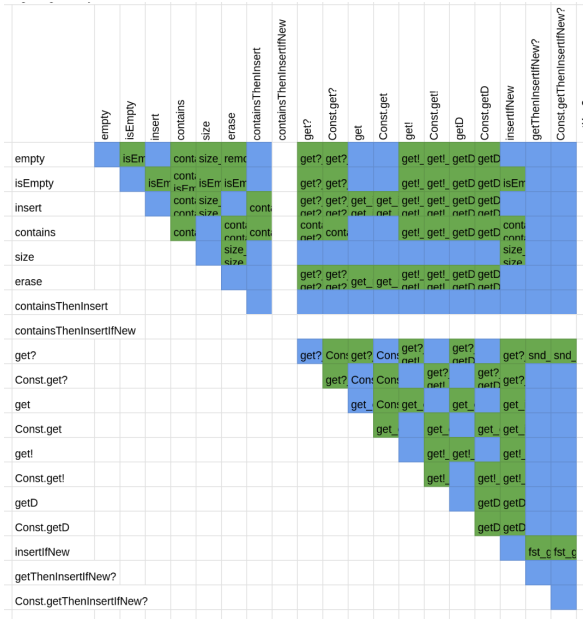
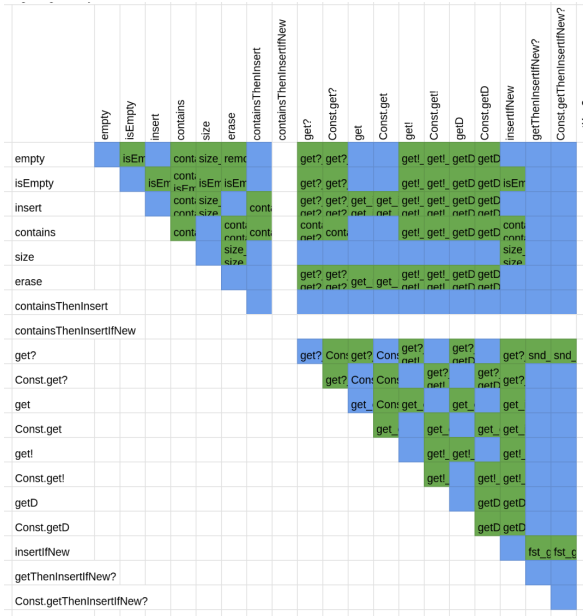


A1 =CONCATENATE("""", JOIN("""","""", A2:A169), """")

	A	B	C	D	E	F
1	"PlainTime","PlainDate","PlainDateTime",[	Std.Time.Plai	Std.Time.Pla	Std.Time.PlainDa	Std.Time.ZonedDa	Std.Time.DateTime
2	PlainTime	X				
3	PlainDate		X			
4	PlainDateTime			X		
5	ZonedDateTime				X	
6	DateTime					X
7	addNanoseconds	X		X	X	X
8	addMilliseconds	X		X	X	X
9	addSeconds	X		X	X	X
10	addMinutes	X		X	X	X
11	addHours	X		X	X	X
12	addDays		X	X	X	X
13	addWeeks		X	X	X	X
14	addMonthsClip		X	X	X	X
15	addMonthsRollOver		X	X	X	X
16	addYearsClip		X	X	X	X
17	addYearsRollOver		X	X	X	X
18	alignedWeekOfMonth		X	X		X
19	atDate	X		X		
20	atTime		X	X		
21	nano					
22	nanosecond	X		X	X	?
23	millisecond	X		X	X	?
24	minute	X		X	X	X
25	second	X		X	X	X
26	hour	X		X	X	X
27	day		X	X	X	X
28	weekOfMonth		X	X	X	X
29	weekOfYear		X	X	X	X
30	weekday		X	X	X	X
31	month		X	X	X	X
32	quarter		X	X	X	X
33	year		X	X	X	X
34	era		X	X	X	X
35	convertZoneRules				X	
36	date			X	X	X
37	time			X	X	?
38	format	X	X	X	X	X
39	fromLeanTime24Hour	X				
40	fromTime12Hour	X				
41	fromTime24Hour	X				
42	fromAmericanDateString		X			
43	fromLeanDateString		X			
44	fromSQLDateString		X			
45	fromAscTimeString			X		X
46	fromDateTimeString			X		
47	fromLeanDateTimeString			X		
48	fromLongDateFormatString			X		X
49	fromDateTimeWithZoneString				X	
50	fromISO8601String				X	
51	fromLeanDateTimeWithZoneString				X	
52	fromRFC822String				X	
53	fromRFC850String				X	
54	toLeanTime24Hour	X				
55	toTime12Hour	X				
56	toTime24Hour	X				

