Verified Software Components

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http://www.cs.clemson.edu/group/resolve
http://cse.osu.edu/rsrg

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Overview

- Two 90-min sessions (separated by afternoon break):
  1. Formal Specification and "Push-Button" Verification
  2. Proof of Correctness of Data Representation

Over

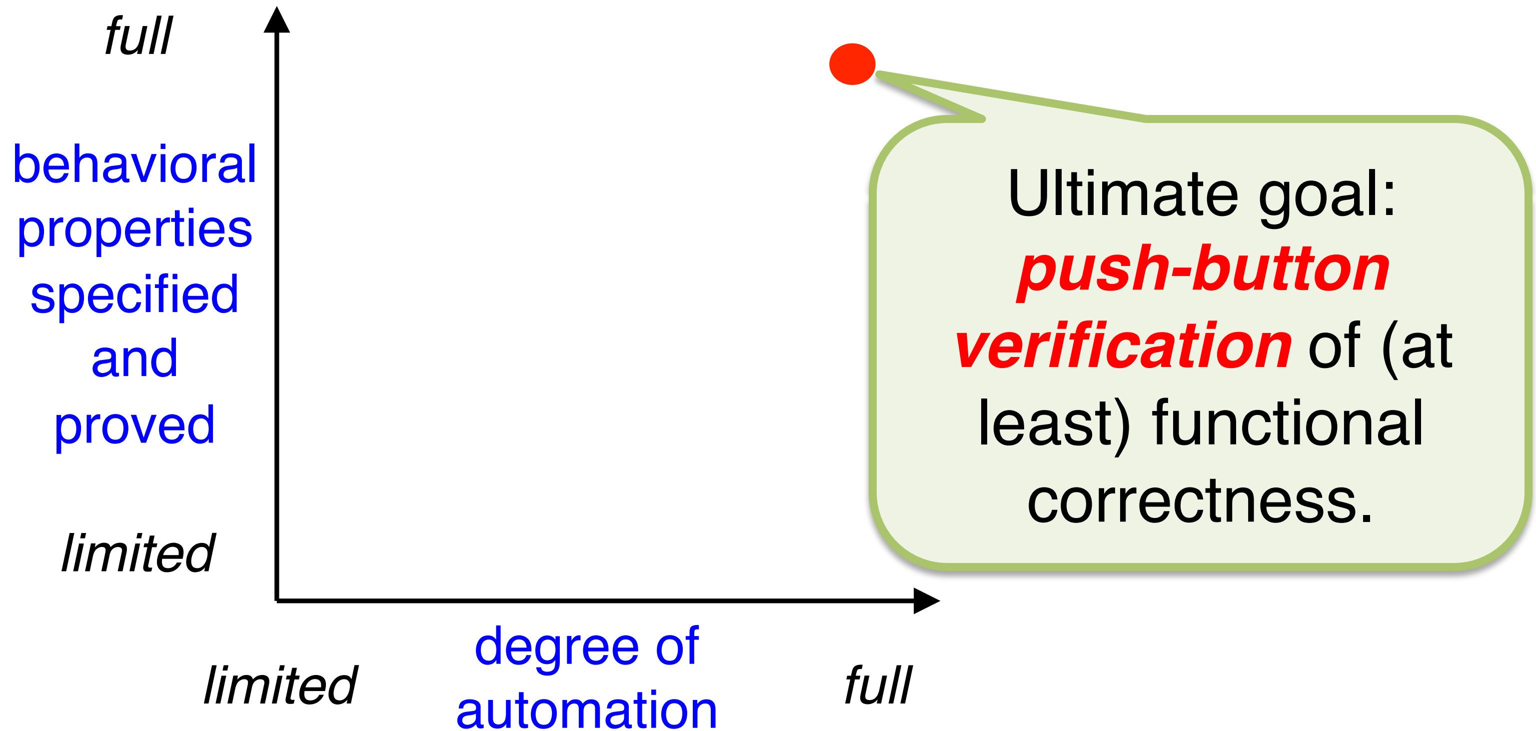
- Two 90-min sessions
  afternoon break):
  1. Formal Specification a "Push-Button" Verification
  2. Proof of Correctness of Data Representation

Session 2 includes time for discussion of audience-suggested research and education issues; so, think of some...

1. Formal Specification and "Push-Button" Verification

- Context: goals; verifying compilers
  - Activity
- Describing behavior of software: mathematical modeling; design-by-contract
  - Activity
- Iteration: loop invariants
  - Activity

Goal and Approaches



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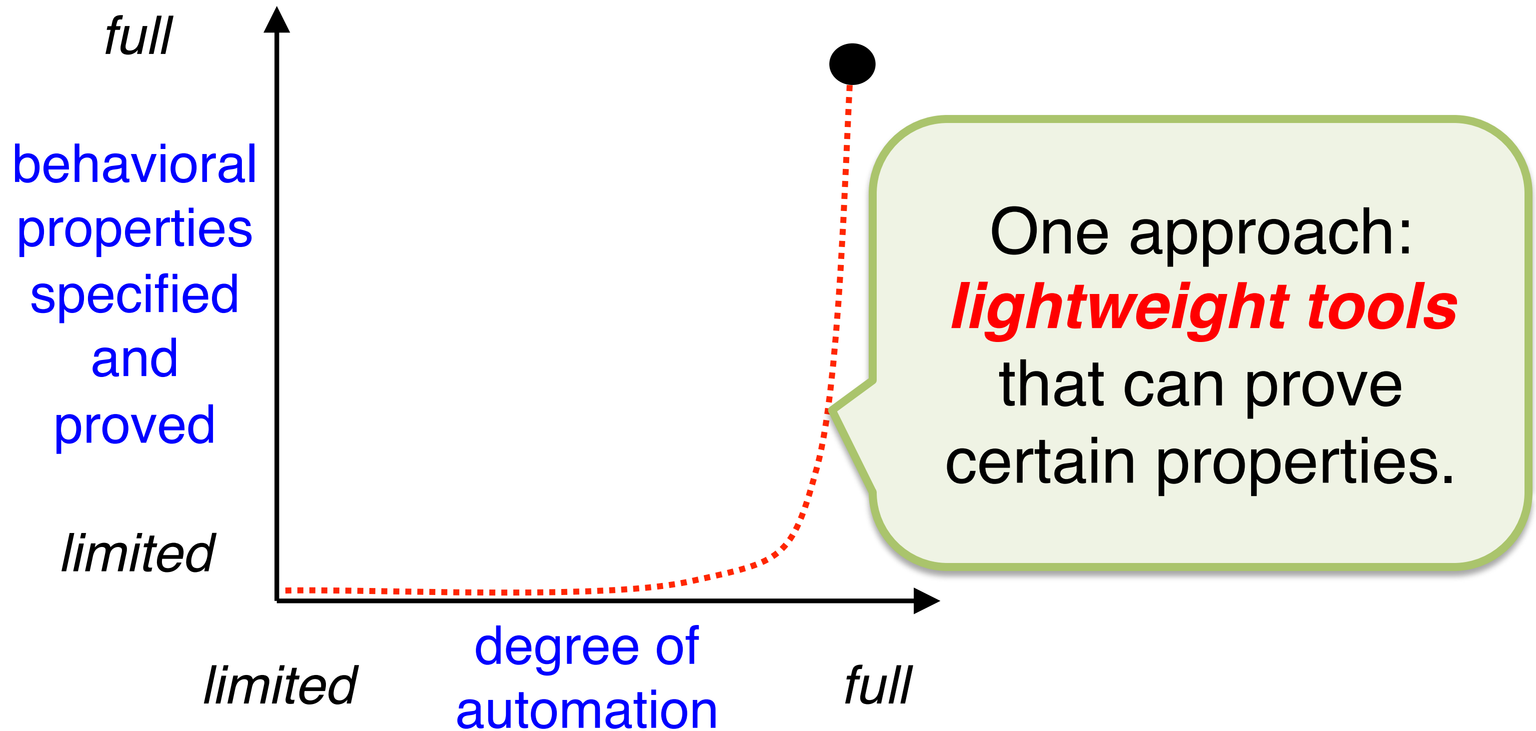

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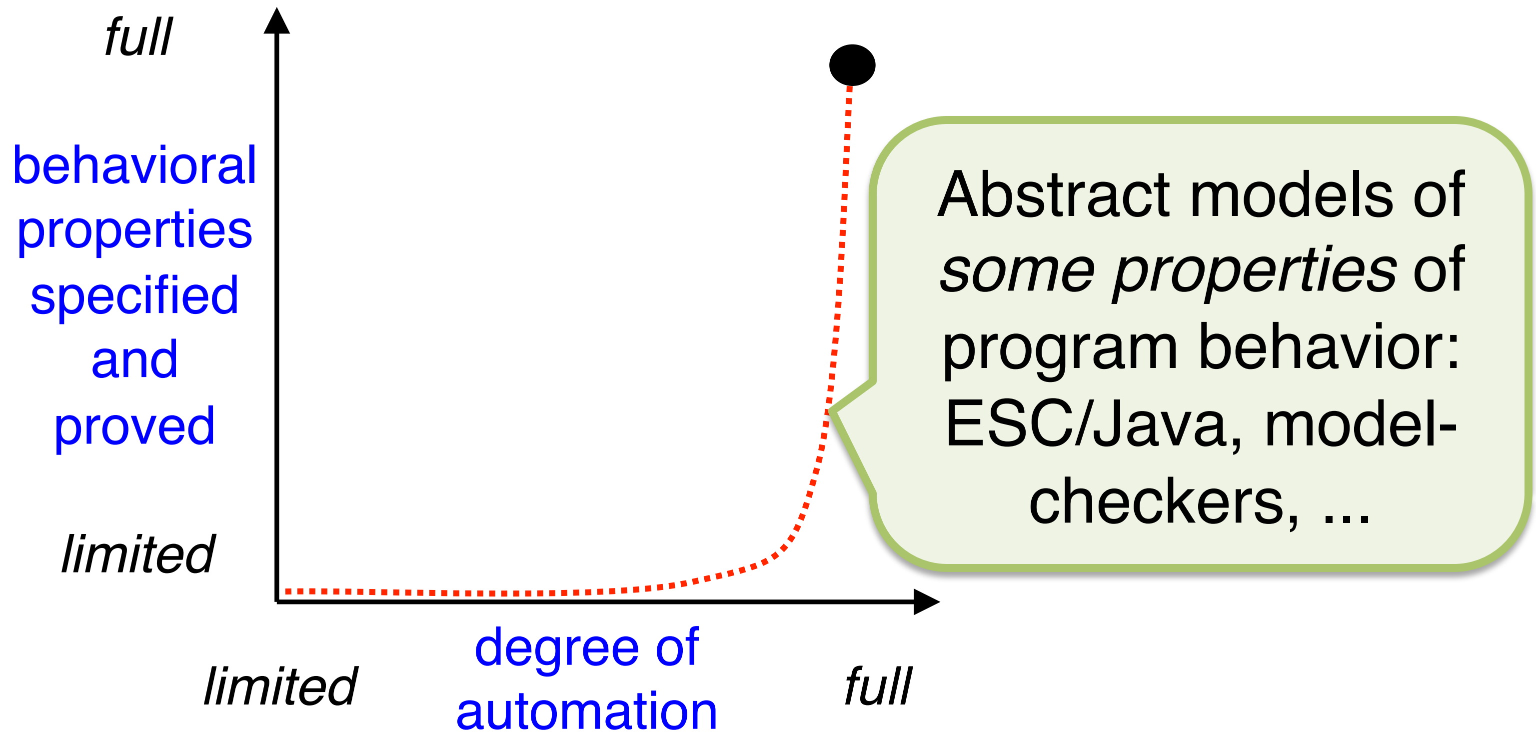

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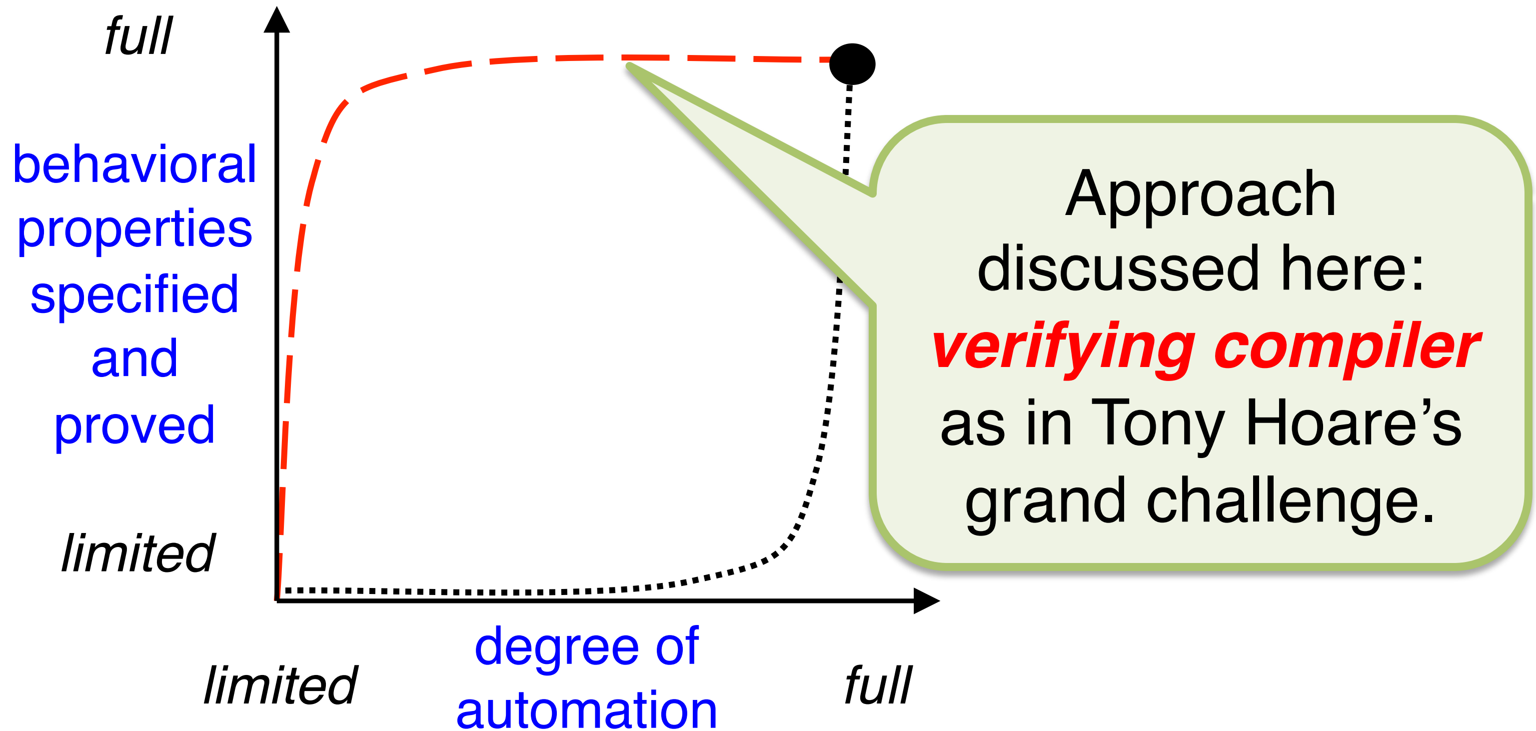

