Solvers
for
Software Reliability and Security

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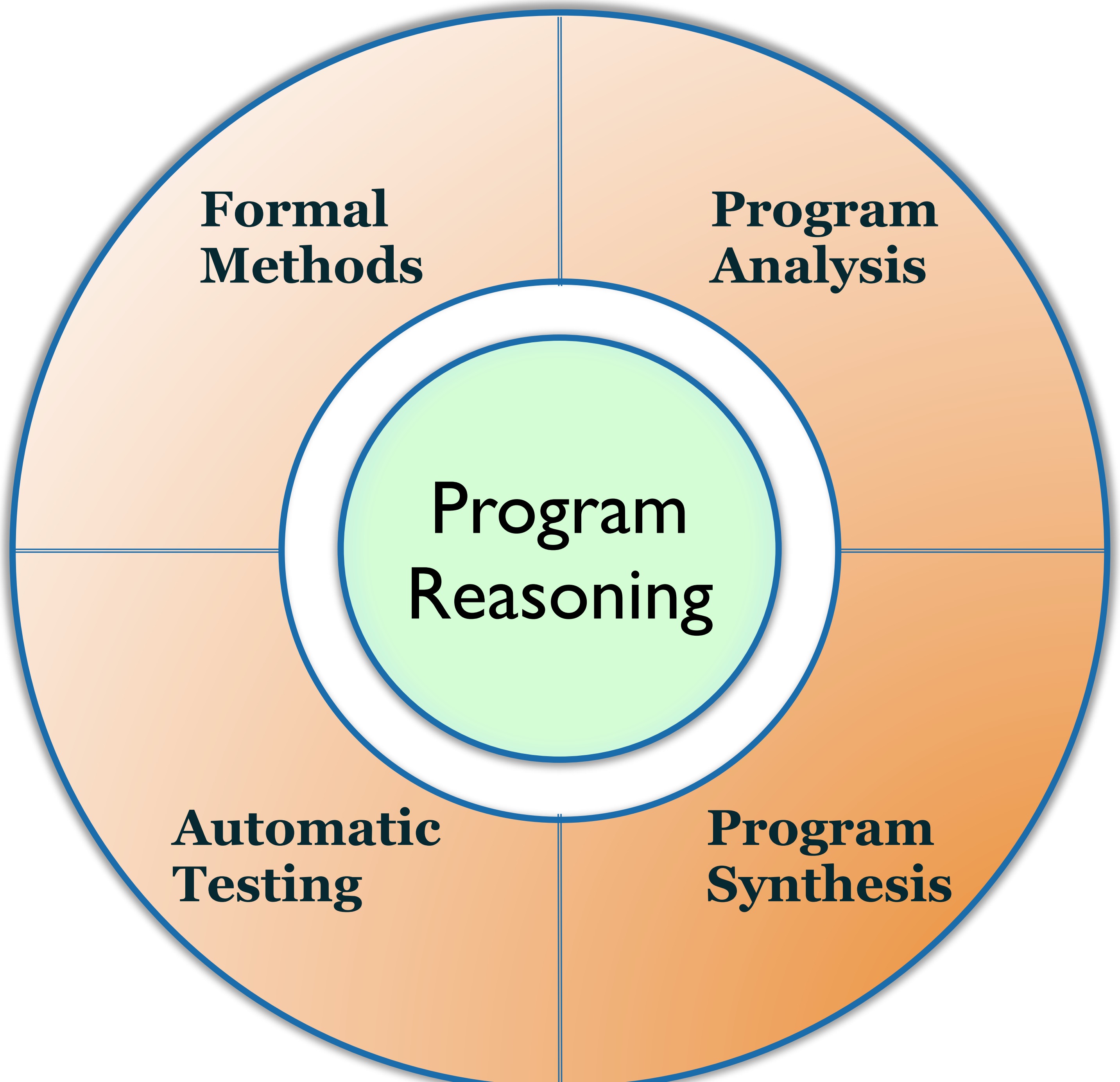
MIT
2011

The Software Reliability Problem

- Software is error-prone
- Significant and increasing costs
- Foundational research problem and opportunity

What is at the Core?

Logic Abstractions of Computation



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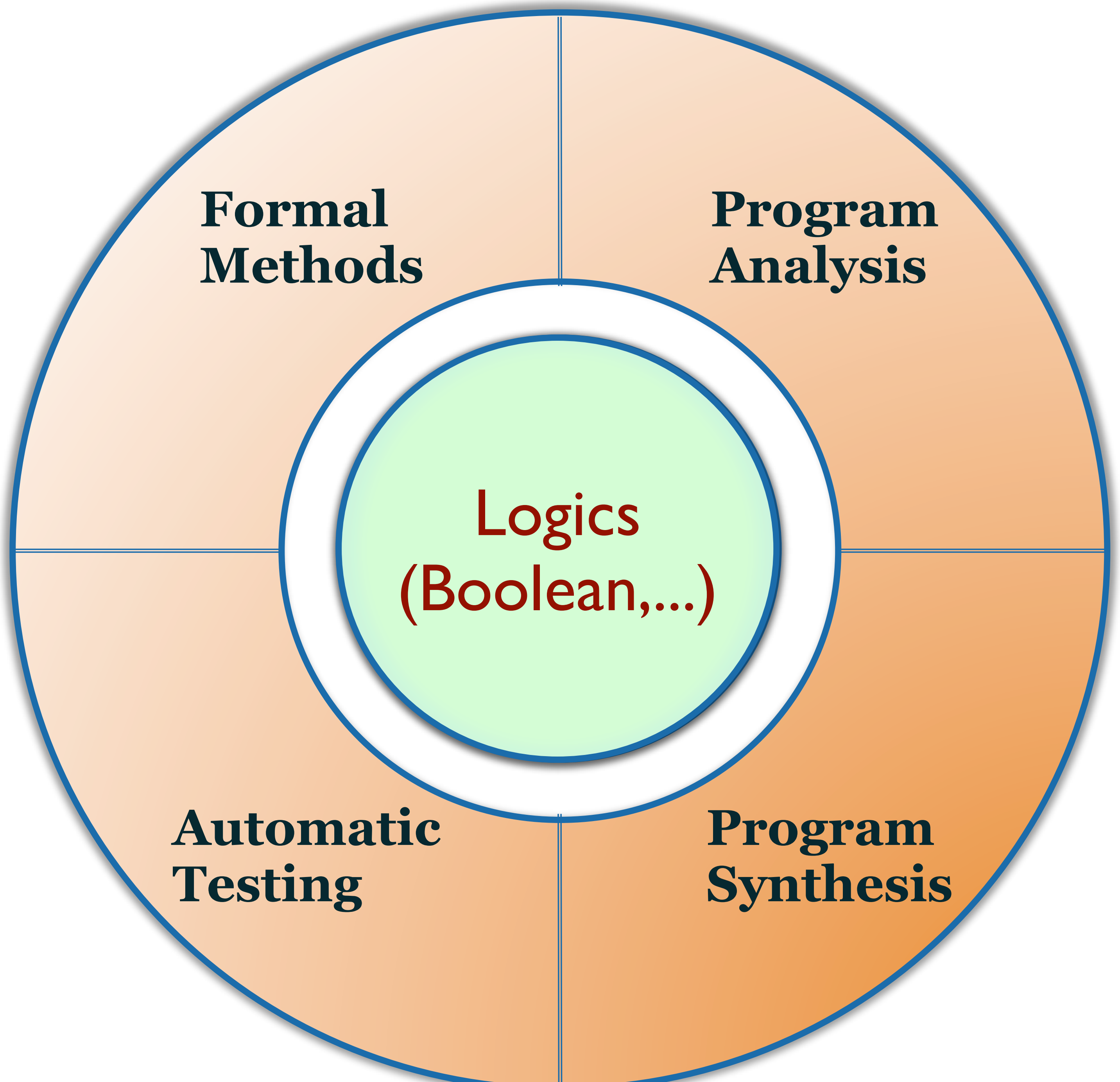
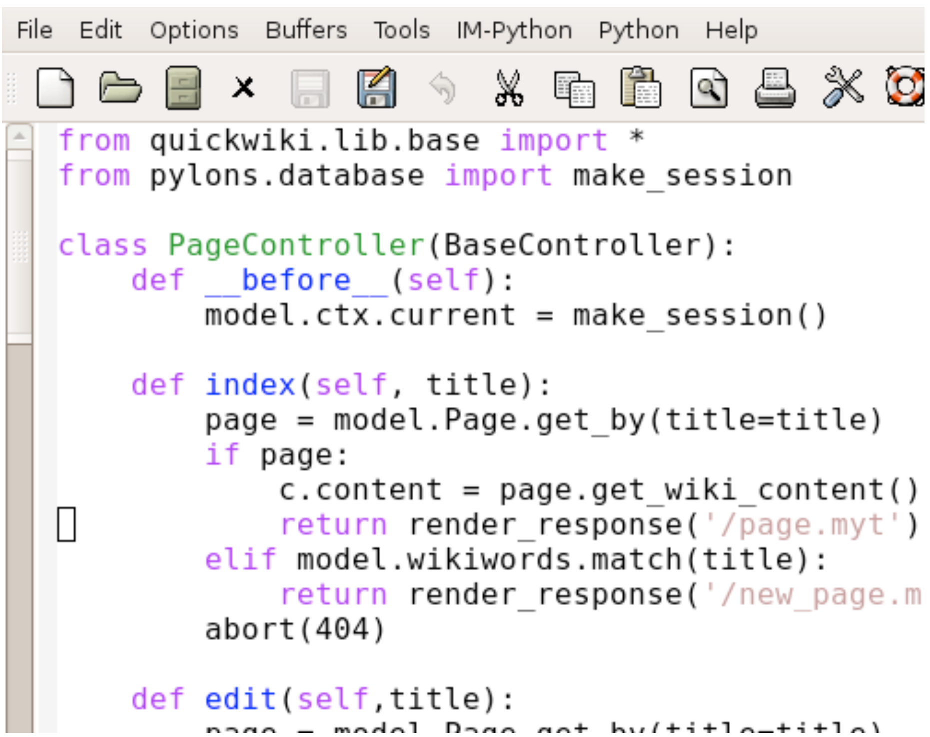