Early experiments



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18	alignedWeekOfMonth		X	X		X
19	atDate	X		X		
20	atTime		X	X		
21	nano					
22	nanosecond	X		X	X	?
23	millisecond	X		X	X	?
24	minute	X		X	X	X
25	second	X		X	X	X
26	hour	X		X	X	X
27	day		X	X	X	X
28	weekOfMonth		X	X	X	X
29	weekOfYear		X	X	X	X
30	weekday		X	X	X	X
31	month		X	X	X	X
32	quarter		X	X	X	X
33	year		X	X	X	X
34	era		X	X	X	X
35	convertZoneRules				X	
36	date			X	X	X
37	time			X	X	?
38	format	X	X	X	X	X
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42	fromAmericanDateString		X			
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45	fromAscTimeString			X		X
46	fromDateTimeString			X		
47	fromLeanDateTimeString			X		
48	fromLongDateFormatString			X		X
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51	fromLeanDateTimeWithZoneString				X	
52	fromRFC822String				X	
53	fromRFC850String				X	
54	toLeanTime24Hour	X				
55	toTime12Hour	X				
56	toTime24Hour	X				

	=CONCATENAT	Fin	BitVec	UInt8	UInt16	UInt32	UInt64	USize	Int8	Int16	Int32	Int64	ISize
120	reduceZeroExtend		X										
121	**Signed arithmetic**												
122	abs		X						?	?	?	?	?
123	neg		X						X	X	X	X	X
124	sdiv		X										
125	smod		X										
126	smtSDiv		X										
127	smtUDiv		X										
128	srem		X										
129	**Unsigned arithmetic**												
130	add	X	X	X	X	X	X	X	X	X	X	X	X
131	div	X		X	X	X	X	X	X	X	X	X	X
132	mod	X		X	X	X	X	X	X	X	X	X	X
133	udiv		X										
134	umod		X										
135	log2	X		X	X	X	X	X					
136	modn	X		X	X	X	X	X					
137	mul	X	X	X	X	X	X	X	X	X	X	X	X
138	sub	X	X	X	X	X	X	X	X	X	X	X	X
139	subNat	X											
140	**Bitwise operations**												
141	land	X		X	X	X	X	X	X	X	X	X	X
142	and		X										
143	lor	X		X	X	X	X	X	X	X	X	X	X
144	or		X										
145	complement			X	X	X	X	X	X	X	X	X	X
146	not		X										
147	xor	X	X	X	X	X	X	X	X	X	X	X	X
148	extractLsb		X										
149	extractLsb'		X										
150	reverse		X										
151	rotateLeft		X										
152	rotateLeftAux		X										
153	rotateRight		X										
154	rotateRightAux		X										
155	shiftConcat		X										
156	shiftLeft	X	X	X	X	X	X	X	X	X	X	X	X
157	shiftRight	X		X	X	X	X	X	X	X	X	X	X
158	sshiftRight		X										
159	sshiftRight'		X										
160	ushiftRight		X										

Next steps

API Manager

Std.DHashMap	Std.HashMap	Std.HashSet
empty	empty	empty
erase	erase	erase
isEmpty	isEmpty	isEmpty
getKey?	getKey?	get?
Membership.mem	Membership.mem	Membership.mem
contains	contains	contains
insertIfNew	insertIfNew	insert
insert	insert	
getD	getD	
get?	get?	
get?	GetElem?.getElem?	