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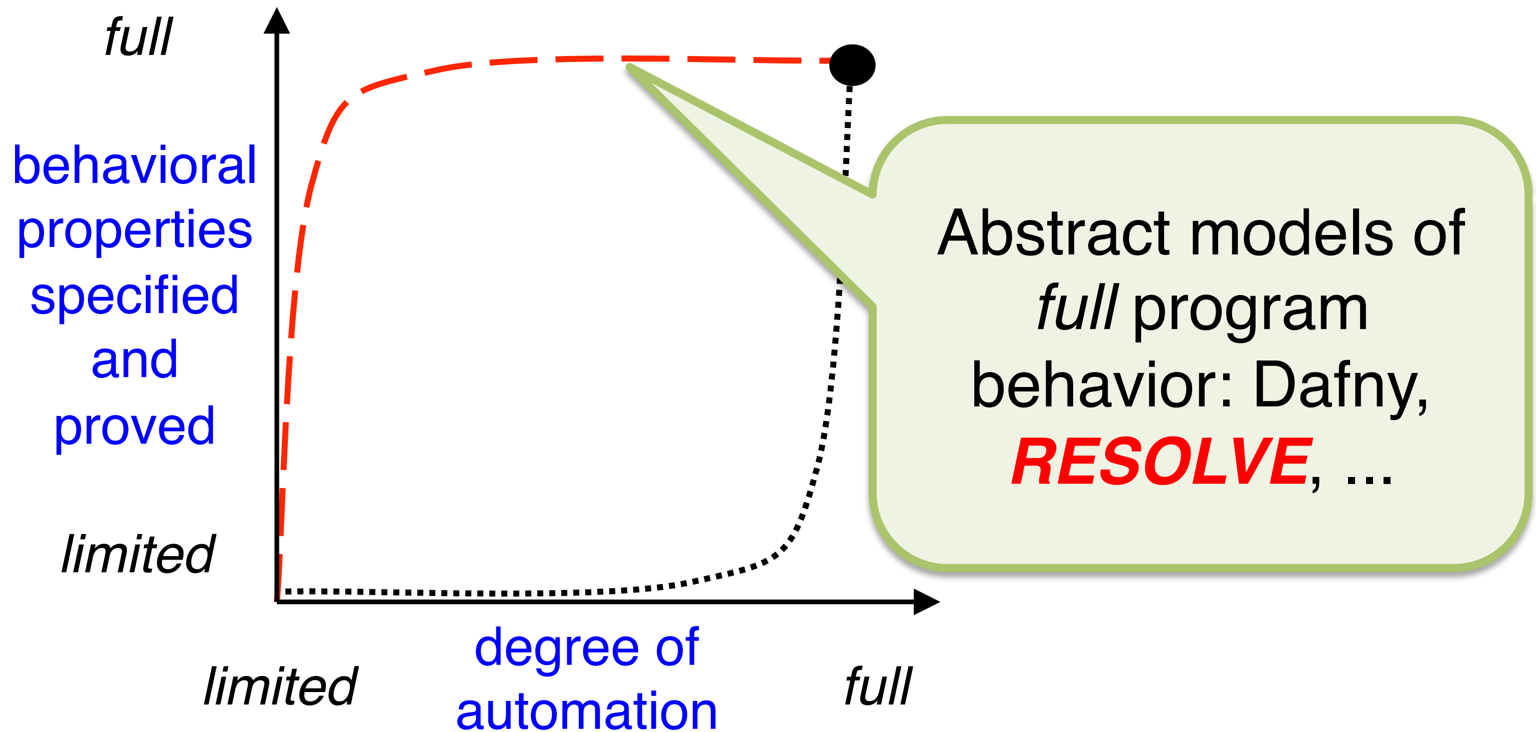
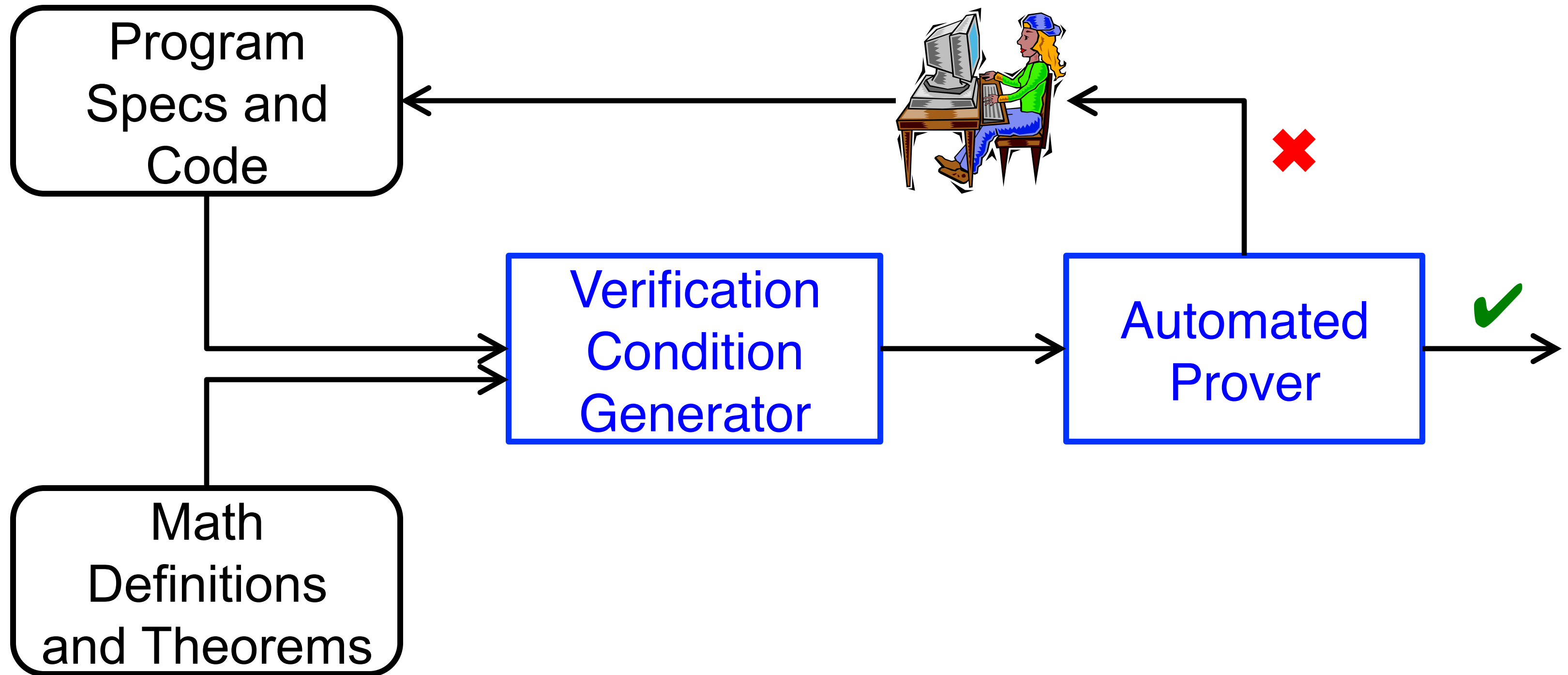


Verifying Compiler Overview



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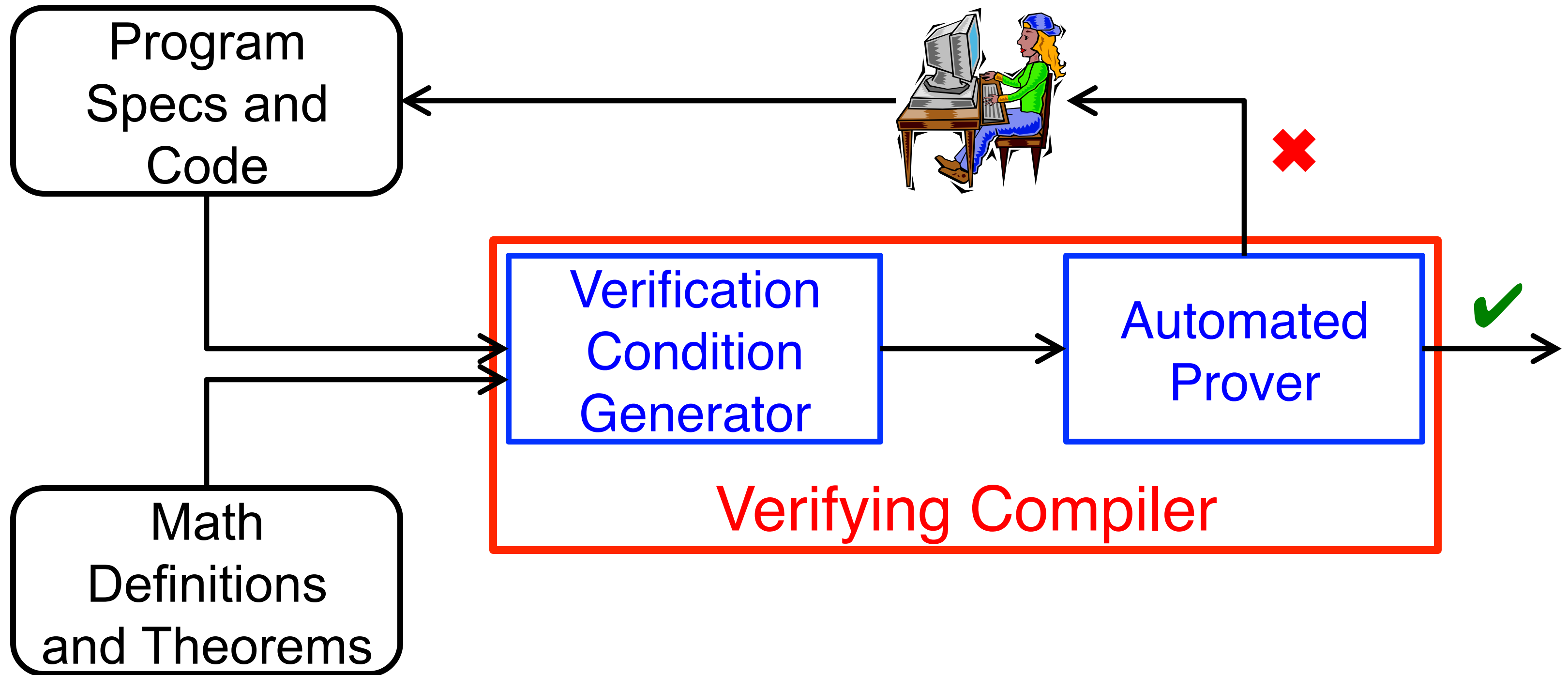

Some FAQ Answers Up Front

- Language?
  - Needs to support writing both ***formal specifications*** and ***code for implementations***

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Activity: Key Points Preview

- Code may involve ***user-defined types*** of the kind familiar in OO software
- Recursion presents no serious problems
- Main ideas involved in formal specification and verification are not particular to a given language

Given `Queue<T>` in Java ...

- **`void`** `enqueue(T x)`
  - Adds `x` to the rear of **`this`**
- `T dequeue()`
  - Removes and returns the entry at the front of **`this`**
- **`boolean`** `isEmpty()`
  - Reports whether **`this`** is empty

... Implement This Method

- **`void`** `invert()`
  - Reverses the order of the entries in **`this`**

... Implement This Method

Hint: Do it recursively.