Why Logic for Program Reasoning

Logic Abstractions of Computation

Imperative Code: Operational view



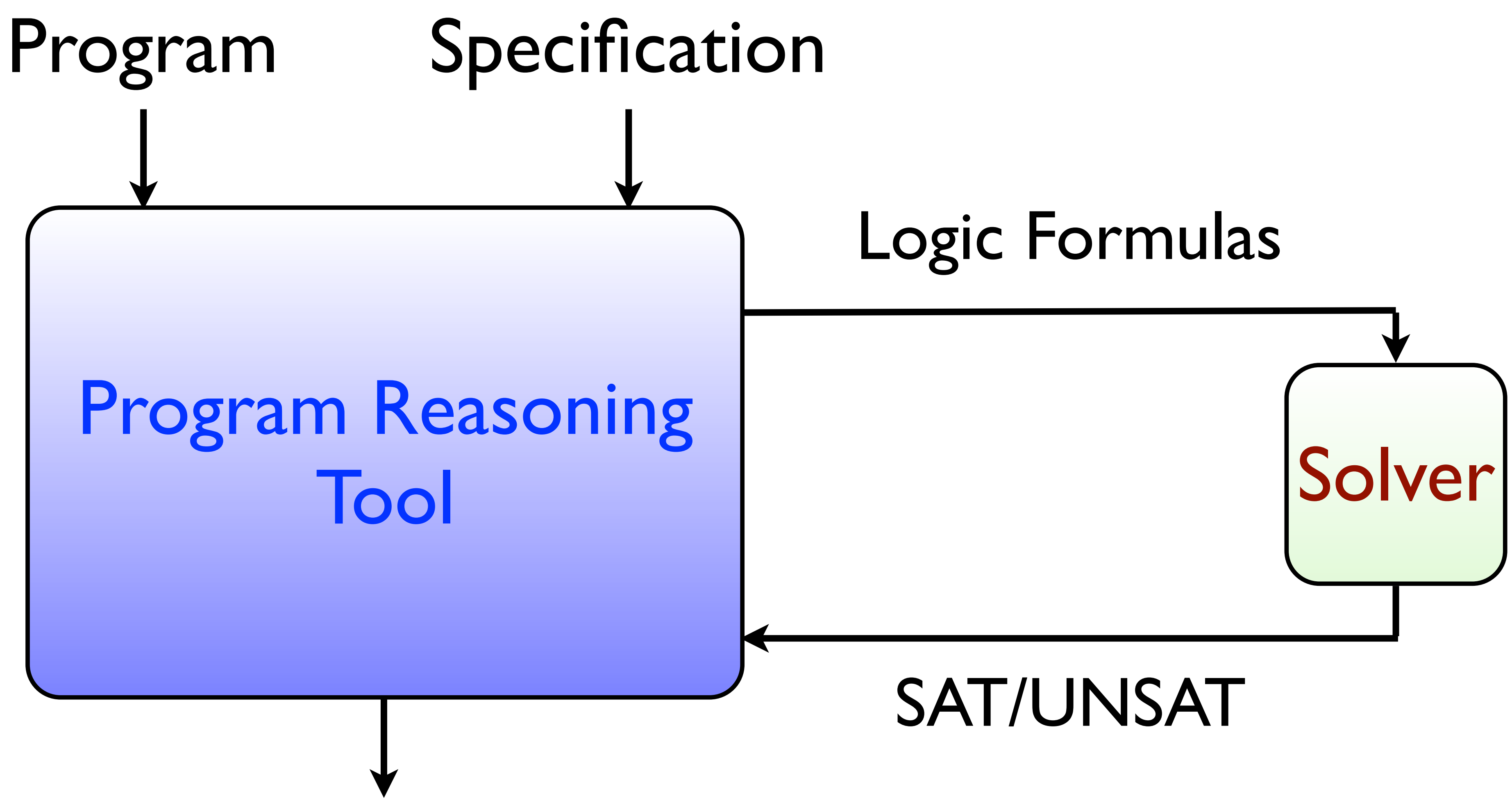
Logic Formula: Declarative View

$(\forall x.(P(x) \wedge Q(x)) \leftrightarrow ((\forall x.P(x)) \wedge (\forall x.Q(x)))$
$(\exists x.(P(x) \wedge Q(x)) \rightarrow ((\exists x.P(x)) \wedge (\exists x.Q(x)))$
$(\exists x.(P(x) \vee Q(x)) \leftrightarrow ((\exists x.P(x)) \vee (\exists x.Q(x)))$
$((\forall x.P(x)) \vee (\forall x.Q(x))) \rightarrow (\forall x.(P(x) \vee Q(x)))$
$(\exists x.\forall y.R(x,y)) \rightarrow (\forall y.\exists x.R(x,y))$
$(\neg(\exists x.P(x))) \leftrightarrow (\forall x.(\neg P(x))$
$(\neg(\forall x.P(x))) \leftrightarrow (\exists x.(\neg P(x))$
$(\neg(\exists x pt.P(x))) \leftrightarrow (\forall x pt.(\neg P(x))$
$(\neg(\forall x pt.P(x))) \leftrightarrow (\exists x pt.(\neg P(x))$
$(\forall x.(x = t \rightarrow F(x))) \leftrightarrow F(t)$
$(\exists x.(x = t \wedge F(x))) \leftrightarrow F(t)$

- Logic provides abstractions of computation
- Easy to work with abstractions
- Compact representation of desired properties

Reliability through Logical Reasoning

Engineering, Usability, Novelty



Program is Correct?
or Generate Counterexamples (Test cases)

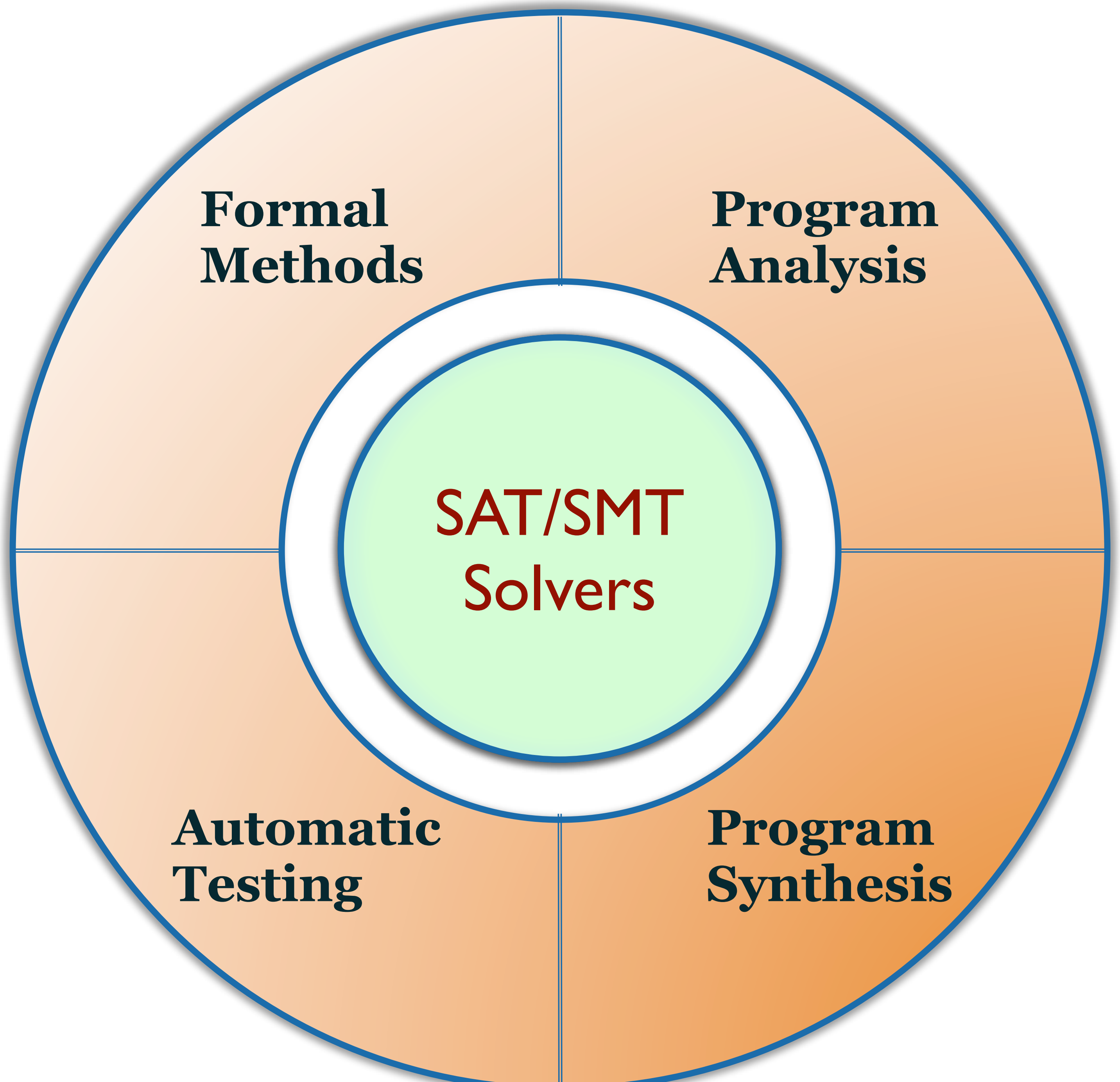
What is at the Core?