Add Row | Delete Selected Rows | Copy JSON

Step 1: Associate operations across namespaces

Step 2: See which lemmas exist

Step 3: Check lemmas for consistency

Std.HashMap

·	empty	erase	isEmpty	getKey?	contains	insertIfNew	insert	getD	get?	GetElem?.getElem
empty	0|0|0	1|1|1	1|1|1	1|1|1	1|1|1	0|0|0	0|0|0	1|1|0	1|0|0	1|1|0
erase		0|0|0	1|1|1	2|2|2	3|3|3	0|0|0	0|0|0	2|2|0	2|0|0	2|2|0
isEmpty			0|0|0	1|1|1	4|4|4	1|1|1	1|1|0	1|1|0	1|0|0	1|1|0
getKey?				0|0|0	4|4|4	1|1|1	2|2|0	0|0|0	0|0|0	0|0|0
contains					1|1|1	4|4|4	3|3|0	2|2|0	4|0|0	4|4|0
insertIfNew						0|0|0	0|0|0	1|1|0	1|0|0	1|1|0
insert							0|0|0	2|2|0	2|0|0	2|2|0
getD								0|1|0	3|0|0	3|3|0
get?									0|0|0	0|1|0
GetElem?.getElem?										0|0|0

```
Std.DHashMap.getKey?_erase.{u, v} {α : Type u} {β : α → Type v} {xt : BEq α} {xt¹ : Hashable α} {m : Std.DHashMap α β}
  [EquivBEq α] [LawfulHashable α] {k a : α} : (m.erase k).getKey? a = if (k == a) = true then none else m.getKey? a
Std.DHashMap.getKey?_erase_self.{u, v} {α : Type u} {β : α → Type v} {xt : BEq α} {xt¹ : Hashable α}
  {m : Std.DHashMap α β} [EquivBEq α] [LawfulHashable α] {k : α} : (m.erase k).getKey? k = none

Std.HashMap.getKey?_erase_self.{u, v} {α : Type u} {β : Type v} {xt : BEq α} {xt¹ : Hashable α} {m : Std.HashMap α β}
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Std.HashSet.get?_erase.{u} {α : Type u} {xt : BEq α} {xt¹ : Hashable α} {m : Std.HashSet α} [EquivBEq α]
  [LawfulHashable α] {k a : α} : (m.erase k).get? a = if (k == a) = true then none else m.get? a