- **`void`** `invert()`
  - Reverses the order of the entries in **`this`**

Demo

http://resolve.cs.clemson.edu/research

Components ➔

Concepts ➔

`Globally_Bounded_Queue_Template` ➔

Enhancements ➔

`Inverting_Capability` ➔

Realizations ➔

`Recursive_Inverting_Realiz`

Tools: General Points

- Sound
- Incomplete (for many reasons)
  - Inadequate justification
  - Inadequate mathematical developments, which are work in progress
  - Web IDE time out
  - Backend provers are efforts in progress
  - Incompleteness in number theory

Demo

http://resolve.cs.clemson.edu/research

Components →

Concepts →

Specification of a generic `Queue` interface

`Globally_Bounded_Queue_Template` →

Enhancements →

`Inverting_Capability` →

Realizations →

`Recursive_Inverting_Realiz`

Demo

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Components ➔

Concepts ➔

Globally_Bounded_Queu

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Specification of a Queue Invert operation

Demo

http://resolve.cs.clemson.edu/research

Components ➔

Concepts ➔

`Globally_Bounded_Queue_Template` ➔

Enhancements ➔

`Inverting_Capability` ➔

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Recursive implementation of `Invert` operation

Activity:
Key Points Review

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Inadequate Specifications

- *Imprecise*: `enqueue` enqueues item to the rear of the queue
- *Implementation-dependent*: `enqueue` does the same thing as `addElement` on a `vector`
- *Metaphorical*: `enqueue` has the same behavior as adding an item to the end of a line

Formal Specifications

- When we use variables of types such as `int` in programming, we think of their values as coming from mathematical domains such as Z (with constraints)
- Similarly, we need a mathematical domain to conceptualize values of variables of types such as `Queue`

Formal Specifications

- When we use integer operations in programming (e.g., `+`), we understand them in terms of their math counterparts on `Z`
- Similarly, we will use terms appropriate from the chosen math domain to specify `Queue` operations

`Queue` Concept Specification

- Parameterized by an `Entry` type
- ***Mathematical modeling***: Conceptualize `Queue` values as mathematical ***strings*** of entries with appropriate computational constraints
- Specifications of `Queue` operations use math string notations

`Queue` Concept Specification

Other options: sets, multisets, functions, …

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Queue Concept Specification

a.k.a. “contract”

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- Specifications of Queue operations use math string notations

String Theory Notation

- General idea: Σ^* is strings over Σ
  - `Str(Entry)` is strings over `Entry`
- Notations
  - Empty_String: Λ
  - Concatenation: α o β
  - String containing a single entry: <x>
  - Length: $|\alpha|$

Design-by-Contract

- Articulated clearly in the 1980s (by Meyer)
- Design-by-contract has become *the standard policy* governing "separation of concerns" across modern software engineering
- Major difference for verification (as opposed to runtime assertion checking): ***mathematical modeling*** of program types

Specification of Operations

- Based on the mathematical model of a program type, such as `Queue`, each operation has:
  - A ***requires clause*** (***precondition***) that characterizes the responsibility of the client code that ***calls*** that operation
  - A ***ensures clause*** (***postcondition***) that characterizes the responsibility of the code that ***implements*** that operation

Specification Example: Key Points Preview

- This contract specification is ***generic*** (i.e., parameterized)
- Mathematical model for a `Queue` is a string, and operations are specified using the notations of string theory
- Parameters have ***specification modes***
- Specifications are designed to avoid (needless, inefficient) copying

Specification Example

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Components ➔

Concepts ➔

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This responsibility results in generating ***verification conditions*** (VCs) for each call in client code.

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This responsibility results in generating VCs at the end of the code that implements an operation.

Verification Example: Key Points Preview

- Verification requires an integrated specification + implementation language
- Verification is ***modular*** (e.g., uses only specifications of called operations)
- Verification conditions (VCs) are raised not only for the end results, but also to make sure that intervening calls are legit

Verification Example

http://resolve.cs.clemson.edu/research

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Activity: Key Points Preview

- Even apparently simple code that's "just about `int`s" can be subtle enough to benefit from automated verification
- Main ideas involved in formal specification and verification are not particular to a given language, e.g., RESOLVE

Clock Arithmetic

- The value of `a mod b`, or `a` ***modulo*** `b`, where `a` and `b` are mathematical **`integer`**s and `b > 0`, is computed by doing ***clock arithmetic*** on a clock face with `b` positions labelled `0` through `b-1`

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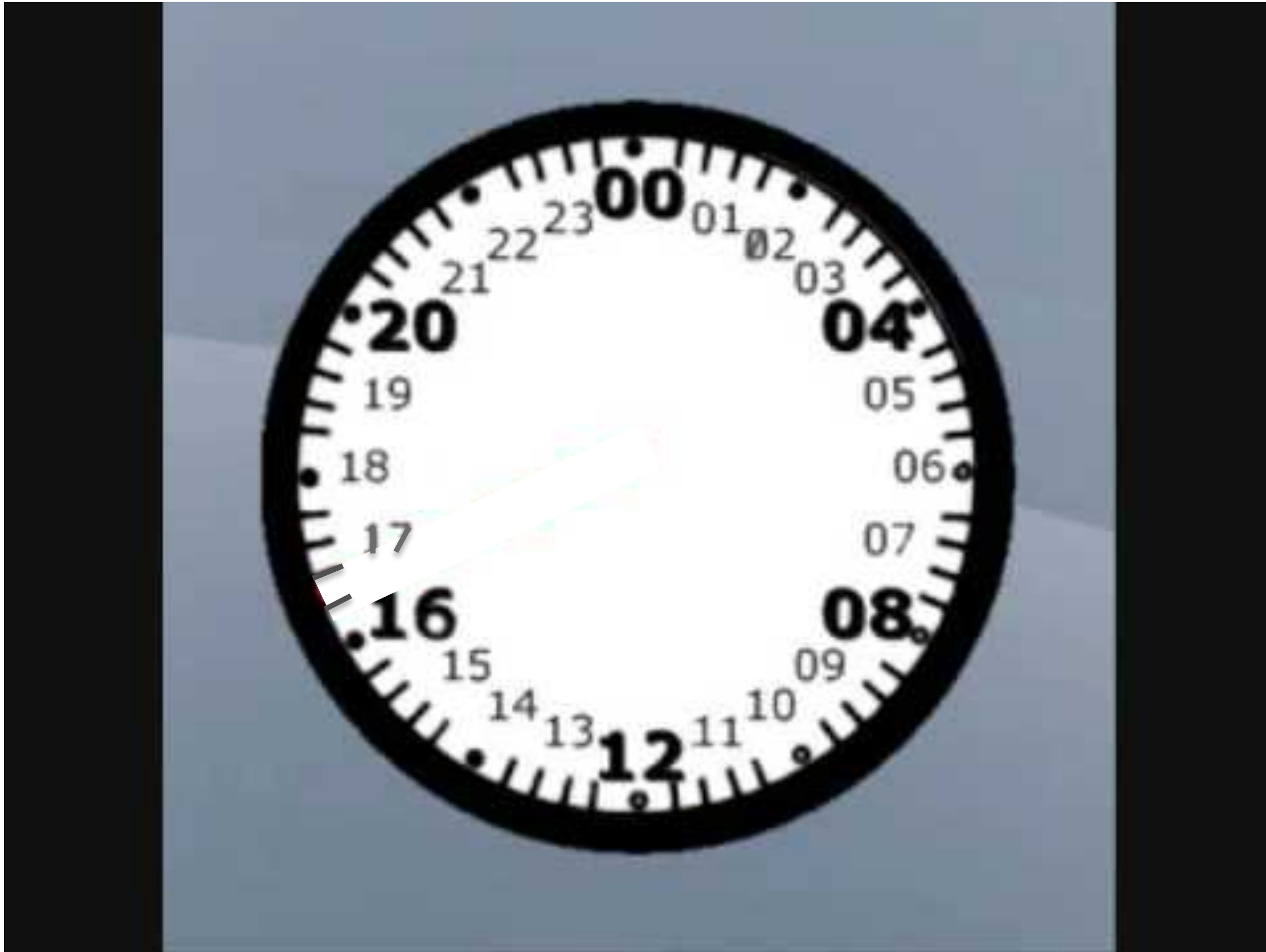
  - If `a > 0`, the "hand" on the clock starts at `0` and moves `|a|` positions clockwise
  - If `a < 0`, it moves `|a|` counter-clockwise
  - Where it ends up is the value of `a mod b`

Example: 24-hr Clock



Mod ≠ Remainder

- What is the ***remainder*** upon dividing `67` by `24`?

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- What is the ***remainder*** upon dividing `67` by `24`? It is `19`.
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  - At least most people (and Java) say it is...
- What is `(-67)` **`mod`** `24`? It is `5`.

Given ...

- The `%` operator in Java (which, despite sometimes being called the "mod" operator, actually computes the remainder of integer division), e.g.:

  `67 % 24` evaluates to `19`

  `-67 % 24` evaluates to `-19`

... Implement This Method

- `int clockMod(int a, int b)`
- Contract specification:

  requires *b > 0*

  ensures *clockMod = a* ***mod*** *b*

... Implement This Method

- `int clockMod(int a, int b)`
- Contract specification:

  requires *b > 0*

  ensures *clockMod = a **mod** b*

You can do it in one concise line of Java code...

Demo

http://resolveonline.cse.ohio-state.edu

`IntegerFacility` ➔

`ClockMod`

Activity: Key Points Review

- Even apparently simple code that's "just about `int`s" can be subtle enough to benefit from automated verification
- Main ideas involved in formal specification and verification are not particular to a given language, e.g., RESOLVE

Iteration and Loop Invariants

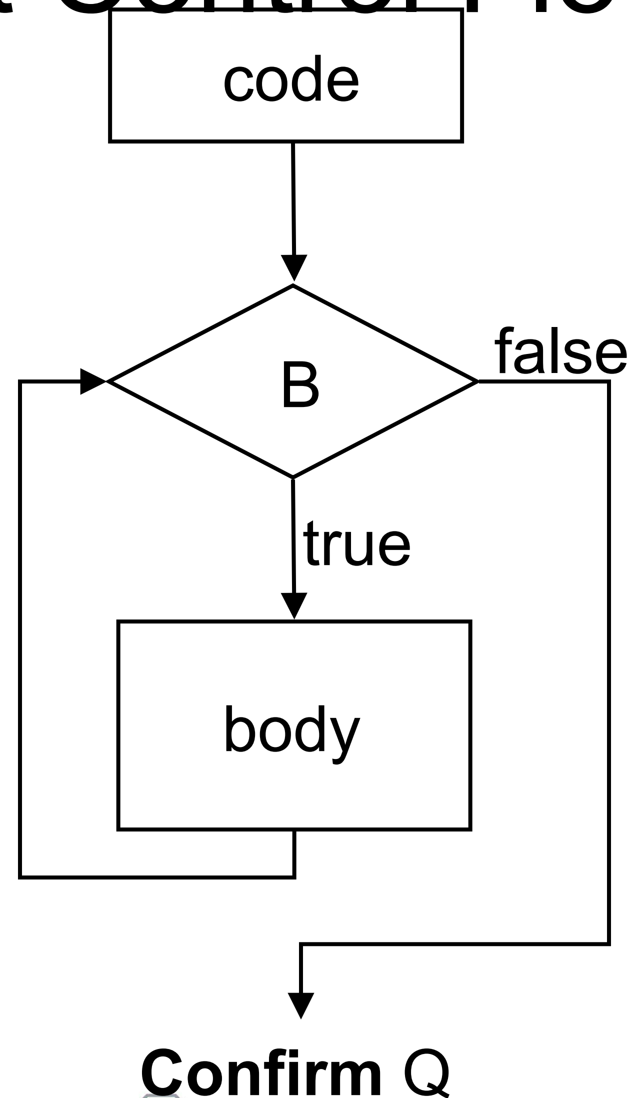
- Developer must sometimes write a ***justification*** of correctness of code
  - Assertion that the developer claims to be true and that will be checked to be true by the verifier (for soundness)
  - Proving and using such an assertion is easier for a mechanical verifier than inventing it
  - Writing it requires education and experience
- A ***loop invariant*** is one kind of justification

What Is a Loop Invariant?