The SAT/SMT Problem

- Rich logics (Modular arithmetic, Arrays, Strings,...)
- NP-complete, PSPACE-complete,...
- Practical, scalable, usable, automatic
- Enable novel software reliability approaches

So, What's New?

From Reliability Problem to Solvers



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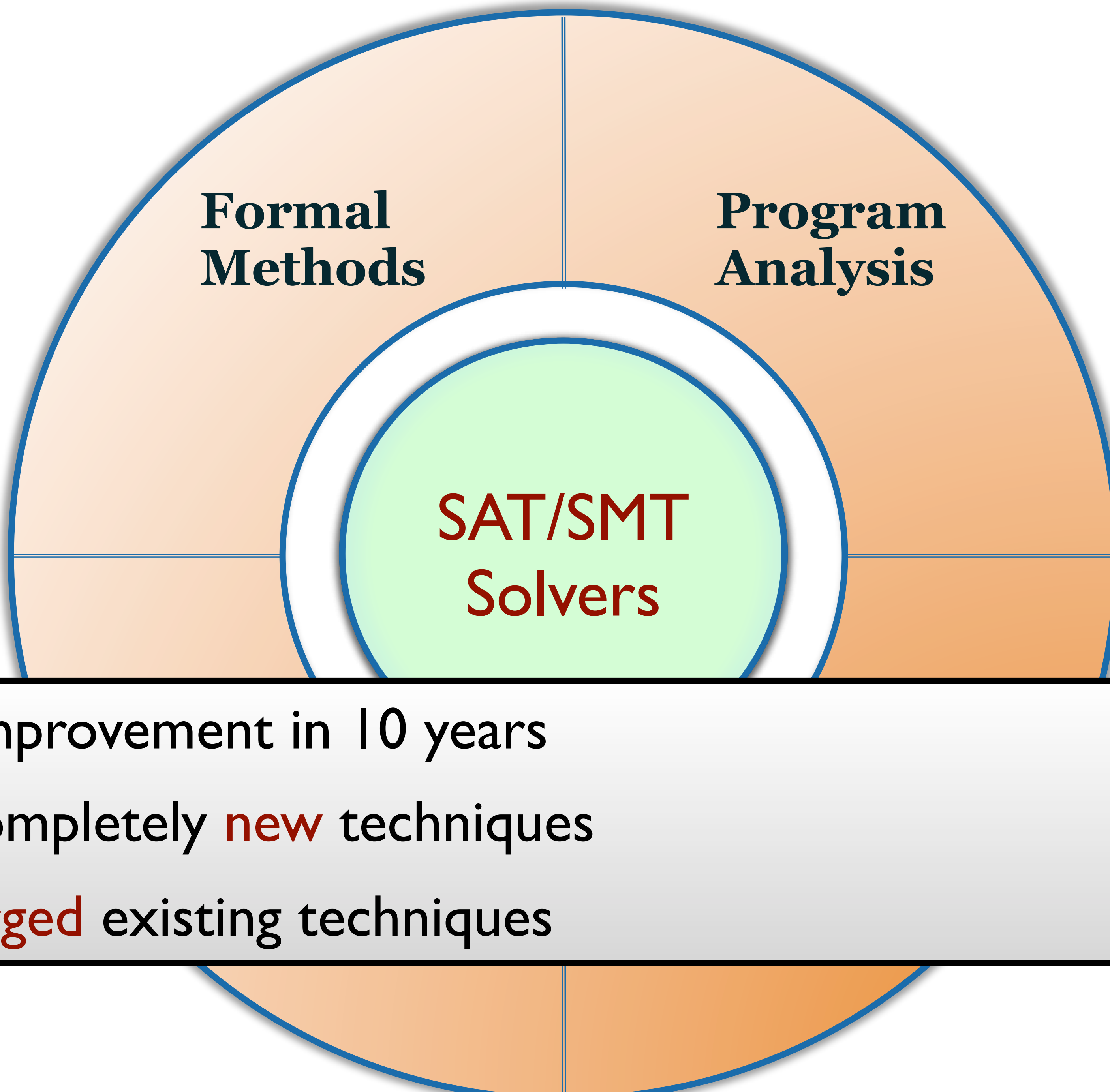
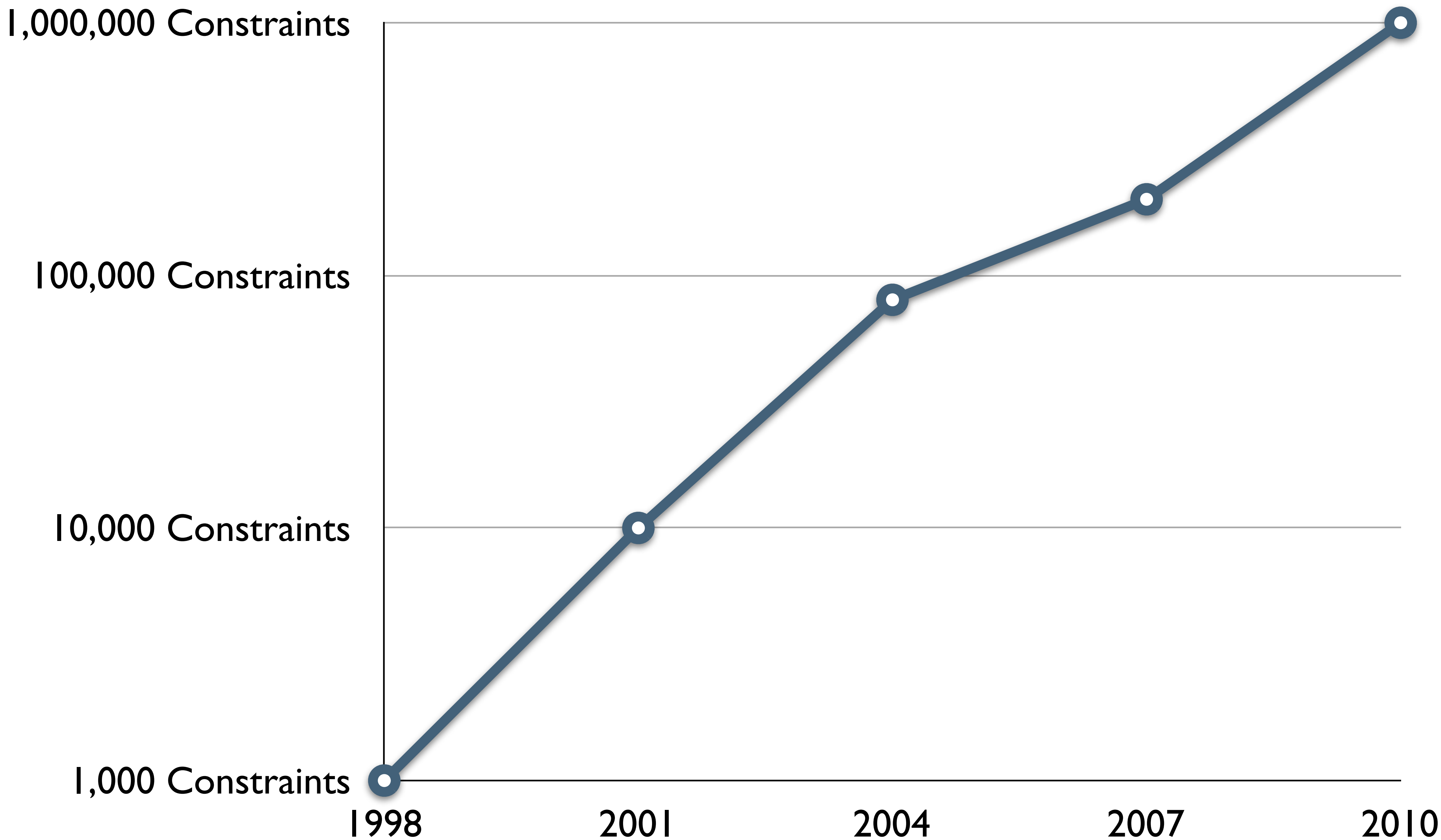
From Reliability Problem to Solvers



- 1000+X improvement in 10 years
- Enabled completely new techniques
- Super-charged existing techniques

And, The Research Story is....