Std.HashSet.get?_erase_self.{u} {α : Type u} {xt : BEq α} {xt¹ : Hashable α} {m : Std.HashSet α} [EquivBEq α]
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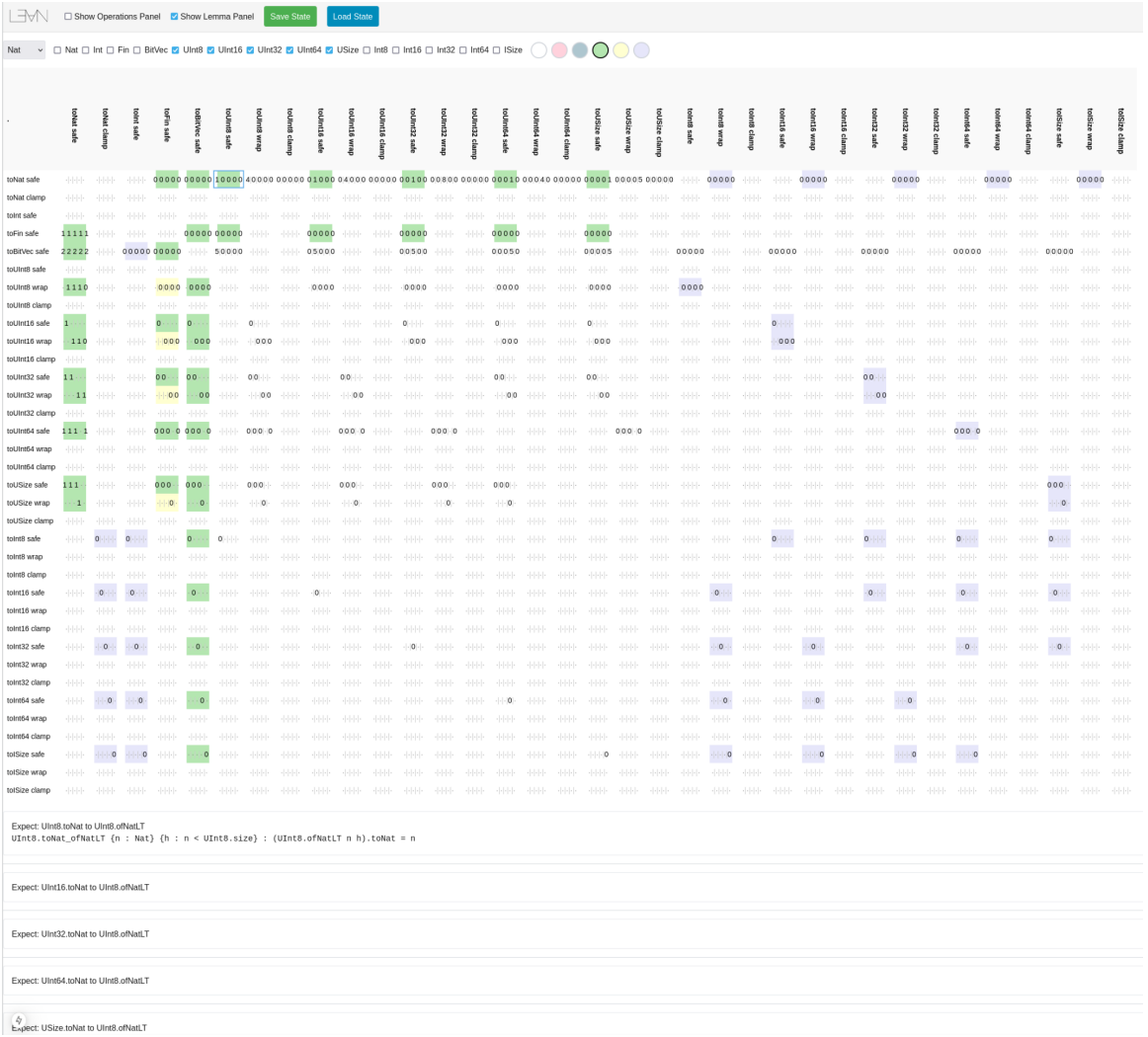
Show Operations Panel
Show Lemma Panel
Save State
Load State
Nat
Int
Fin
BitVec
UInt8
UInt16
UInt32
UInt64
USize
Int8
Int16
Int32
Int64
ISize
Expect: UInt8.toNat to UInt8.ofNatLT
UInt8.toNat_ofNatLT {n : Nat} {h : n < UInt8.size} : (UInt8.ofNatLT n h).toNat = n
Expect: UInt16.toNat to UInt8.ofNatLT
Expect: UInt32.toNat to UInt8.ofNatLT
Expect: UInt64.toNat to UInt8.ofNatLT
Expect: USize.toNat to UInt8.ofNatLT

The result: Grove

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Tool for tracking changes to the entire library

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Basic question: **what do we know?** (and when do we no longer know it?)

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Declaratively and imperatively describe the library and how it should look

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Full power of Lean metaprogramming for extracting state

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Full power of Lean metaprogramming for extracting state

Web UI for analyzing the library

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Basic question: **what do we know?** (and when do we no longer know it?)

Declaratively and imperatively describe the library and how it should look

Full power of Lean metaprogramming for extracting state

Web UI for analyzing the library

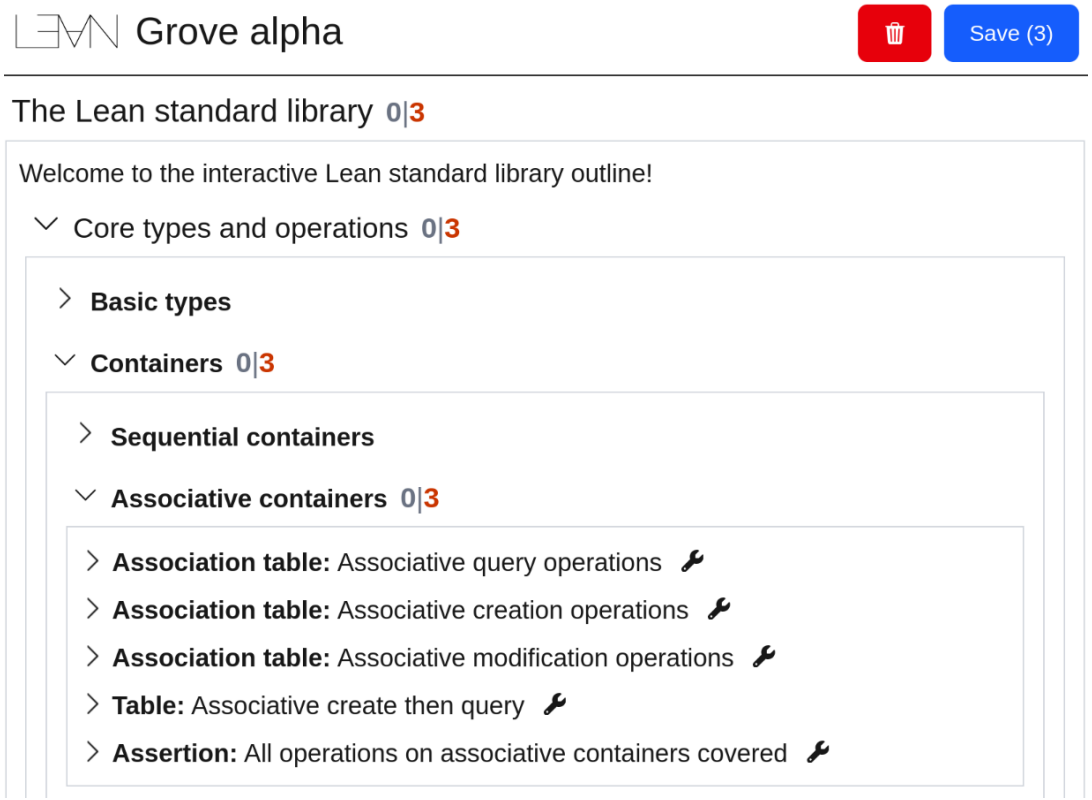
Detects changes in PRs

Grove impressions