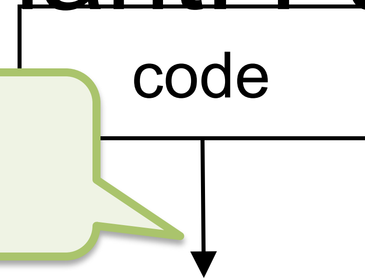
- For a typical while loop, an assertion that is true at the beginning and at the end of each iteration, including the first and the last
- More generally: an invariant is a property that is true *every time* execution reaches a certain point—in the case of a loop invariant, the loop condition test

While Statement Control Flow

```
Code;
While B
  maintaining Inv;
do
  body;
end;
Confirm Q;
```



Checking the Invariant: Part 1




```
Code
While B
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do
  body;
end;
Confirm Q;
```
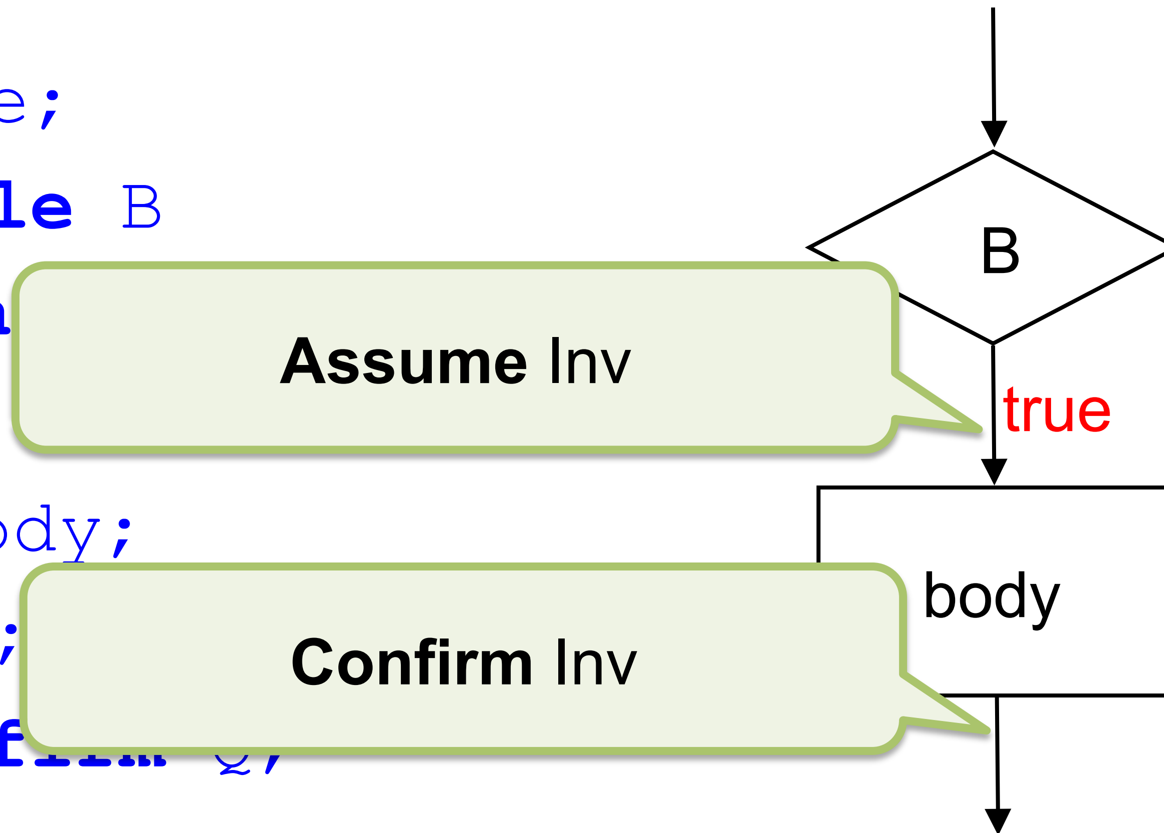
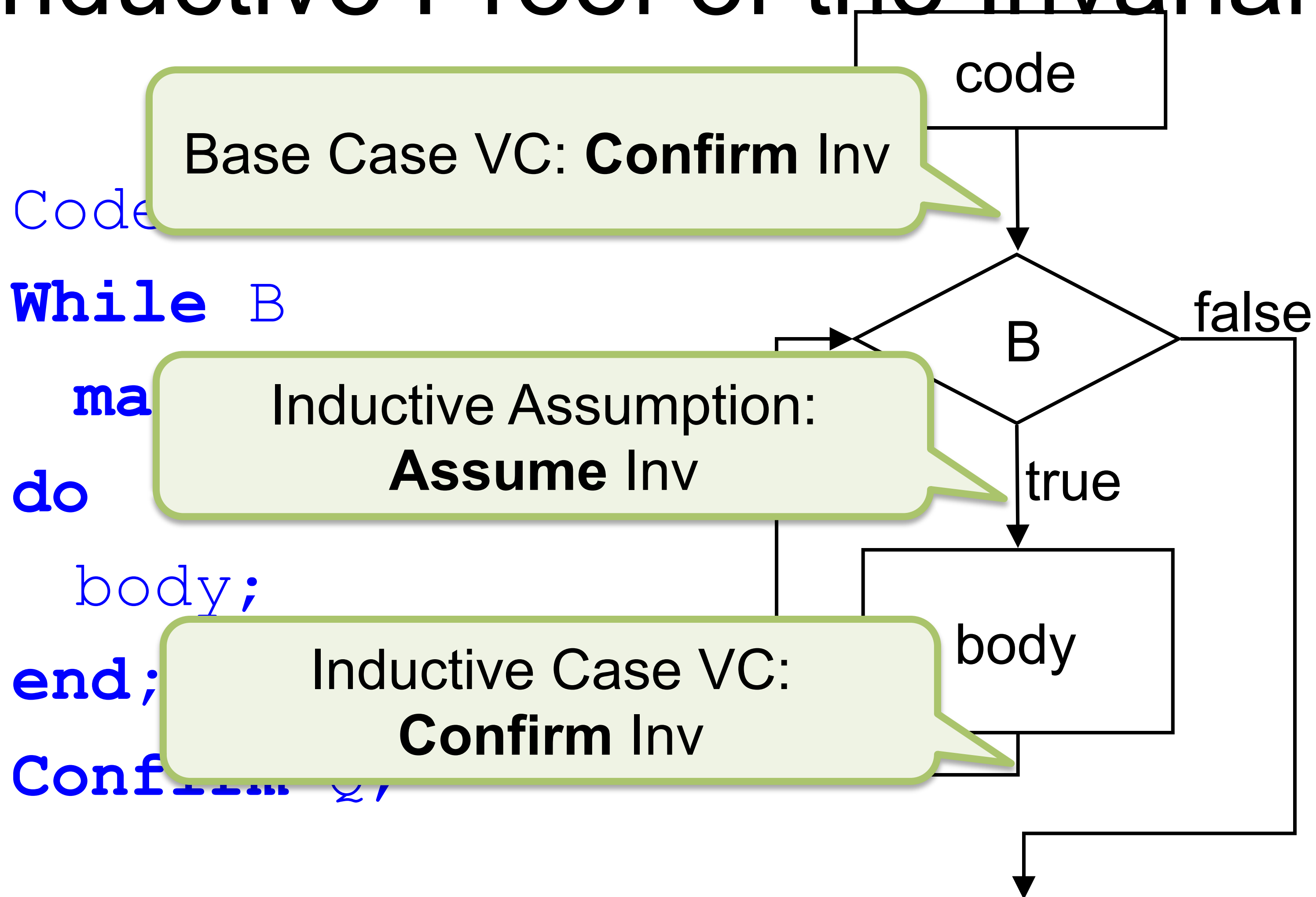

Checking the Invariant: Part II

```
Code;
While B
  ma
do
  body;
end;
Conf
```



Inductive Proof of the Invariant



Using the Invariant

```
Code;
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do
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end;
Confirm Q;
```

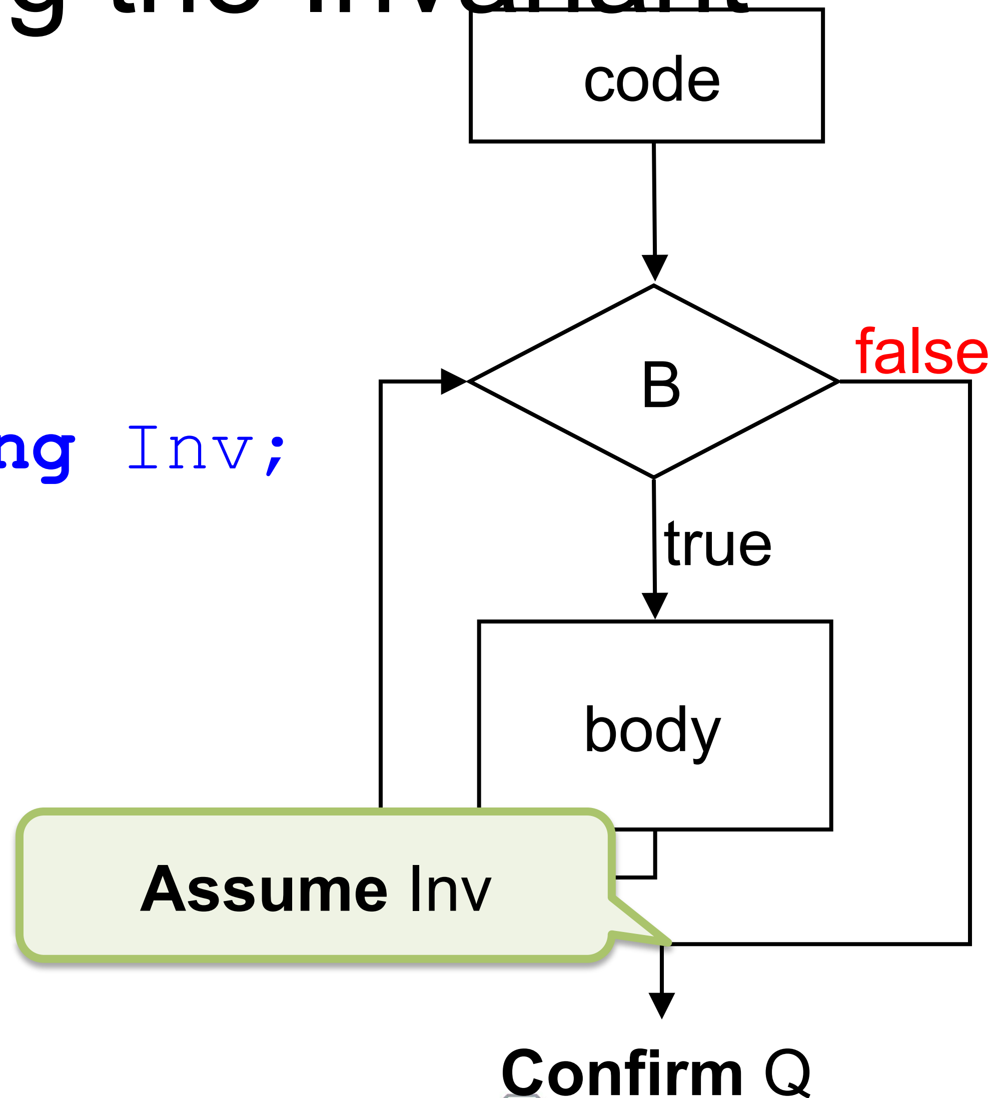

Identifying a Suitable Invariant

- Pick an assertion such that the assertion and the negation of loop condition together imply the assertion to be confirmed after the loop (i.e., `not B and Inv ⇒ Q`)
- Make sure the assertion is indeed an invariant (see checking the invariant, parts I and II)!

Loop Invariant Example

http://resolve.cs.clemson.edu/research

Components →

Concepts →

`Globally_Bounded_Stack_Template` →

Enhancements →

`Flipping_Capability` →

Realizations →

`Obvious_Flipping_Realiz`

Identifying a Suitable Invariant

- Need to confirm (or prove) the **ensures** clause of Flip at the end of the code:

```
S = Reverse(#S)
```

- Need to confirm the following before the swap statement (`S :=: Temp;`)

```
Temp = Reverse(#S)
```

- Identify an invariant, Inv:

```
S = Empty_String and Inv ⇒
                    Temp = Reverse(#S)
```

Observing the Loop in Action

After Iteration Number...	`S =`	`Temp =`
0	`< 10, 20, 30, 40 >`	`< >`
1		

Observing the Loop in Action

After Iteration Number...	`S =`	`Temp =`
0	`< 10, 20, 30, 40 >`	`< >`
1	`< 20, 30, 40 >`	`< 10 >`
2		

Observing the Loop in Action

After Iteration Number...	S =	Temp =
0	< 10, 20, 30, 40 >	< >
1	< 20, 30, 40 >	< 10 >
2	< 30, 40 >	< 20, 10 >
3		

Observing the Loop in Action

After Iteration Number...	`S =`	`Temp =`
0	`< 10, 20, 30, 40 >`	`< >`
1	`< 20, 30, 40 >`	`< 10 >`
2	`< 30, 40 >`	`< 20, 10 >`
3	`< 40 >`	`< 30, 20, 10 >`
4		

Observing the Loop in Action

After Iteration Number...	`S =`	`Temp =`
0	`< 10, 20, 30, 40 >`	`< >`
1	`< 20, 30, 40 >`	`< 10 >`
2	`< 30, 40 >`	`< 20, 10 >`
3	`< 40 >`	`< 30, 20, 10 >`
4	`< >`	`< 40, 30, 20, 10 >`

What Doesn't Change?

- Claim: the concatenation of the reverse of `Temp`, with `S`, is always the same: it is equal to the value of `S` before the first iteration
- Loop invariant (goal driven):

```
Reverse(S) ∘ Temp = Reverse(#S)
```

- Alternative loop invariant (fact driven):

```
#S = Reverse(Temp) ∘ S
```

Progress Metric for Termination

- Progress metric is a natural number (an ordinal, in general) that is decreasing
- Programmer specifies a progress metric for loop termination and the verifier checks its validity and uses it in its proof
- Suitable progress metric for example:

```
decreasing |S|;
```

- Unsuitable one: `decreasing |Temp|;`

Activity:
Key Points Preview

- Ideas are language-independent
- Programmer supplies an adequate invariant and progress metric for termination to justify loop correctness
- Verifier checks the validity of the above (otherwise it won’t be sound)
- Verifier uses them to complete its proof of code correctness

Given…

http://resolve.cs.clemson.edu/research

Components ➔

Concepts ➔

`Globally_Bounded_Queue_Template` ➔

Enhancements ➔

`Inverting_Capability` ➔

Realizations ➔

`Invariantless_Iterative_Realiz`

... Do This

- Write invariants for loops
  - Write the invariant for the second loop first

Activity: Key Points Review

- Invariants may involve mathematical models of multiple objects
  - Stacks and queues just happen to have the same string model
- No deep thinking is necessary to complete the proofs given the invariant

Another One?

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Components ➔

Concepts ➔

`Globally_Bounded_Queue_Template` ➔

Enhancements ➔

`Remove_Last_Capability` ➔

Realizations ➔

`Invariantless_Remove_Last_Realiz`

Survey Questions

- Please briefly and anonymously answer the following questions on a sheet of paper and turn them in at the front table:
  1. Which part of the first session did you find ***most*** interesting and/or helpful? If you have time: why?
  2. Which part of the first session did you find ***least*** interesting and/or helpful? If you have time: why?