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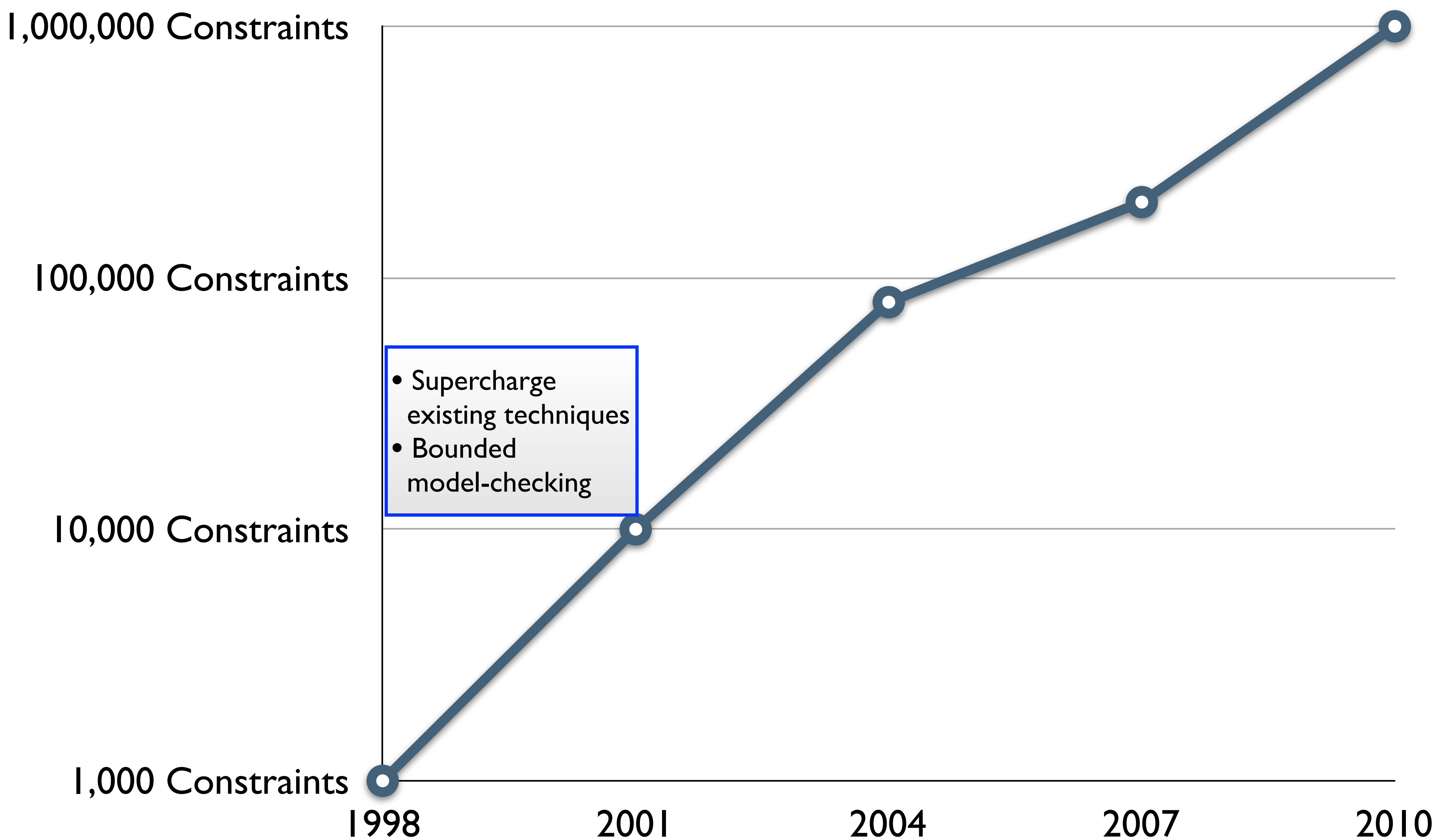

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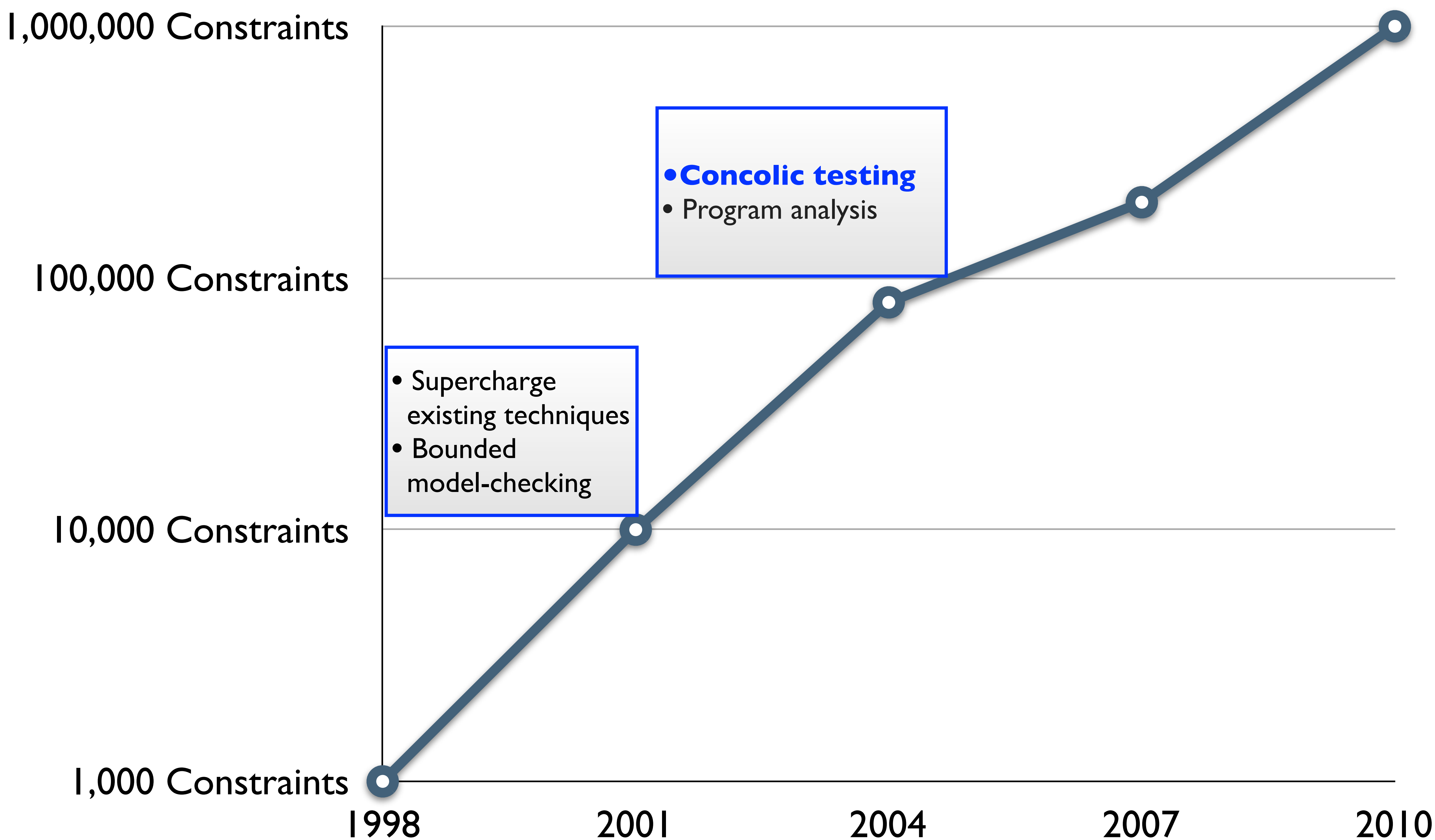