```
def associativeContainers : List Lean.Name :=
  [`Std.DHashMap, `Std.DHashMap.Raw, `Std.ExtDHashMap, `Std.DTreeMap,
   `Std.DTreeMap.Raw, `Std.ExtDTreeMap, `Std.HashMap, `Std.HashMap.Raw,
   `Std.ExtHashMap, `Std.TreeMap, `Std.TreeMap.Raw, `Std.ExtTreeMap,
   `Std.HashSet, `Std.HashSet.Raw, `Std.ExtHashSet, `Std.TreeSet,
   `Std.TreeSet.Raw, `Std.ExtTreeSet]

def associativeQueryOperations : AssociationTable .subexpression associativeContainers where
  id := "associative-query-operations"
  title := "Associative query operations"
  description := "Operations that take as input an associative container and return a 'single' pi
  dataSources n :=
    (DataSource.definitionsInNamespace n)
      |>.map Subexpression.declaration
      |>.or (DataSource.getElem n)
```

Grove impressions



Grove impressions

Grove alpha The Lean standard library / Core types and operations / Containers / Associative containers / **Associative query operations**

Title	Std.DHashMap	Std.DHashMap.Raw	Std.ExtDHashMap	Std.DTreeMap	Std.DTreeMap.Raw	Std.ExtDTreeMap	Std.HashMap	Std.HashMap.Raw
isEmpty	Std.DHashMap.isEmpty	Std.DHashMap.Raw.isEmpty	Std.ExtDHashMap.isEmpty	Std.DTreeMap.isEmpty	Std.DTreeMap.Raw.isEmpty	Std.ExtDTreeMap.isEmpty	Std.HashMap.isEmpty	Std.HashMap.Raw.isEmpty