2. Proof of Correctness of Data Representation

- Correctness of data representation: representation invariants and abstraction relations
  - Philosophical discussion
  - Mathematical framework for thinking about it
  - Activity

So, What's Inside the Computer?

- Consider any popular video game, e.g., Nintendo Wii bowling
- Are there bowling balls and bowling pins inside the game console's computer?

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- Are there bowling balls and bowling pins inside the game console's computer?
  - ***Of course not!***
- What's *really* inside the computer, then, that makes bowling-like behavior?

So, What's Inside the Computer?

- Consider any pop Nintendo Wii bow
- Are there bowling inside the gam
  - ***Of course ot!***
- What's *really* inside the computer, then, that makes bowling-like behavior?

A thought experiment:
What ***dynamic behavior*** would you see if you had a magical magnifying glass and could see inside the computer at any level of detail while it's running?

A Possible Metaphor

A Tower of Abstractions

- Bowling pins?
- Vectors?
- Numbers?
- Bits?
- Voltages?
- Electrons?
- ???

A Tower of Abstractions

- Bowling pins?
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These are *all* “just” ***mathematical models***, i.e., ***abstractions*** used to explain and predict observable behavior.

A Tower of Abstractions

- Bowling pins?
- Vectors?
- Numbers?
- Bits?

- Voltages?
- Electrons?
- ???

Domain: ***Physics***
These models are supposed to match physical reality, and are discarded if they do not; limited by the physical world.

A Tower of Abstractions

- Bowling pins?
- Vectors?
- Numbers?
- Bits?

Domain: ***Computing***
These models are entirely artificial (need not match physical reality); limited only by the creativity of the software engineer.

- Voltages?
- Electrons?
- ???

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Numbers may be built on top of bits…

A Tower of Abstractions

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Bits may be built on top of voltages…

A Tower of Abstractions

- Bowling pins
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Voltages may be built on top of (?) electrons…

Interpretation of Representation

- Let's not take the tower-building metaphor too far!
- A better approach is to think about ***interpreting*** a lower-level configuration (a.k.a. a ***representation***) to get a higher-level value

A Tower of Abstractions

- Bowling pins
- Vectors
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(Configurations of) bits may be interpreted as numbers...

A Tower of Abstractions

- Bowling pins
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(Configurations of) voltages may be interpreted as bits…

A Tower of Abstractions

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- Numbers
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- Electrons
- ???

(Configurations of) electrons may be interpreted as voltages…

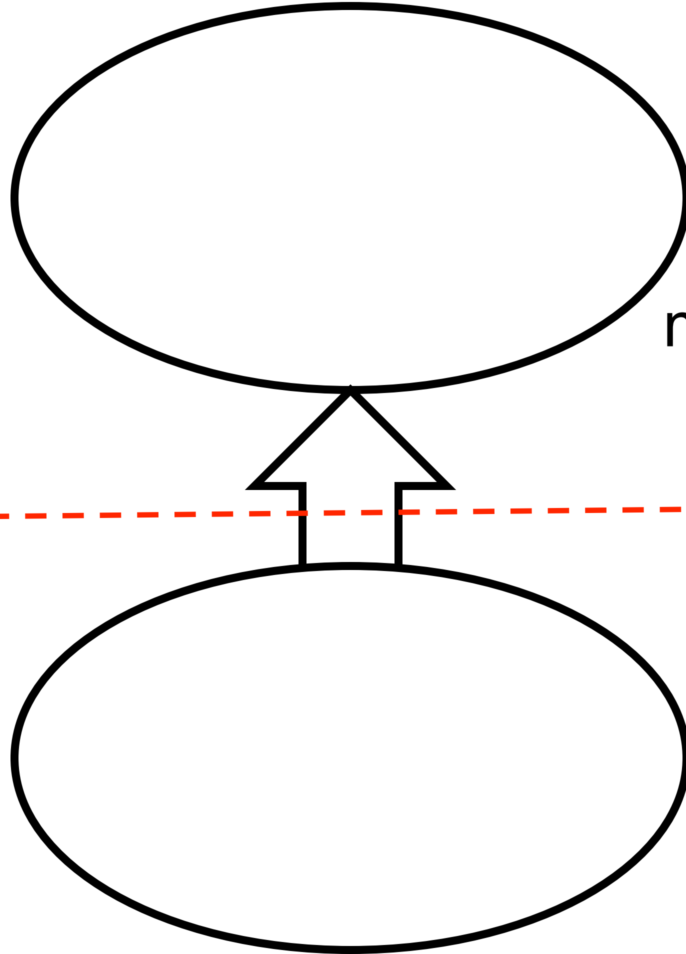
Example

http://resolveonline.cse.ohio-state.edu

`SetTemplate` ➔

`QueueRealization`

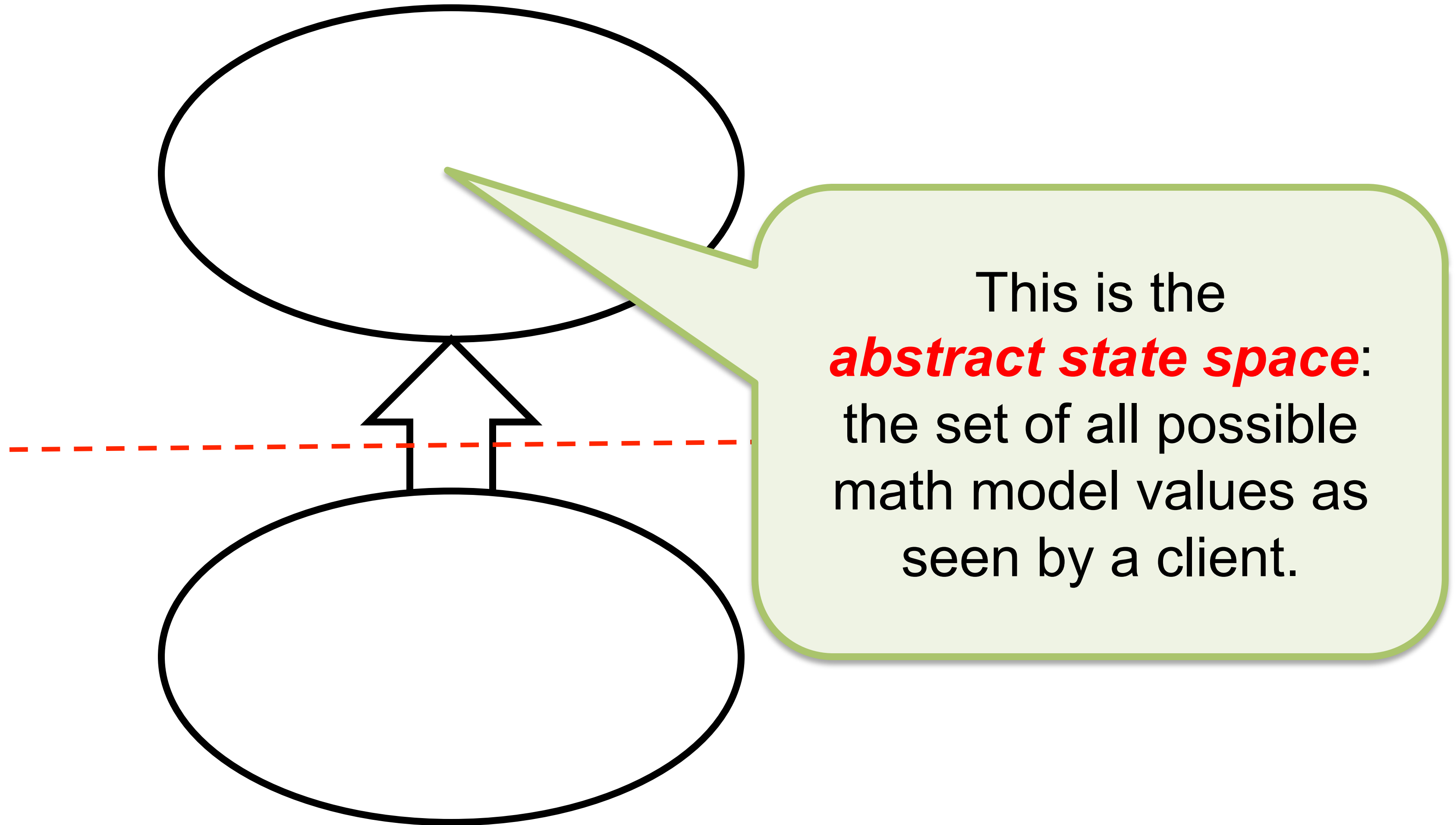
Two-Level Thinking



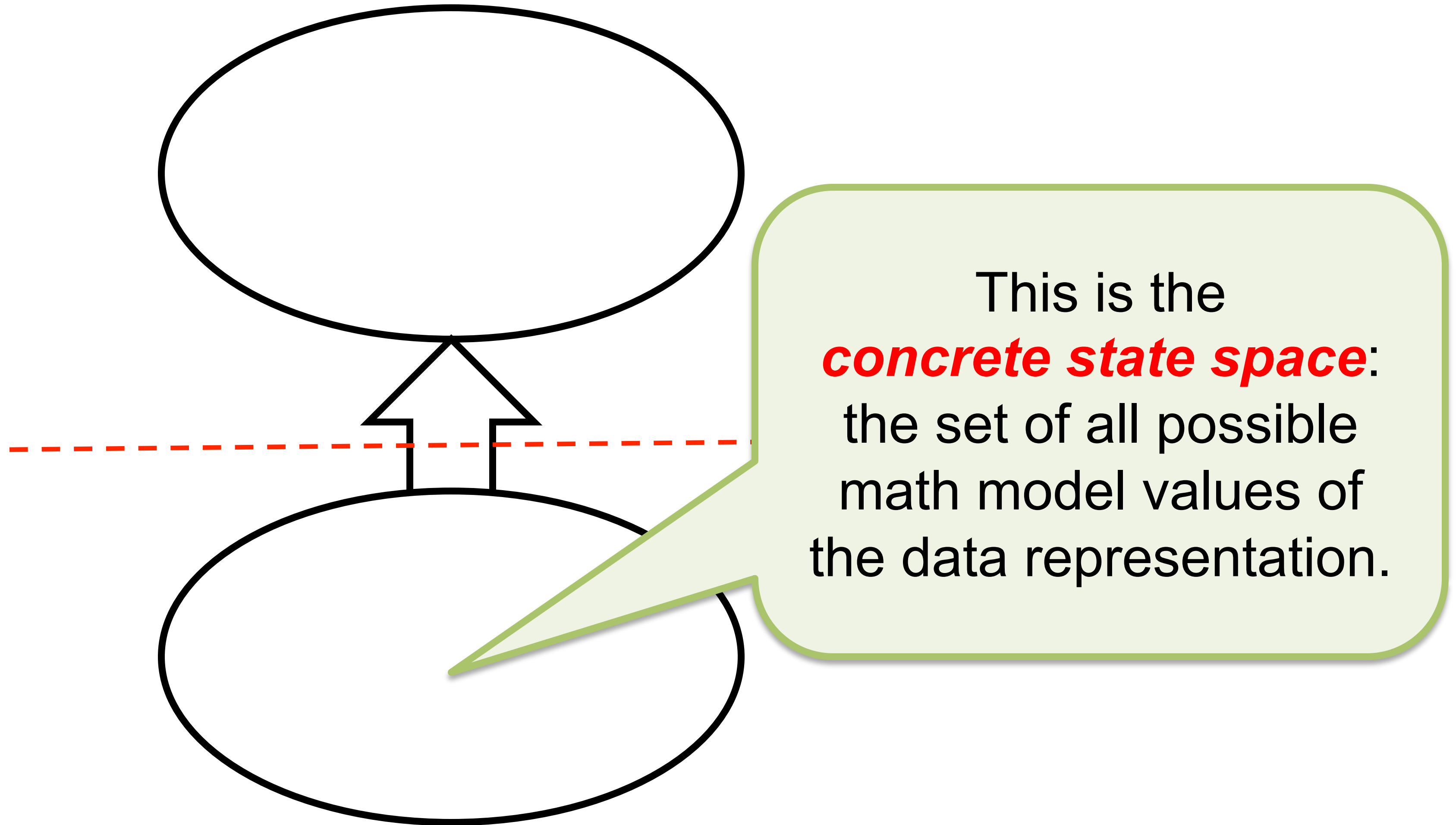
client view:
mathematical model for type,
contracts for operations