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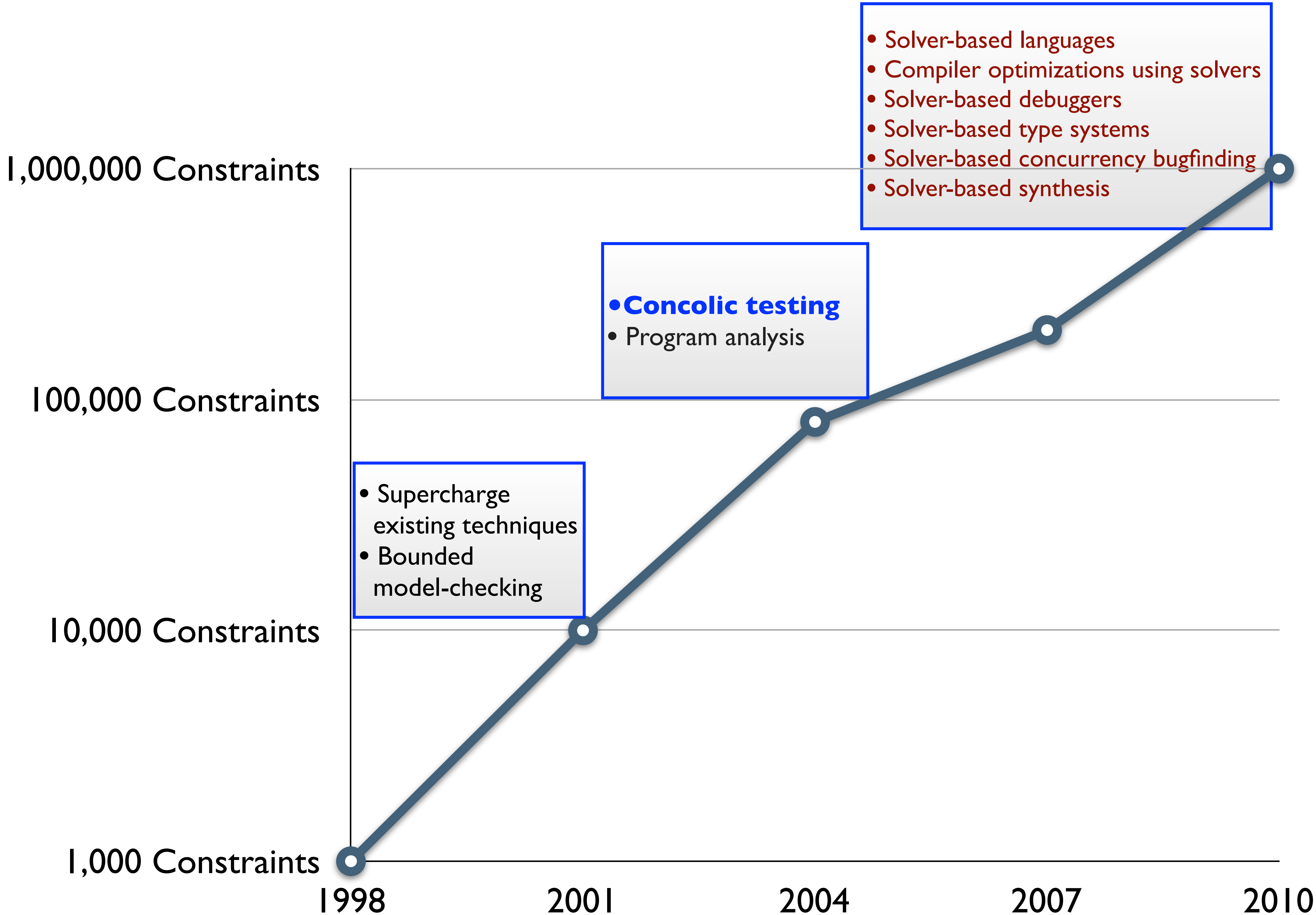
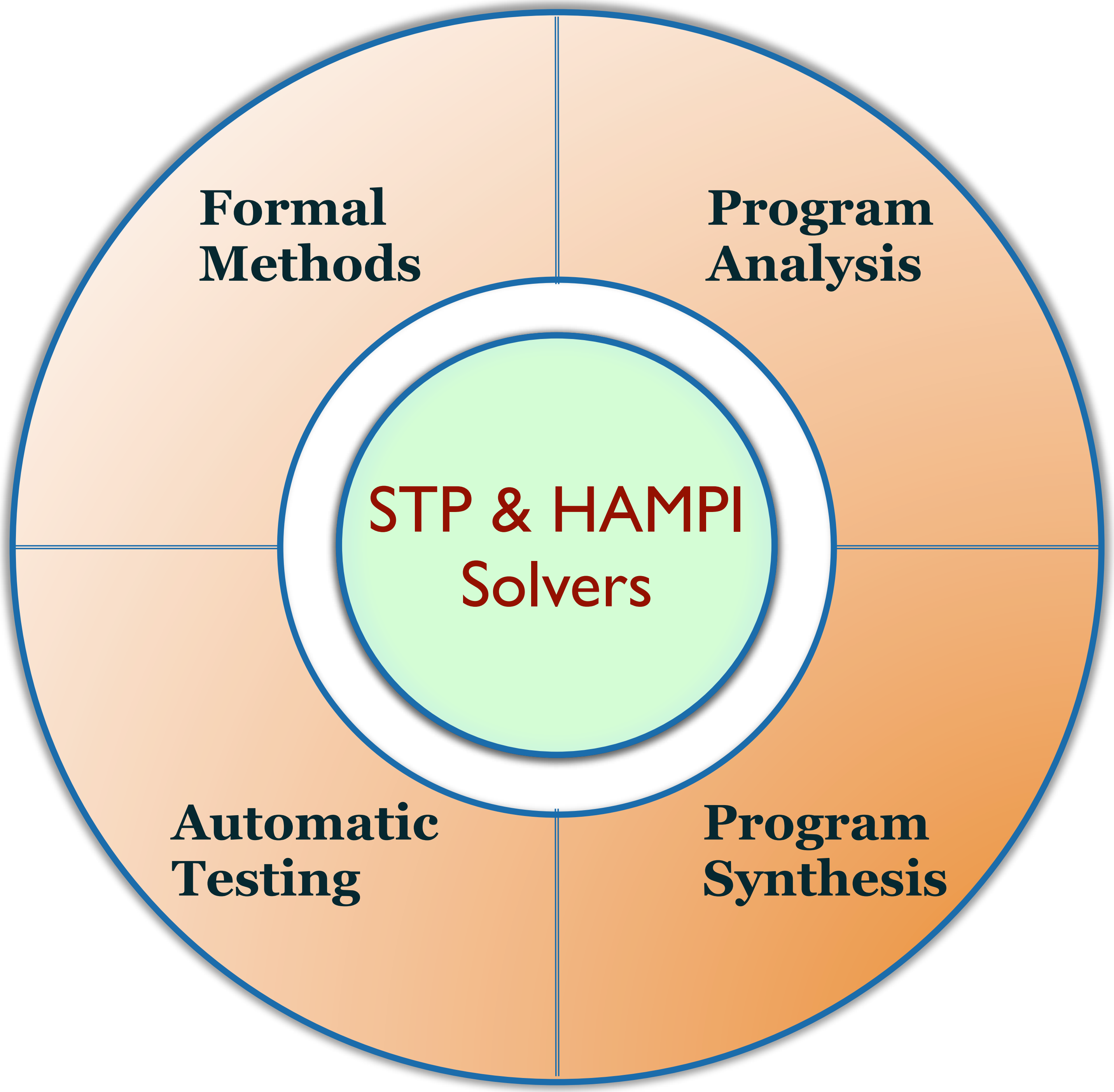


My Contributions

STP & HAMPI Solvers



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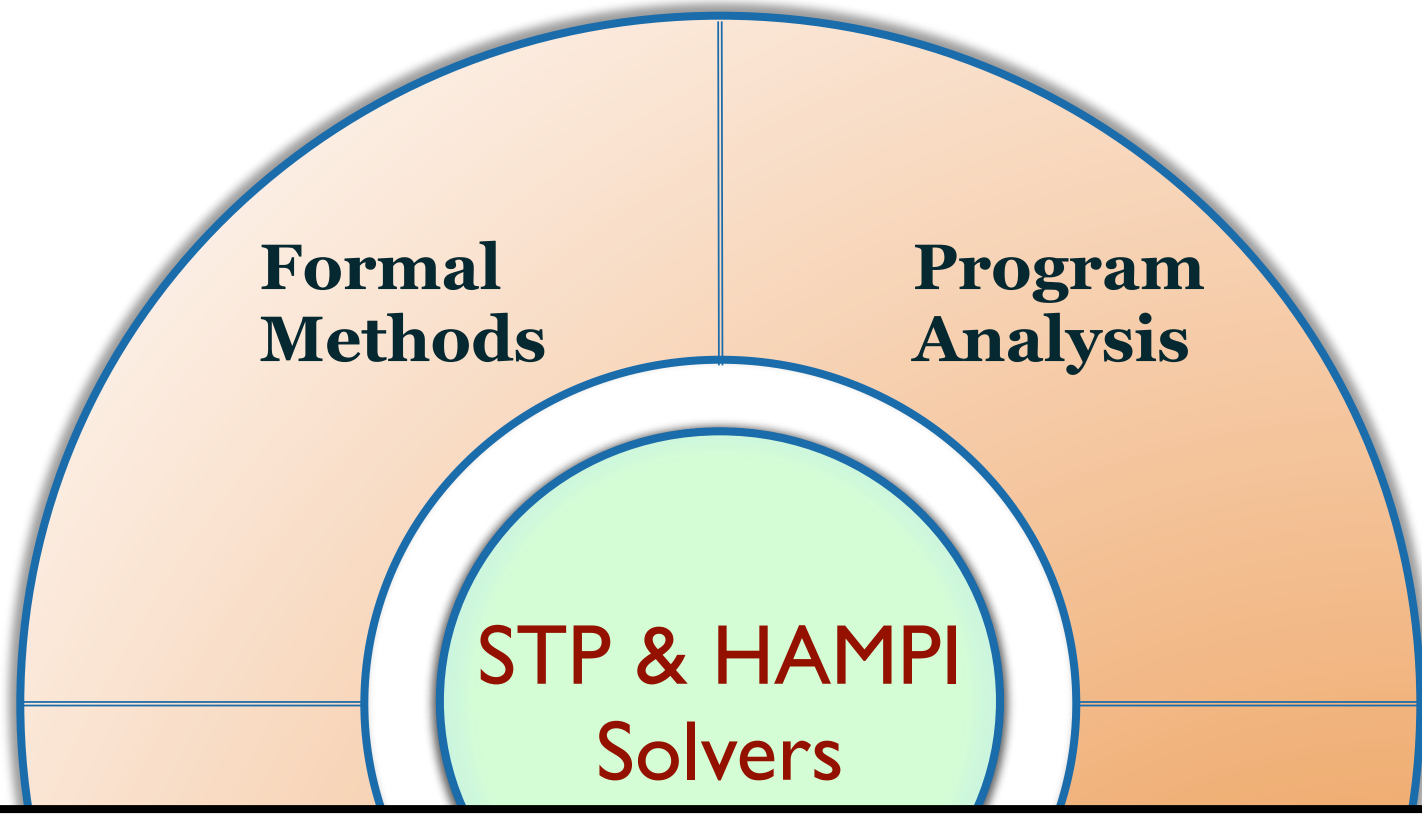
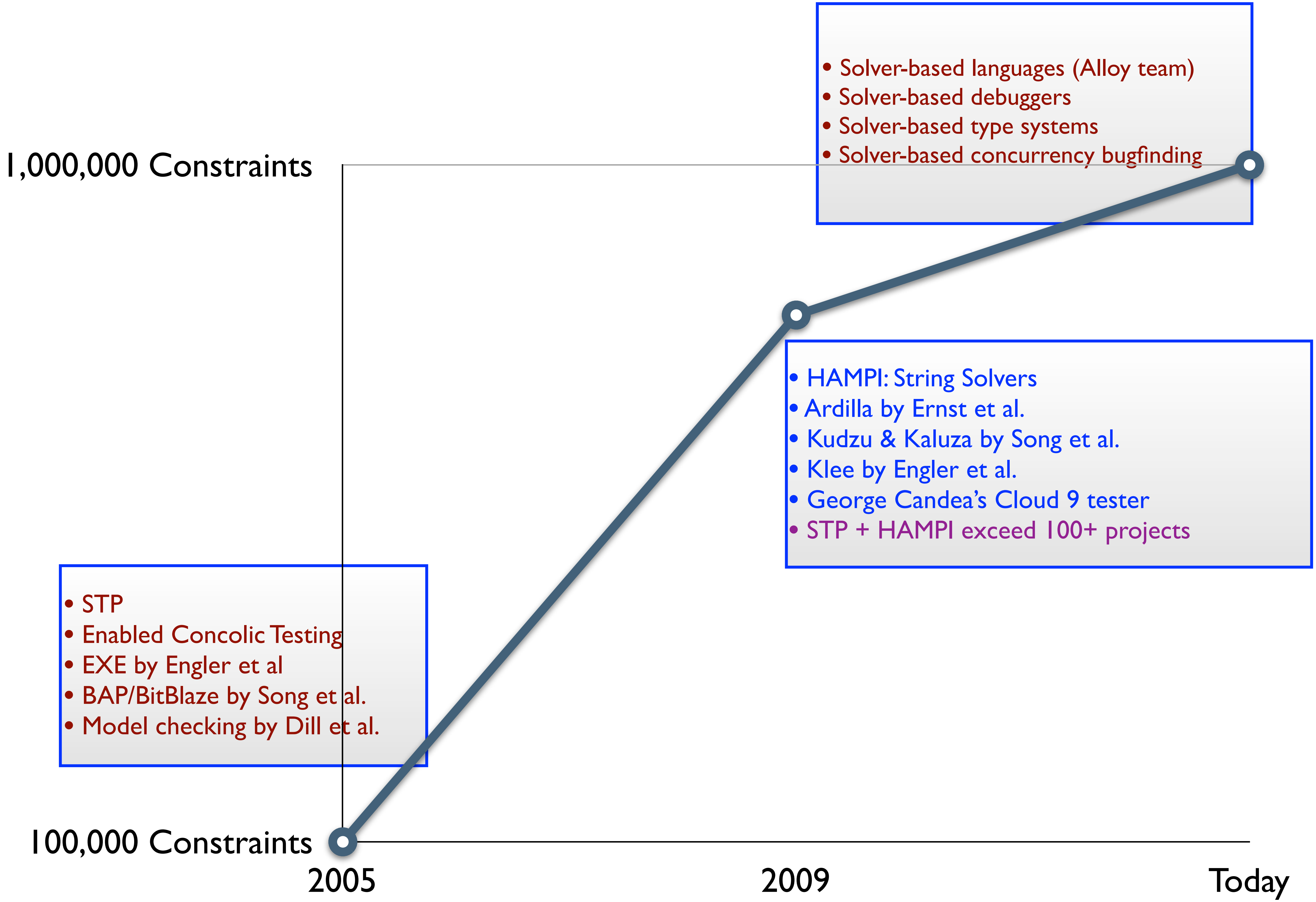