size	Std.DHashMap.size	Std.DHashMap.Raw.size	Std.ExtDHashMap.size	Std.DTreeMap.size	Std.DTreeMap.Raw.size	Std.ExtDTreeMap.size	Std.HashMap.size	Std.HashMap.Raw.size
any				Std.DTreeMap.any	Std.DTreeMap.Raw.any	Std.ExtDTreeMap.any		
all				Std.DTreeMap.all	Std.DTreeMap.Raw.all	Std.ExtDTreeMap.all		
getD	Std.DHashMap.getD	Std.DHashMap.Raw.getD	Std.ExtDHashMap.getD	Std.DTreeMap.getD	Std.DTreeMap.Raw.getD	Std.ExtDTreeMap.getD	Std.HashMap.getD	Std.HashMap.Raw.getD
getElem	Std.DHashMap.get	Std.DHashMap.Raw.Const.get	Std.ExtDHashMap.get	Std.DTreeMap.get	Std.DTreeMap.Raw.get	Std.ExtDTreeMap.get	Std.HashMap[·]	Std.HashMap.Raw[·]
isSingleton						Std.ExtDTreeMap.isSingleton		

	isEmpty	size	getD	getElem
empty	330220	110000	110000	000000
ofList	110000	222112	222222	101111
emptyCollection	653113	225115	221201	002000

Grove impressions

github-actions bot commented on Jul 14 Contributor ···

Grove for revision `ffd9cce`.

Grove invalidations

- `associative-all-operations-covered` / `all-covered`
- `associative-query-operations` / `f084f852-af71-45b6-8ab3-d251a8144f72`

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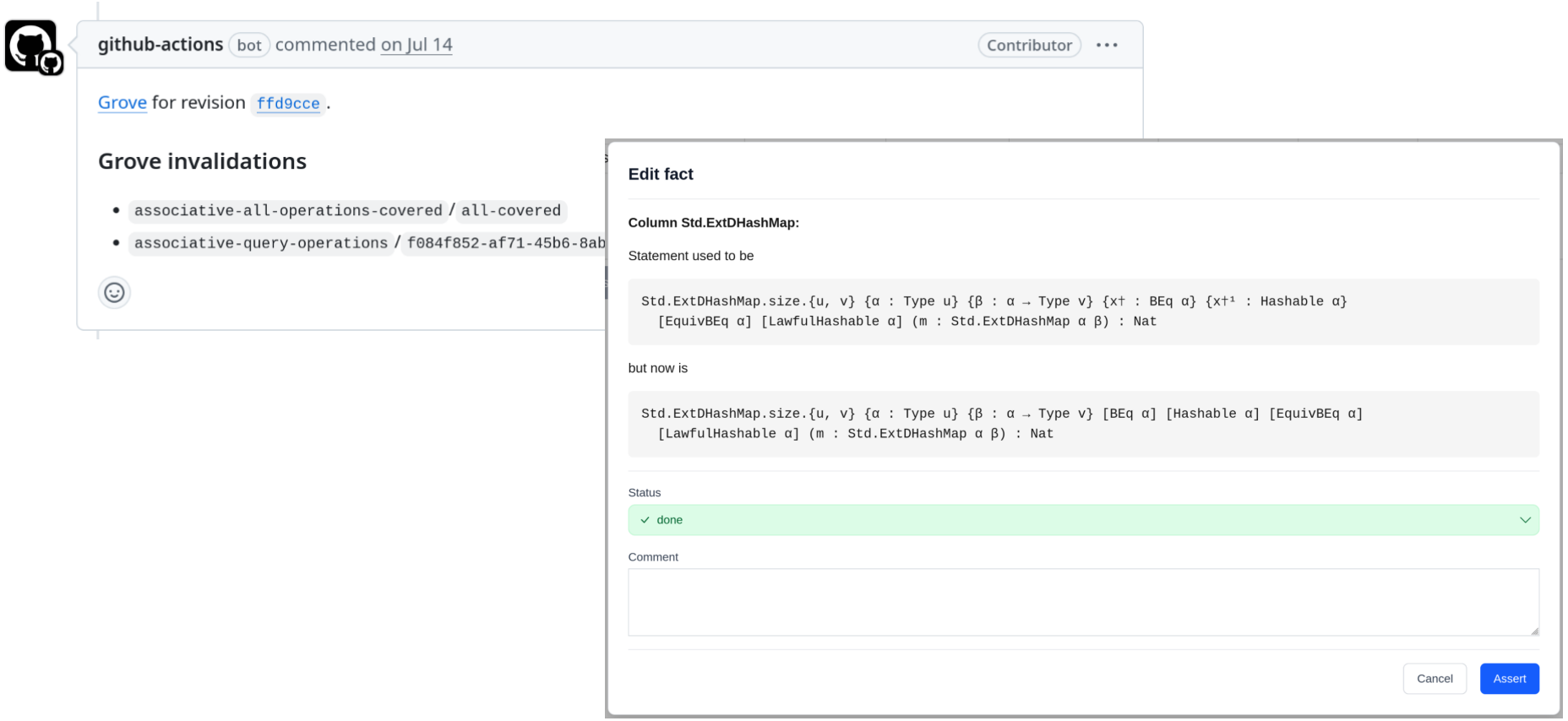

Grove impressions