implementer view:
data representation for type,
algorithms for operations

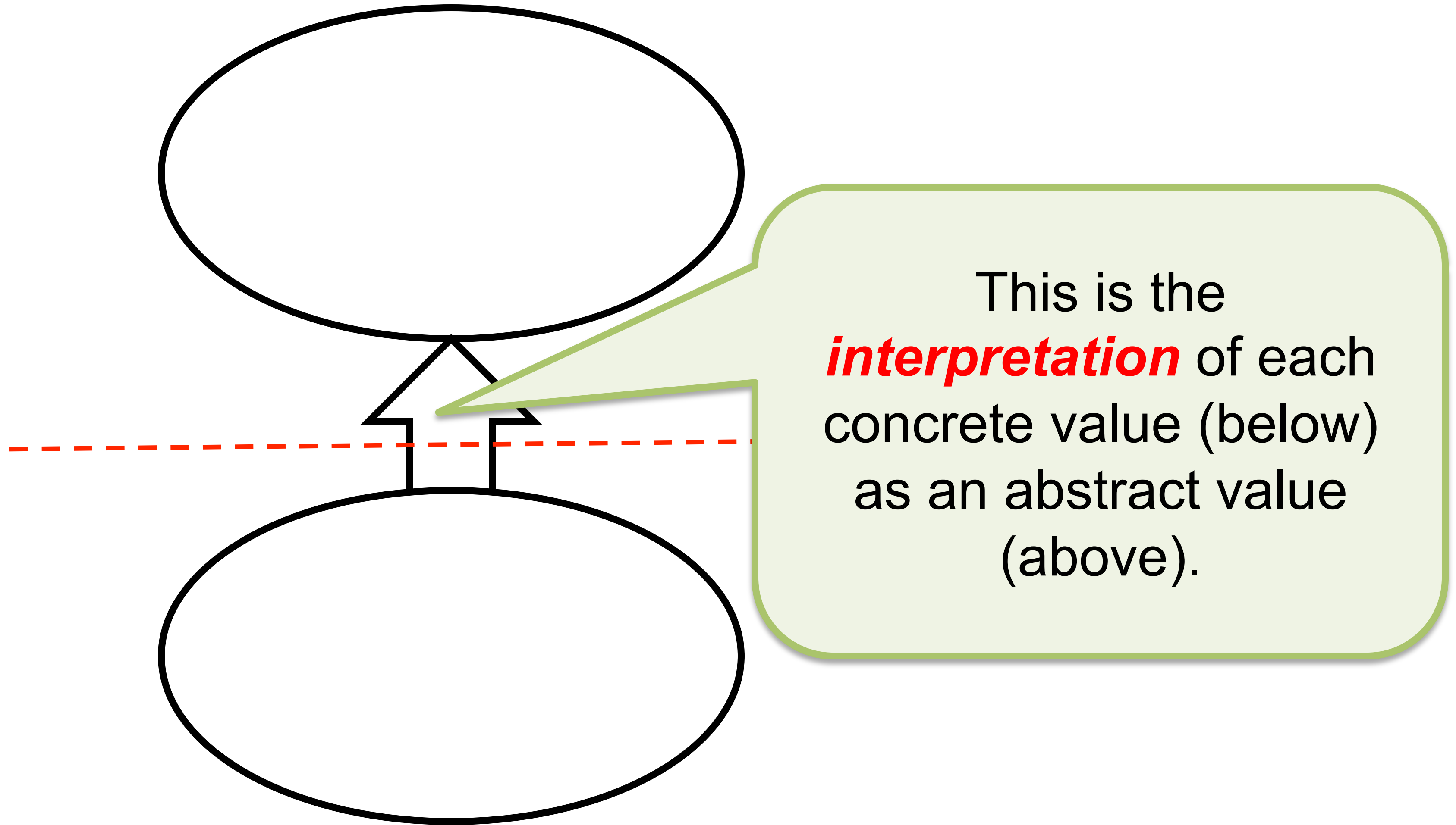
Two-Level Thinking



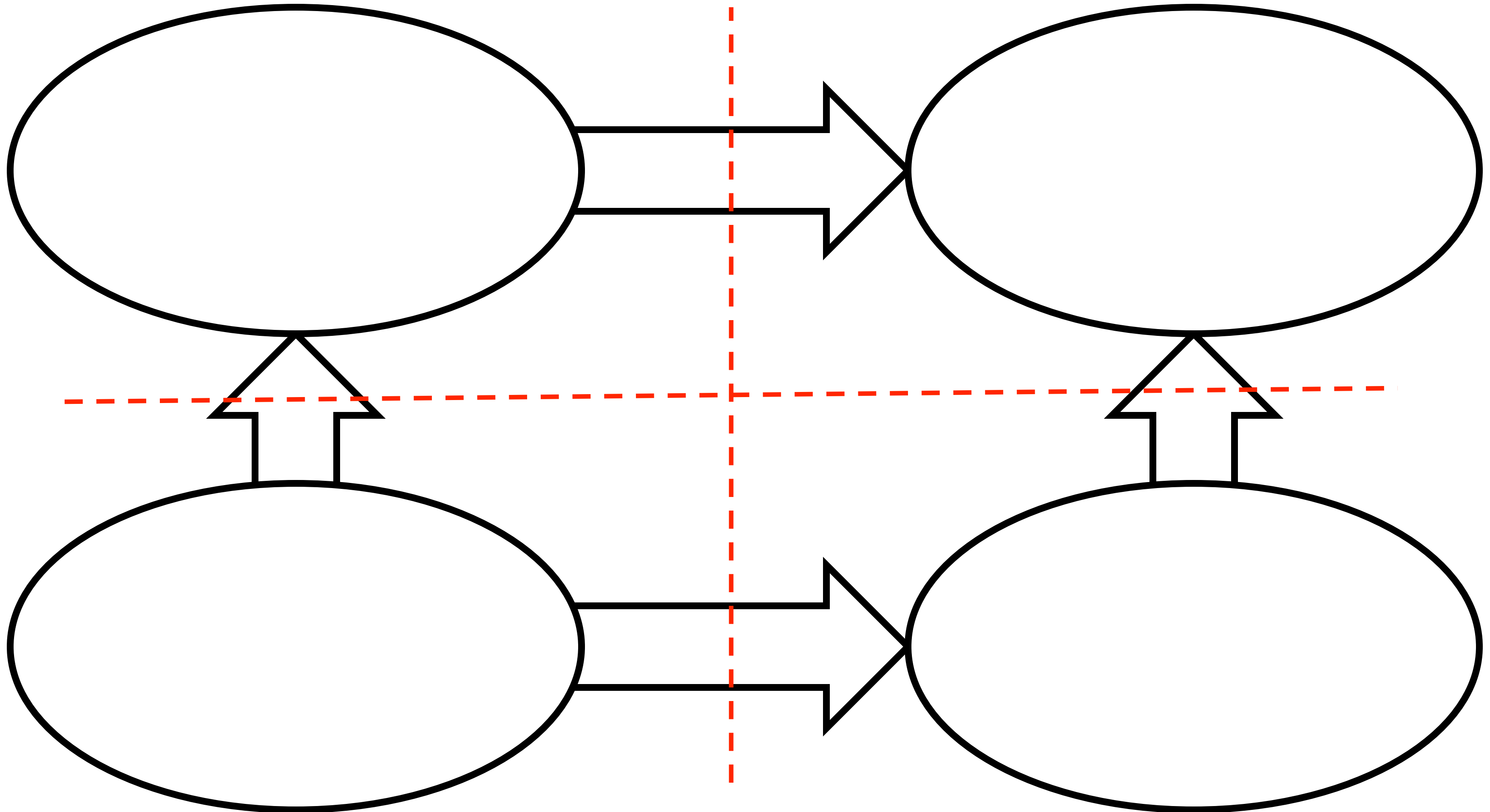
Two-Level Thinking



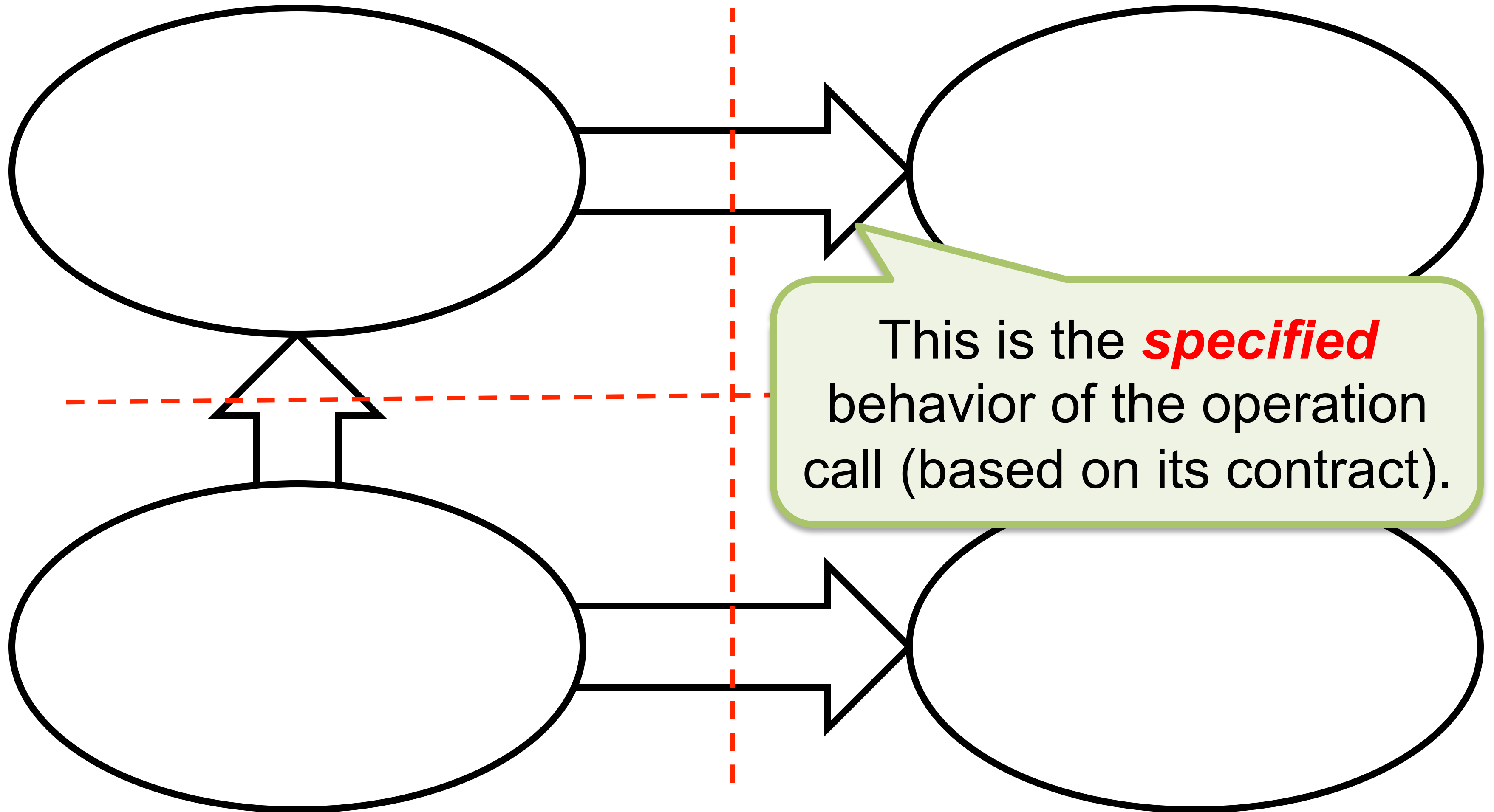
Two-Level Thinking



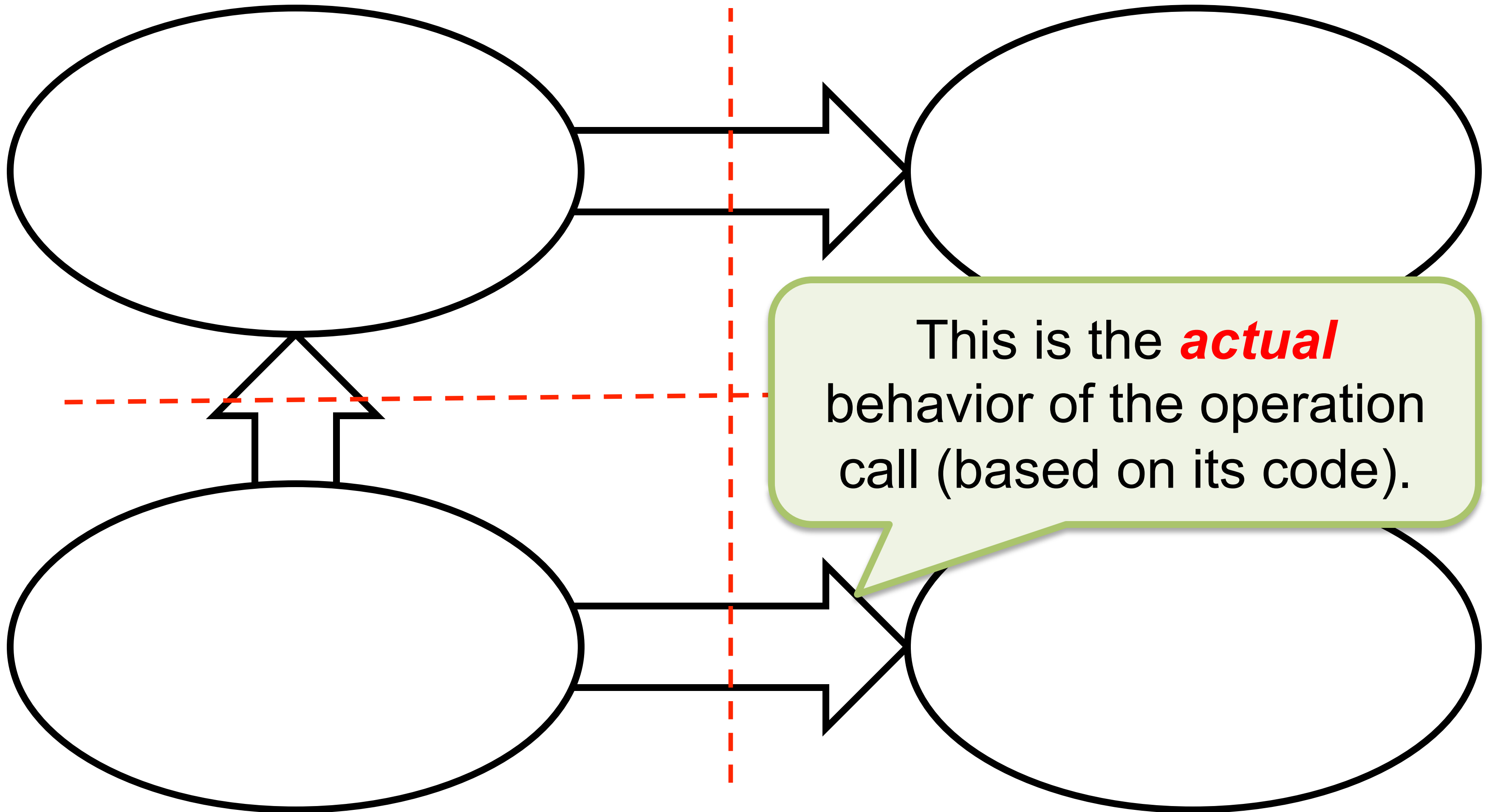
The Commutative Diagram



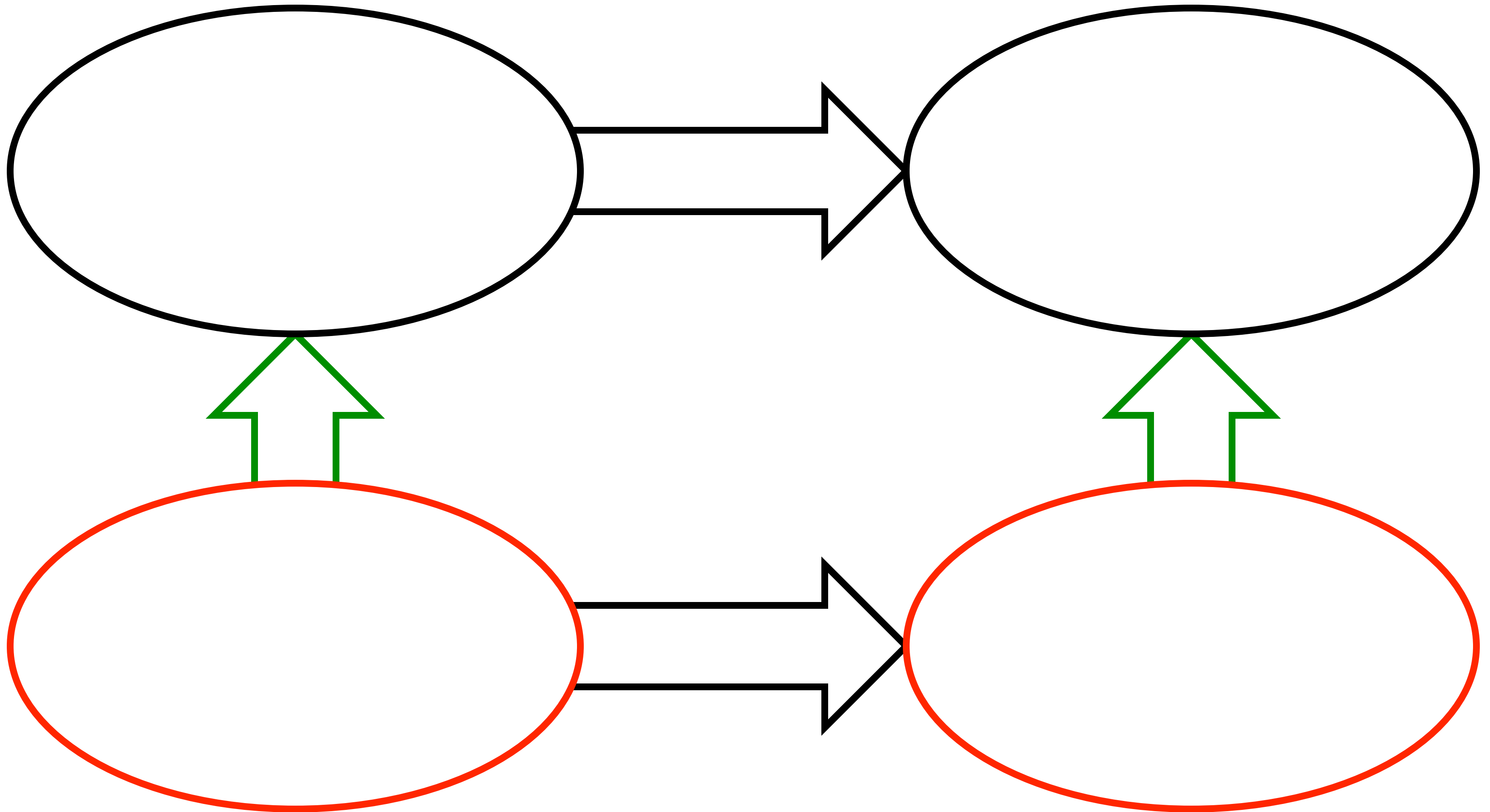
The Commutative Diagram



The Commutative Diagram



What's Left to Write Down?



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What's Left to Write Down?

The developer must ***describe the concrete state space***, i.e., the legitimate values of the data representation: the ***representation invariant***.

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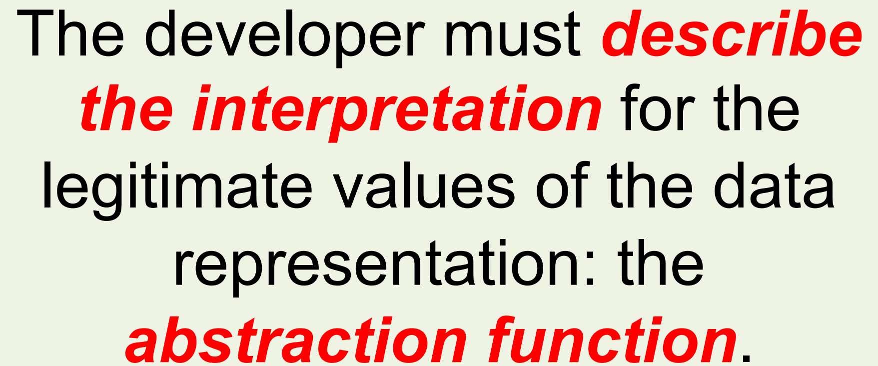
What's Left to Write Down?



Justifications of Correctness

- Two key design decisions justify the correctness of a data representation:
  - The ***representation invariant***: Which "configurations" of the data representation can ever arise, i.e., are considered legitimate?
  - The ***abstraction function***: How is a legitimate data representation to be interpreted to get an abstract value?

Consequences