- Can handle real-world formulas with millions of constraints
- Enabled completely new techniques (e.g., Concolic testing)
- Enable test million-line codes
- Super-charged existing techniques (e.g., Hardware bounded MC)
- Future is bright: Multicore, programming language, runtime systems

And, The Research Story is ...



Key Contributions

Name	**Key Concept**	**Impact**	**Pubs**
STP Bit-vector & Array Solver[1,2]	Abstraction-refinement for Solving	Concolic Testing	CAV 2007 CCS 2006 TISSEC 2008
HAMPI String Solver[1]	App-driven Bounding for Solving	Analysis of Web Apps	ISSTA 2009[3] TOSEM 2011 (Invited/in submission)
(Un)Decidability results for Strings	Insights from Practical Applications	First results for strings+length	In submission

1. 100+ research projects use STP and HAMPI
2. STP won the SMTCOMP 2006 and 2010 competitions for bit-vector solvers
3. ACM Best Paper Award 2009

Rest of the Talk

- STP Bit-vector and Array Solver
  - Why Bit-vectors and Arrays?
  - How does STP scale: Abstraction-refinement
  - Impact: Concolic testing
  - Experimental Results
- HAMPI String Solver
  - Why Strings?
  - How does HAMPI scale: Bounding
  - Impact: String-based program analysis
  - Experimental Results
- Future Work
  - Multicore SAT
  - SAT-based Languages
  - Auto-tuning Solvers
  - Advice-based Solvers

STP Bit-vector & Array Solver

- Bit-vector or machine arithmetic
- Arrays for memory
- C/C++/Java expressions
- NP-complete

Programs Reasoning & STP
Why Bit-vectors and Arrays

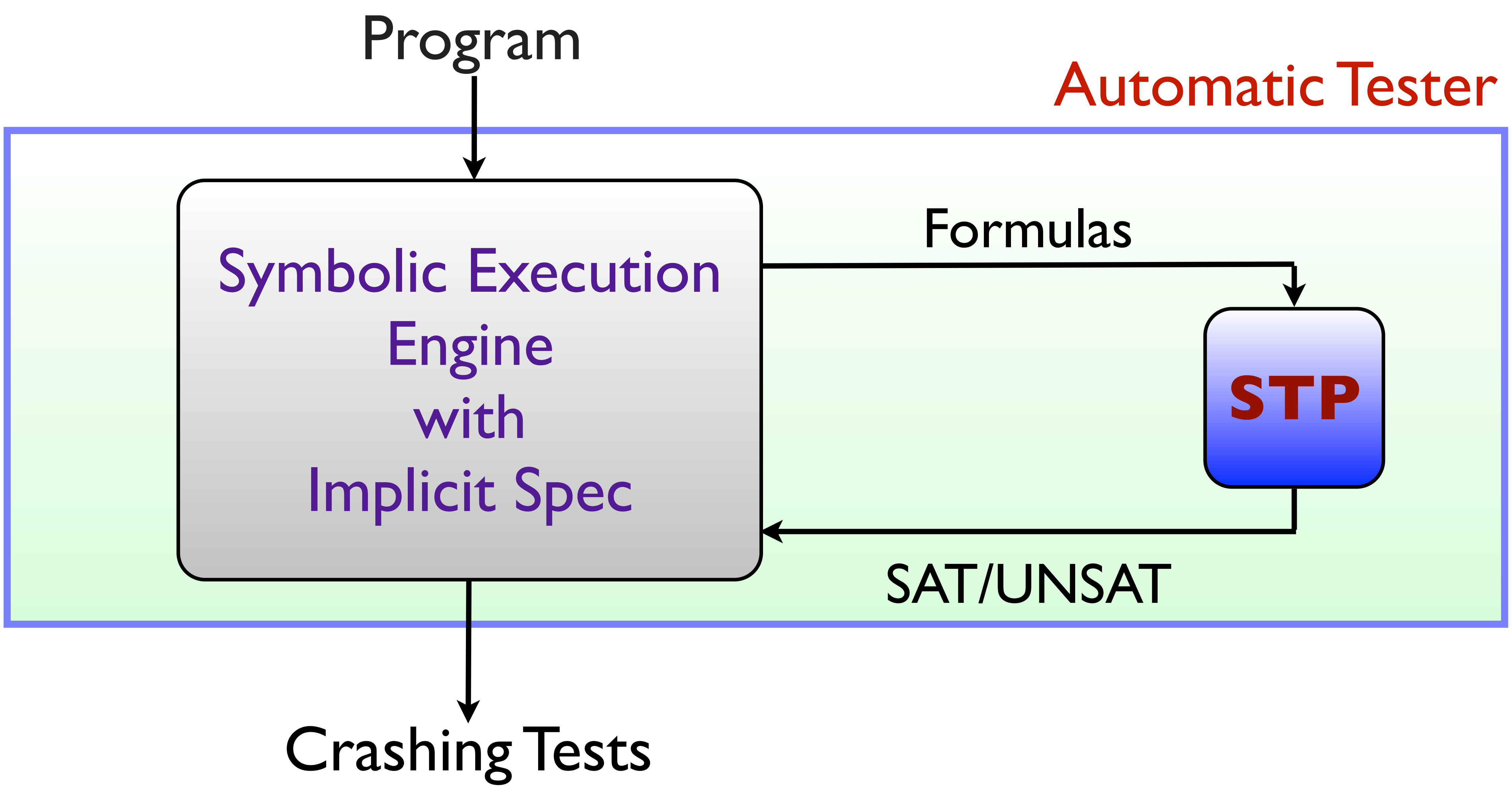
- STP logic tailored for software reliability applications
- Support symbolic execution/program analysis

C/C++/Java/...	Bit-vectors and Arrays
Int Var Char Var	32 bit variable 8 bit variable
Arithmetic operation (x+y, x-y, x*y, x/y,...)	Arithmetic function (x+y,x-y,x*y,x/y,...)
assignments x = expr;	equality x = expr;
if conditional if(cond) x = expr^1 else x = expr^2	if-then-else construct x = if(cond) expr^1 else expr^2
inequality	inequality predicate
Memory read/write x = *ptr + i;	Array read/write ptr[]; x = Read(ptr,i);
Structure/Class	Serialized bit-vector expressions
Function	Symbolic execution
Loops	Bounding

How to Automatically Crash Programs?