```
def «5ceaa26a-d2cb-4df3-9ac8-b5c11db2ae9d:::01f88623-fa5f-4380-9772-b30f2fec5c94:::Std.DHashMap::Std.DHashMap.Raw::Std.ExtDHashMap::Std.DTreeMap::Std.DTreeMap.Raw::Std.ExtD
  widgetId := "associative-create-then-query"
  factId := "5ceaa26a-d2cb-4df3-9ac8-b5c11db2ae9d:::01f88623-fa5f-4380-9772-b30f2fec5c94:::Std.DHashMap::Std.DHashMap.Raw::Std.ExtDHashMap::Std.DTreeMap::Std.DTreeMap.Raw::
  rowAssociationId := "5ceaa26a-d2cb-4df3-9ac8-b5c11db2ae9d"
  columnAssociationId := "01f88623-fa5f-4380-9772-b30f2fec5c94"
  selectedLayers := #["Std.DHashMap", "Std.DHashMap.Raw", "Std.ExtDHashMap", "Std.DTreeMap", "Std.DTreeMap.Raw", "Std.ExtDTreeMap", ]
  layerStates := #[
    {
      layerIdentifier := "Std.DHashMap"
      rowState :=

        some ("app (EmptyCollection.emptyCollection) (Std.DHashMap*)", Grove.Framework.Subexpression.State.predicate
          { key := "app (EmptyCollection.emptyCollection) (Std.DHashMap*)", displayShort := "∅" })

      columnState :=

        some ("Std.DHashMap.isEmpty", Grove.Framework.Subexpression.State.declaration
          (Grove.Framework.Declaration.def
            { name := `Std.DHashMap.isEmpty,
              renderedStatement := "Std.DHashMap.isEmpty.{u, v} {α : Type u} {β : α → Type v} {x† : BEq α} {x†' : Hashable α}\n  (m : Std.DHashMap α β) : Bool",
              isDeprecated := false }))

        selectedCellStates := #[
          ("Std.DHashMap.isEmpty_empty", Grove.Framework.Declaration.thm
{ name := `Std.DHashMap.isEmpty_empty,
  renderedStatement := "Std.DHashMap.isEmpty_empty.{u, v} {α : Type u} {β : α → Type v} {x† : BEq α} {x†' : Hashable α} :\n  ∅.isEmpty = true",
  isSimp := true,
  isDeprecated := false })
,
        ]
    },
    {
      layerIdentifier := "Std.DHashMap.Raw"
      rowState :=

        some ("app (EmptyCollection.emptyCollection) (Std.DHashMap.Raw*)", Grove.Framework.Subexpression.State.predicate
          { key := "app (EmptyCollection.emptyCollection) (Std.DHashMap.Raw*)", displayShort := "∅" })

      columnState :=

        some ("Std.DHashMap.Raw.isEmpty", Grove.Framework.Subexpression.State.declaration
          (Grove.Framework.Declaration.def
            { name := `Std.DHashMap.Raw.isEmpty,
              renderedStatement := "Std.DHashMap.Raw.isEmpty.{u, v} {α : Type u} {β : α → Type v} (m : Std.DHashMap.Raw α β) : Bool",
              isDeprecated := false }))

        selectedCellStates := #[
          ("Std.DHashMap.Raw.isEmpty_emptyc", Grove.Framework.Declaration.thm
{ name := `Std.DHashMap.Raw.isEmpty_emptyc,
  renderedStatement := "Std.DHashMap.Raw.isEmpty_emptyc.{u_1, u_2} {α : Type u_1} {β : α → Type u_2} [BEq α] [Hashable α] :\n  ∅.isEmpty = true",
  isSimp := false,
  isDeprecated := true })
,
        ]
    },
    {
      layerIdentifier := "Std.ExtDHashMap"
      rowState :=

        some ("app (EmptyCollection.emptyCollection) (Std.ExtDHashMap*)", Grove.Framework.Subexpression.State.predicate
```

Grove architecture