- With the representation invariant and abstraction function supplied by the software developer:
  - The code for each operation can be ***written independently*** of the others, and the operations will "play well together"
  - The code for each operation can be ***verified independently*** of the others

Activity: Key Points Preview

- Each operation body, and its proof of correctness, can be done independently of all the others
- No pointers or references or nodes or links are involved in this representation of `QueueTemplate` because `ListTemplate` hides them

Activity

- Representing a `Queue` using a `List`

Demo

http://resolveonline.cse.ohio-state.edu

`ListTemplate`

The Type `List`

```
math subtype LIST_MODEL is
   (left: string of Item,
    right: string of Item)

type List is modeled by LIST_MODEL
     exemplar l
     initialization ensures
        l.left = empty_string and
        l.right = empty_string
```

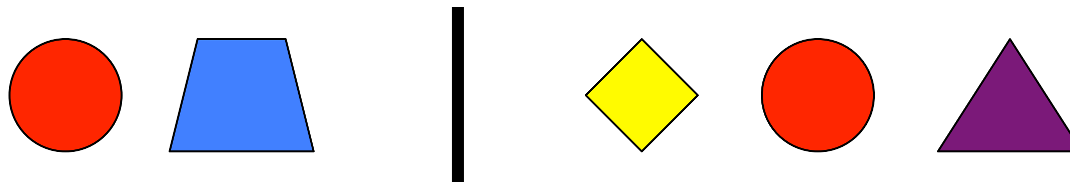
How To Think About It

- An initial `List` value:

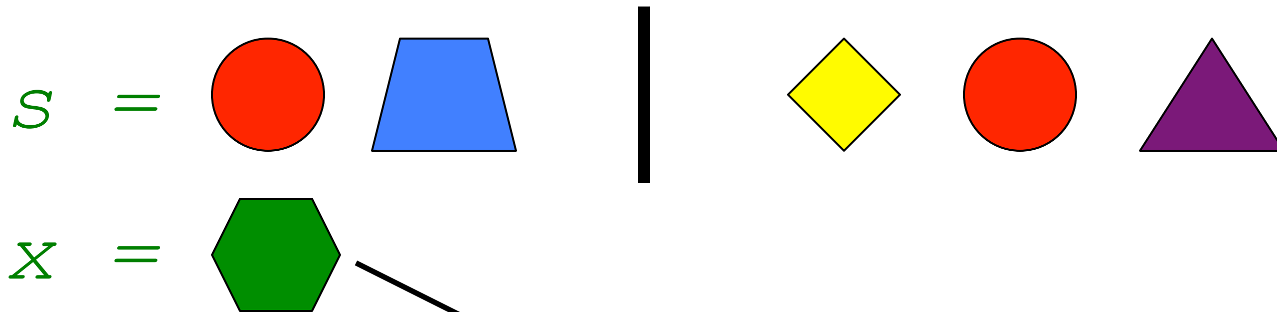
`(< >, < >)`

- A typical `List` value:

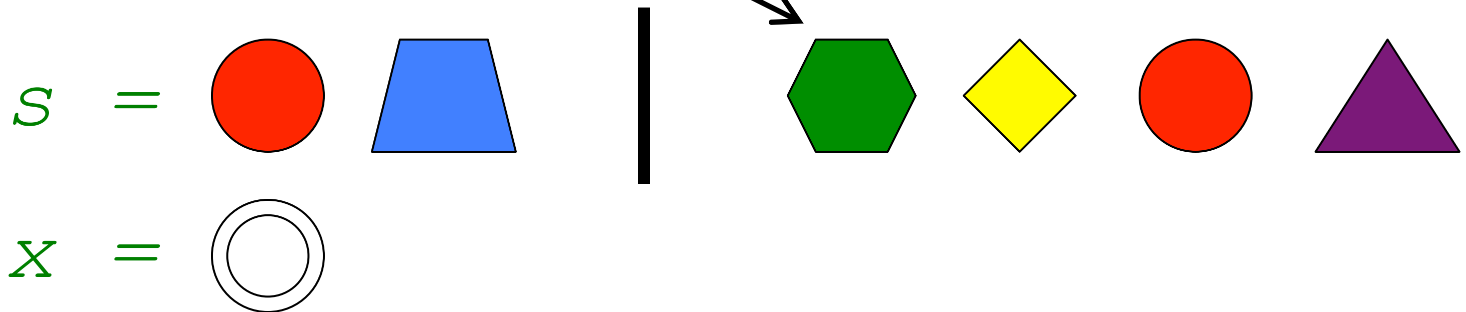
`(<,>, <,,>)`



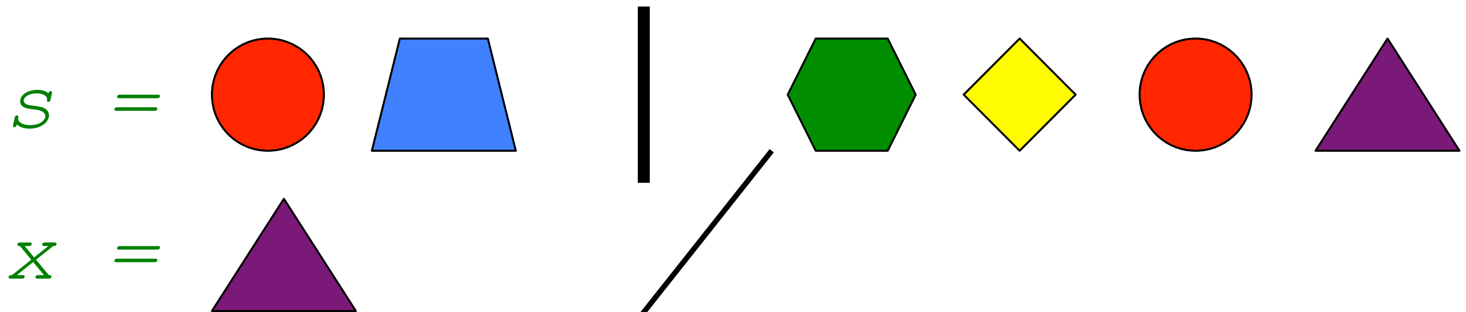
Insert



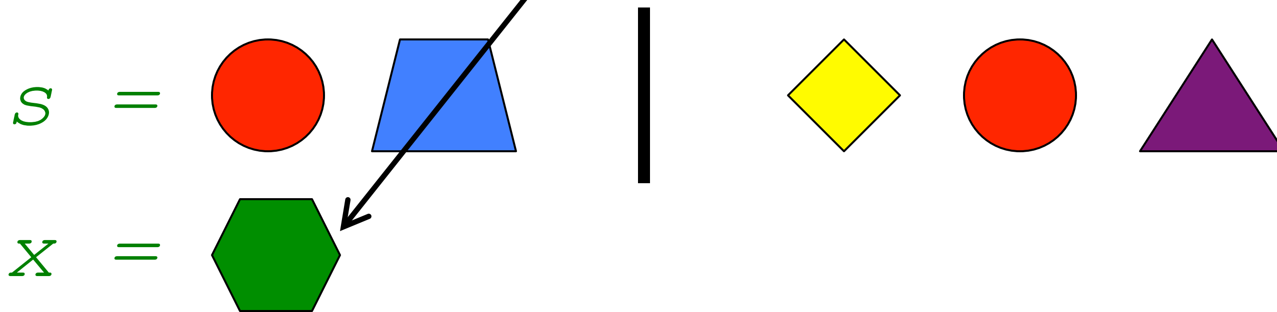
Insert(s, x)