Concolic Execution & STP

Problem: Automatically generate crashing tests given only the code



How to Automate Testing?

Concolic Execution & STP

Structured input processing code:
PDF Reader, Movie Player,...

```
Buggy_C_Program(int* data_field, int len_field) {

    int * ptr = malloc(len_field*sizeof(int));
    int i; //uninitialized

    while (i++ < process(len_field)) {
      //1. Integer overflow causing NULL deref
      //2. Buffer overflow
      *(ptr+i) = process_data(*(data_field+i));
    }
}
```

- Formula captures computation
- Tester attaches formula to capture spec

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    }
}
```

Equivalent Logic Formula derived using
symbolic execution

```
data_field, mem_ptr : ARRAY;
len_field : BITVECTOR(32); //symbolic
i, j, ptr   : BITVECTOR(32);//symbolic
.
.
mem_ptr[ptr+i] = process_data(data_field[i]);
mem_ptr[ptr+i+1] = process_data(data_field[i+1]);
.
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```

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↔

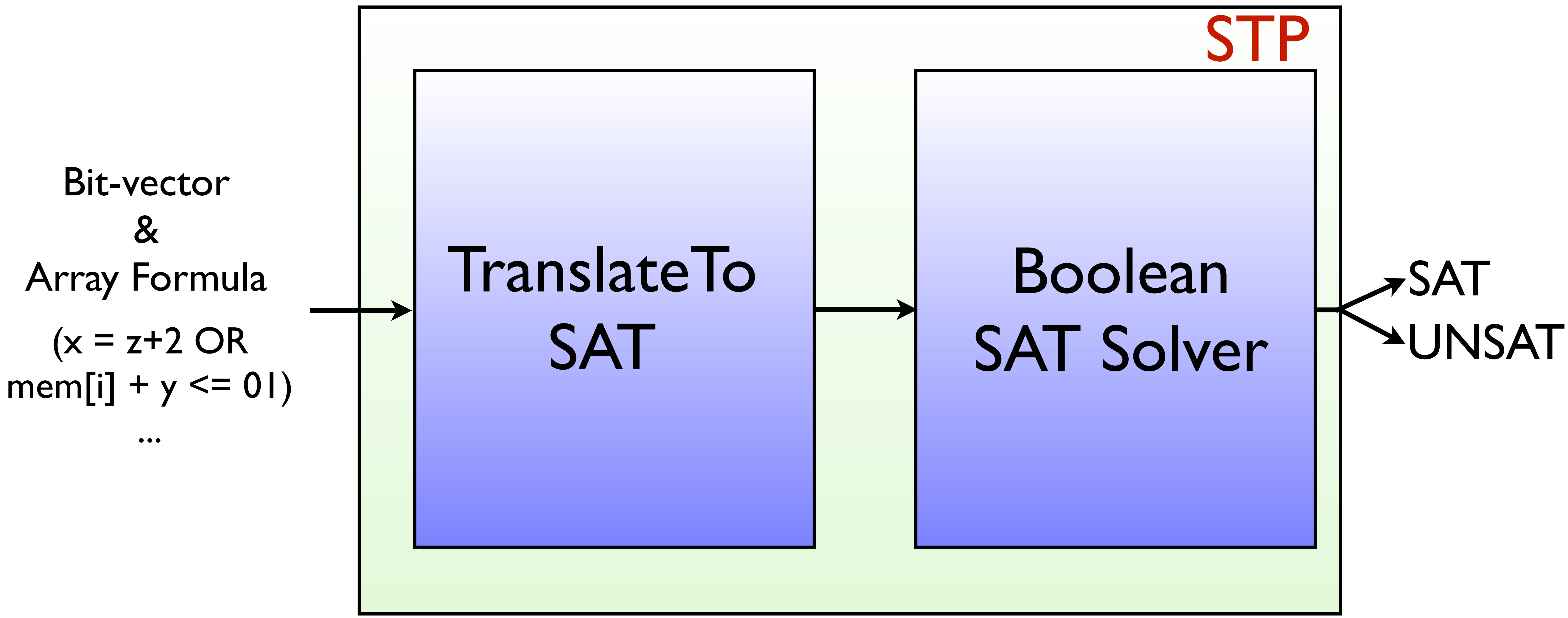
Equivalent Logic Formula derived using symbolic execution

```
data_field, mem_ptr :  ARRAY;
len_field : BITVECTOR(32); //symbolic
i,  j, ptr     : BITVECTOR(32);//symbolic
.
.
mem_ptr[ptr+i] = process_data(data_field[i]);
mem_ptr[ptr+i+1] = process_data(data_field[i+1]);
.
.
//INTEGER OVERFLOW QUERY
0 <= j <= process(len_field);
ptr + i + j = 0?
```

- Formula captures computation
- Tester attaches formula to capture spec

How STP Works

Bird's Eye View: Translate to SAT

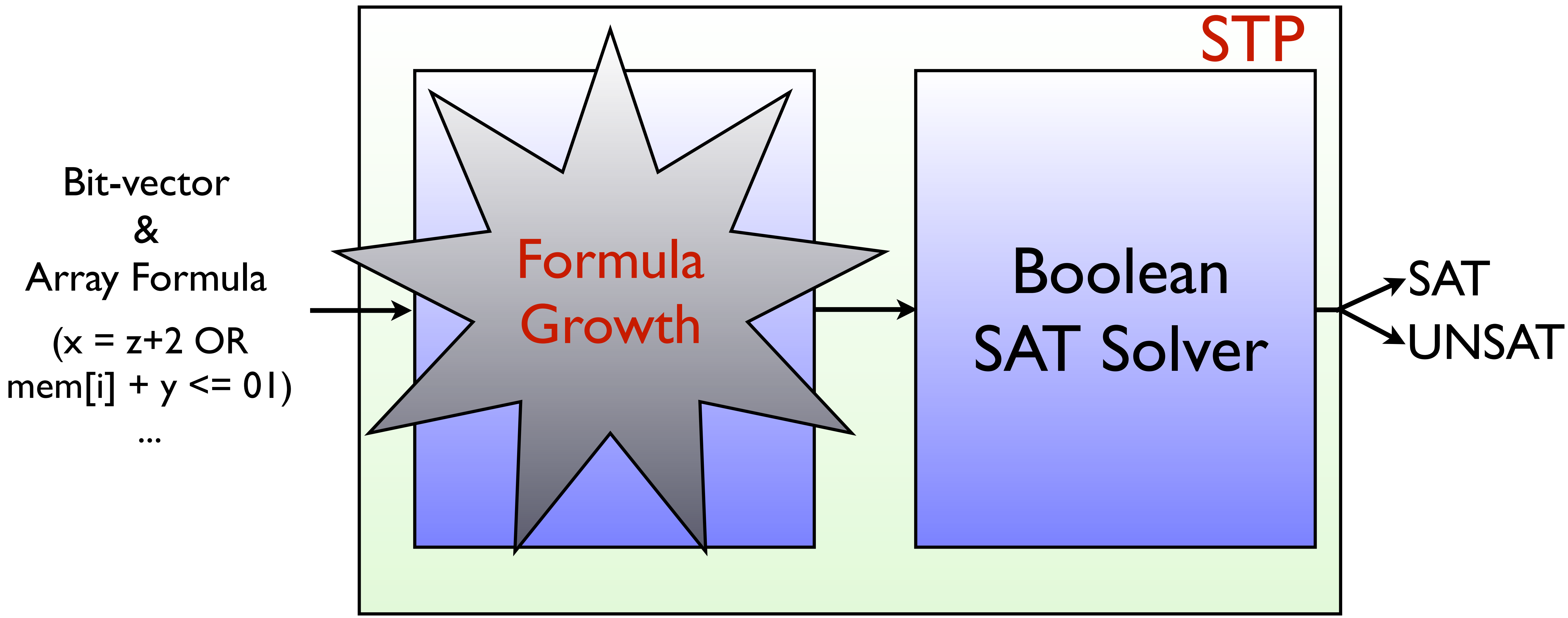


Why Translate to SAT?

- Both theories NP-complete
- Non SAT approaches didn't work
- Translation to SAT leverages solid engineering

How STP Works

Rich Theories cause MEM Blow-up



- Making information explicit
  - Space cost
  - Time cost

Explicit Information causes Blow-up

Array Memory Read Problem

Logic Formula derived using
symbolic execution

```
data_field, mem_ptr :  ARRAY;
len_field : BITVECTOR(32); //symbolic
i,  j, ptr     : BITVECTOR(32);//symbolic
.
.
mem_ptr[ptr+i] = process_data(data_field[i]);
mem_ptr[ptr+i+1] = process_data(data_field[i+1]);
.
.
if(ptr+i = ptr+i+1) then mem_ptr[ptr+i] = mem_ptr[ptr+i+1);

//INTEGER OVERFLOW QUERY
0 <= j <= process(len_field);
ptr + i + j < ptr?
```

- Array Aliasing is implicit
- Need to make information explicit during solving
- Cannot be avoided

How STP Works

Array-read MEM Blow-up Problem

- Problem: $O(n^2)$ axioms added, n is number of read indices
- Lethal, if n is large, say, n = 100,000; # of axioms is 10 Billion

Formula Growth

$Read(Mem,i_0) = expr_0$
$Read(Mem,i_1) = expr_1$
$Read(Mem,i_2) = expr_2$
.
.
.
$Read(Mem,i_n) = expr_n$

$v_0 = expr_0$
$v_1 = expr_1$
.
.
.
$v_n = expr_n$

$(i_0 = i_1) \Rightarrow (v_0 = v_1)$
$(i_0 = i_2) \Rightarrow (v_0 = v_2)$
...
$(i_1 = i_2) \Rightarrow (v_1 = v_2)$
...