Remove

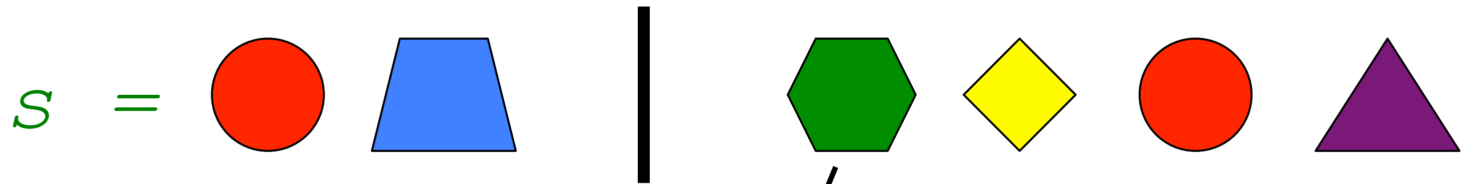


`Remove(s, x)`



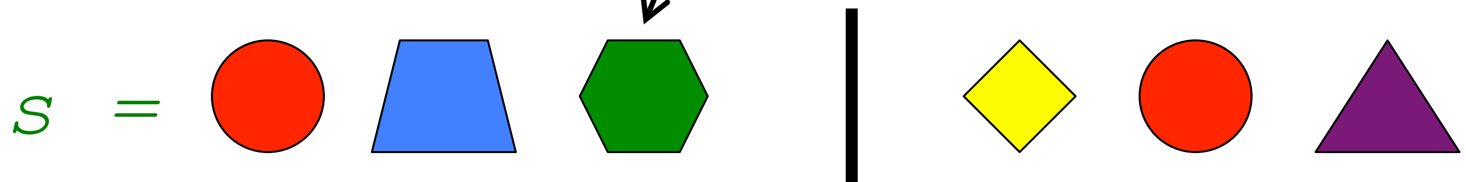
Advance

s =

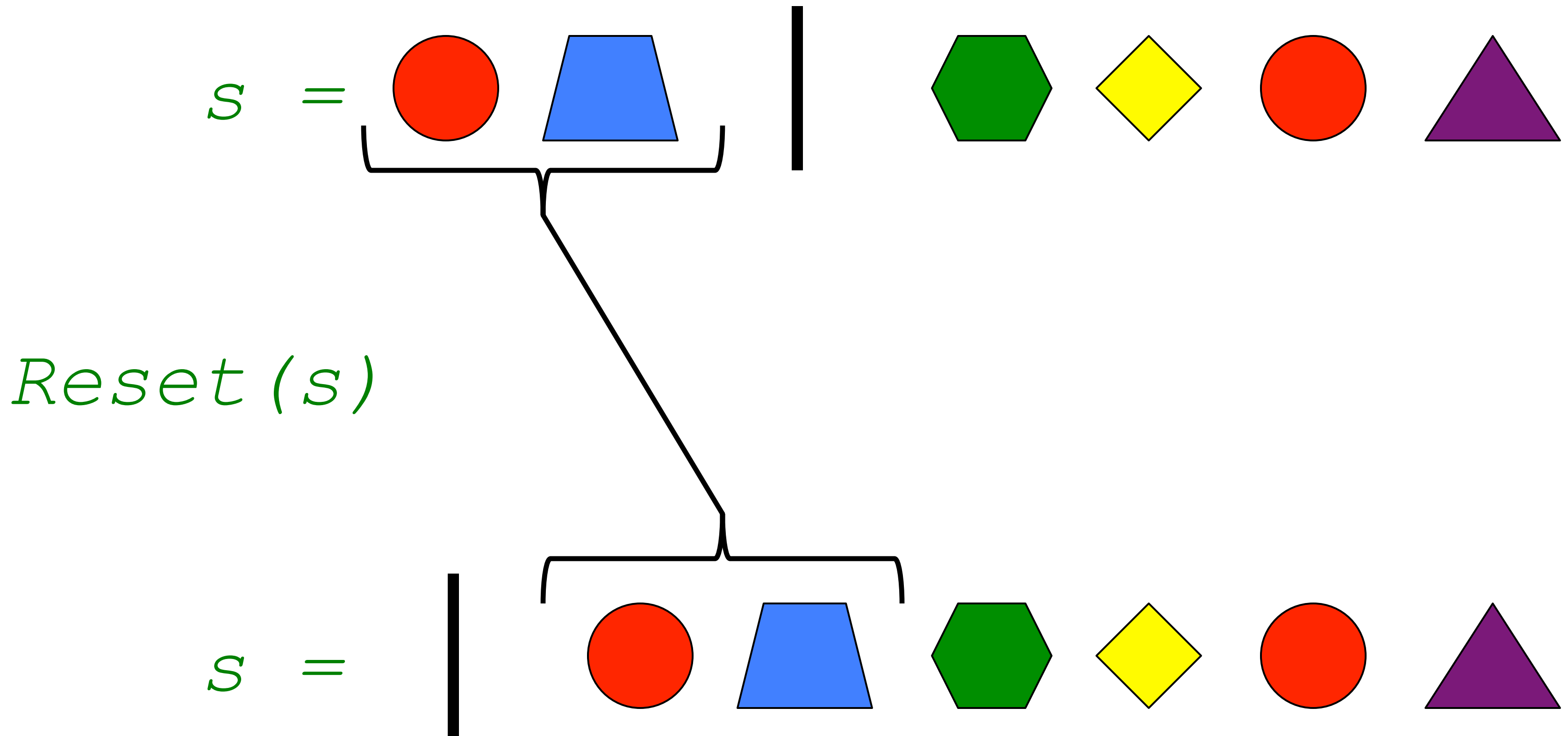


Advance(s)

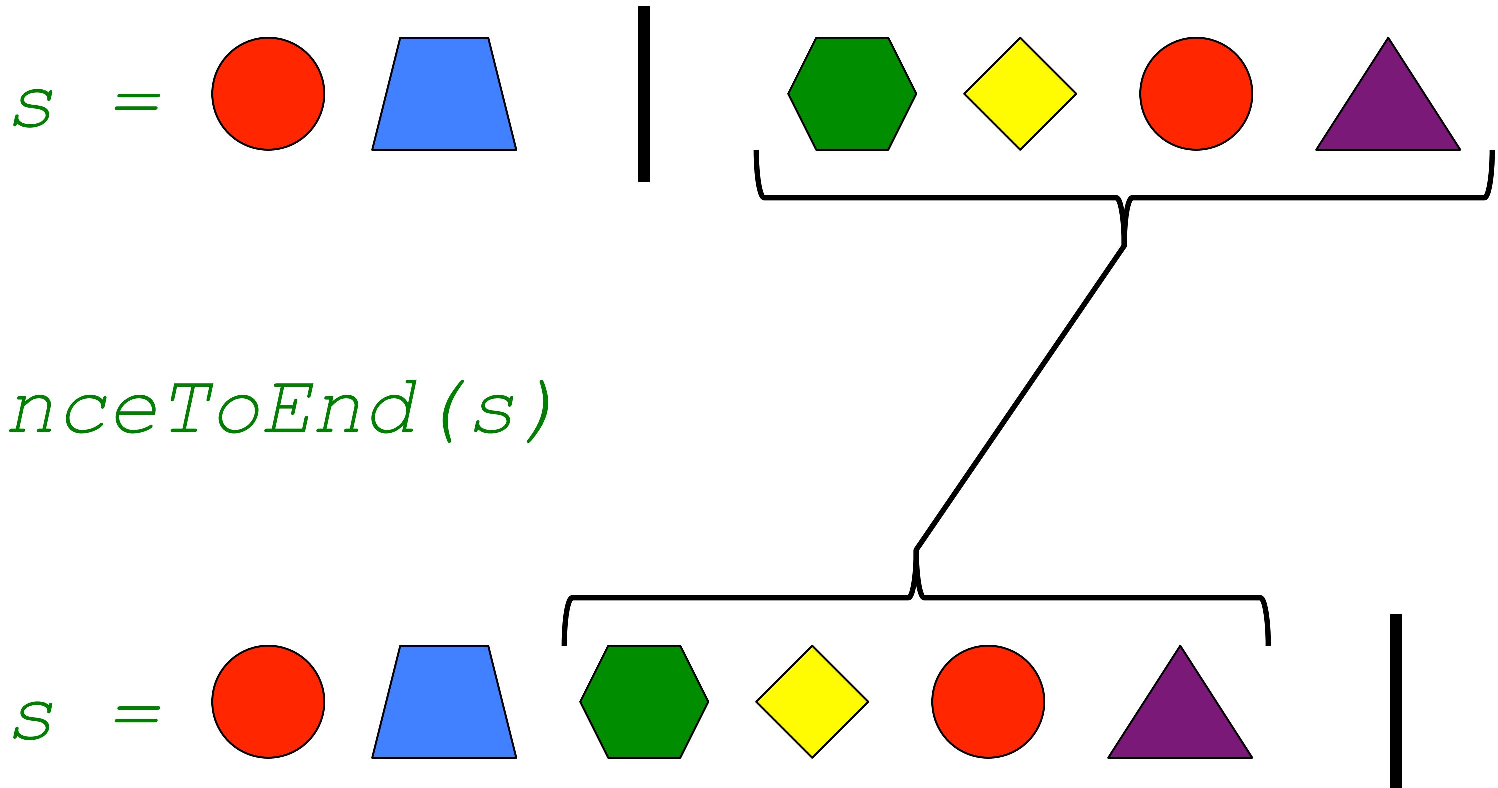
s =



Reset



AdvanceToEnd



Activity and Demo

http://resolveonline.cse.ohio-state.edu

`QueueTemplate` ➔ `ListRealization`

Activity: Key Points Review

- Each operation body, and its proof of correctness, can be done independently of all the others
- No pointers or references or nodes or links are involved in this representation of `QueueTemplate` because `ListTemplate` hides them

Discussion of Research and Education Issues

- Your suggestions?

Overview of Foundations and Tools

- Sitaraman, M., *et al.*, "Building a Push-Button RESOLVE Verifier: Progress and Challenges", *Formal Aspects of Computing 23*, 5 (2011), 607-626.

Empirical Studies

- Kirschenbaum, J., *et al*. “Verifying Component-Based Software: Deep Mathematics or Simple Bookkeeping?”, *Proceedings 11th International Conference on Software Reuse, Springer LNCS 5791*, 2009, 31-40.
- Tagore, A., *et al*., “Automatically Proving Thousands of Verification Conditions Using an SMT Solver: An Empirical Study”, *NASA Formal Methods 4th International Symposium, Springer LNCS 7226*, 2012, 195-209.

VC Generators and Provers

- Harton, H. K., *Mechanical and Modular Verification Condition Generation For Object-Based Software*, Ph.D. Dissertation, Clemson University, 2011.
- Smith, H., *Engineering Specifications and Mathematics for Verified Software*, Ph.D. Dissertation, Clemson University, 2013.

Benchmarks

- Weide, B.W., *et al*., "Incremental Benchmarks for Software Verification Tools and Techniques", *Proceedings Verified Software: Theories, Tools, and Experiments 2008, Springer LNCS 5295*, 2008, 84-98.
- Klebanov, V., *et al*., "The 1st Verified Software Competition: Experience Report", *Proceedings 17th International Symposium on Formal Methods, Springer LNCS 6664*, 2011, 154-168.

Challenge Problems

- Weide, B.W., “SAVCBS 2006 Challenge: Specification of Iterators”, *Proceedings 2006 Conference on Specification and Verification of Component-Based Systems*, ACM, 2006, 75-77.
- Bronish, D., and Smith, H., “Robust, Generic, Modularly-Verified Map: A Software Verification Challenge Problem”, *Proceedings PLPV ’11: 5th ACM Workshop on Programming Languages Meets Program Verification*, 2011, 27-30.

References and Linked Structures

- Weide, B.W., and Heym, W.D., "Specification and Verification with References", *Procs. OOPSLA Workshop on SAVCBS*, 2001.
- Kulczycki, G., *Direct Reasoning*, Ph.D. Dissertation, Clemson University, 2004.
- Kulczycki, G., *et al*., "The Location Linking Concept: A Basis for Verification of Code Using Pointers," *Procs. VSTTE*, 2012, 34-49.

Performance Specification and Verification

- Weide, B.W., *et al*., “Expressiveness Issues in Compositional Performance Reasoning”, *Proceedings 6th ICSE Workshop on Component-Based Software Engineering: Automated Reasoning and Prediction*, 2003, 85-90.
- Krone J., *et al*., “Performance Analysis Based Upon Complete Profiles”, *Proceedings 2006 Conference on Specification and Verification of Component-Based Systems*, ACM, 2006, 3-10.

CS Education

- Numerous papers at educational conferences over the past 20 years including ACM SIGCSE, ACM ITiCSE, and CSEET
- Drachova-Strang S., *Teaching and Assessment of Mathematical Principles for Software Correctness Using a Reasoning Concept Inventory*, Ph.D. Dissertation, Clemson University, 2013.

Survey Questions

- Please briefly and anonymously answer the following questions on a sheet of paper and turn them in at the front table:
  1. Which part of the second session did you find ***most*** interesting and/or helpful? If you have time: why?
  2. Which part of the second session did you find ***least*** interesting and/or helpful? If you have time: why?

For More Information...

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