How STP Works

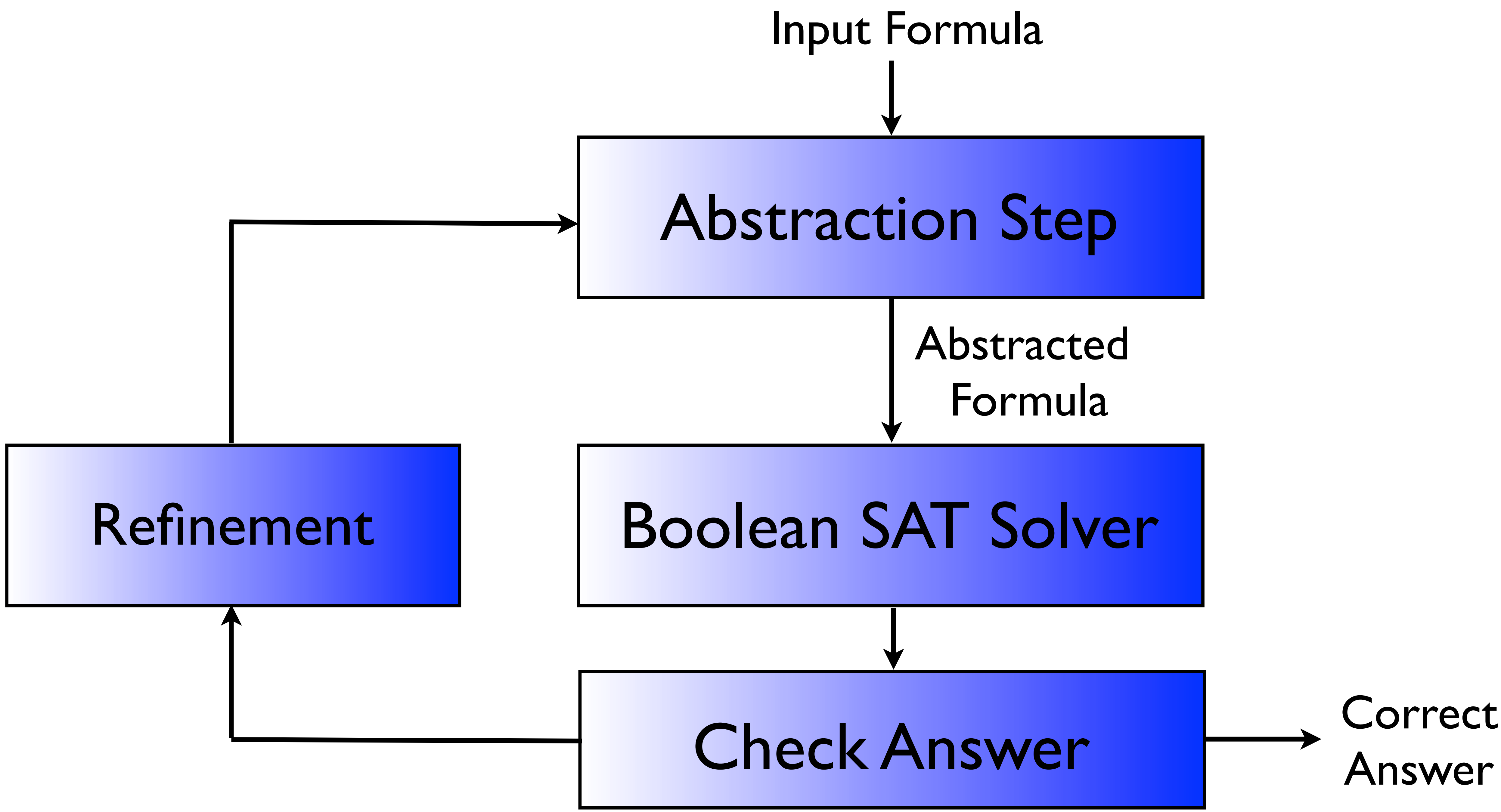
The Array-read Solution

- Key Observation
  - Most indices don't alias in practice
  - Exploit locality of memory access in typical programs
  - Need only a fraction of array axioms for equivalence

$$
\begin{array}{l}
Read(Mem,i_0) = expr_0 \\
Read(Mem,i_1) = expr_1 \\
Read(Mem,i_2) = expr_2 \\
\quad\quad\quad \vdots \\
Read(Mem,i_n) = expr_n
\end{array}
\quad \Longleftrightarrow \quad
\begin{array}{l}
v_0 = expr_0 \\
v_1 = expr_1 \\
\quad \vdots \\
v_n = expr_n \\
\\
(i_0 = i_1) \Rightarrow (v_0 = v_1)
\end{array}
$$

STP Key Conceptual Contribution

Abstraction-refinement Principle



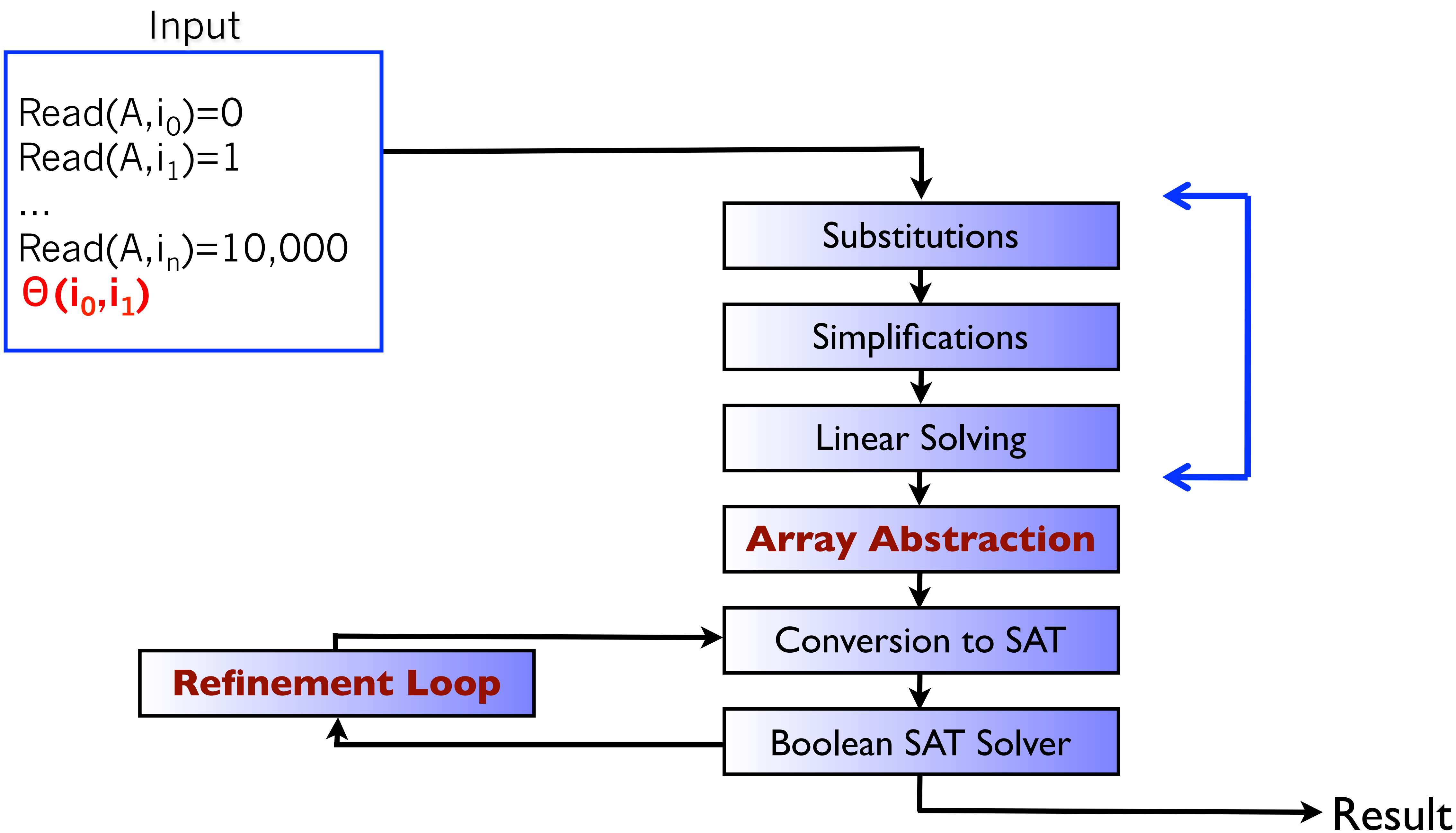
How STP Works

What to Abstract & How to Refine?

Abstraction	Refinement
1. Less essential parts 2. Causes MEM blow-up	1. Guided 2. Must remember
Abstraction manages formula growth hardness	Refinement manages search-space hardness

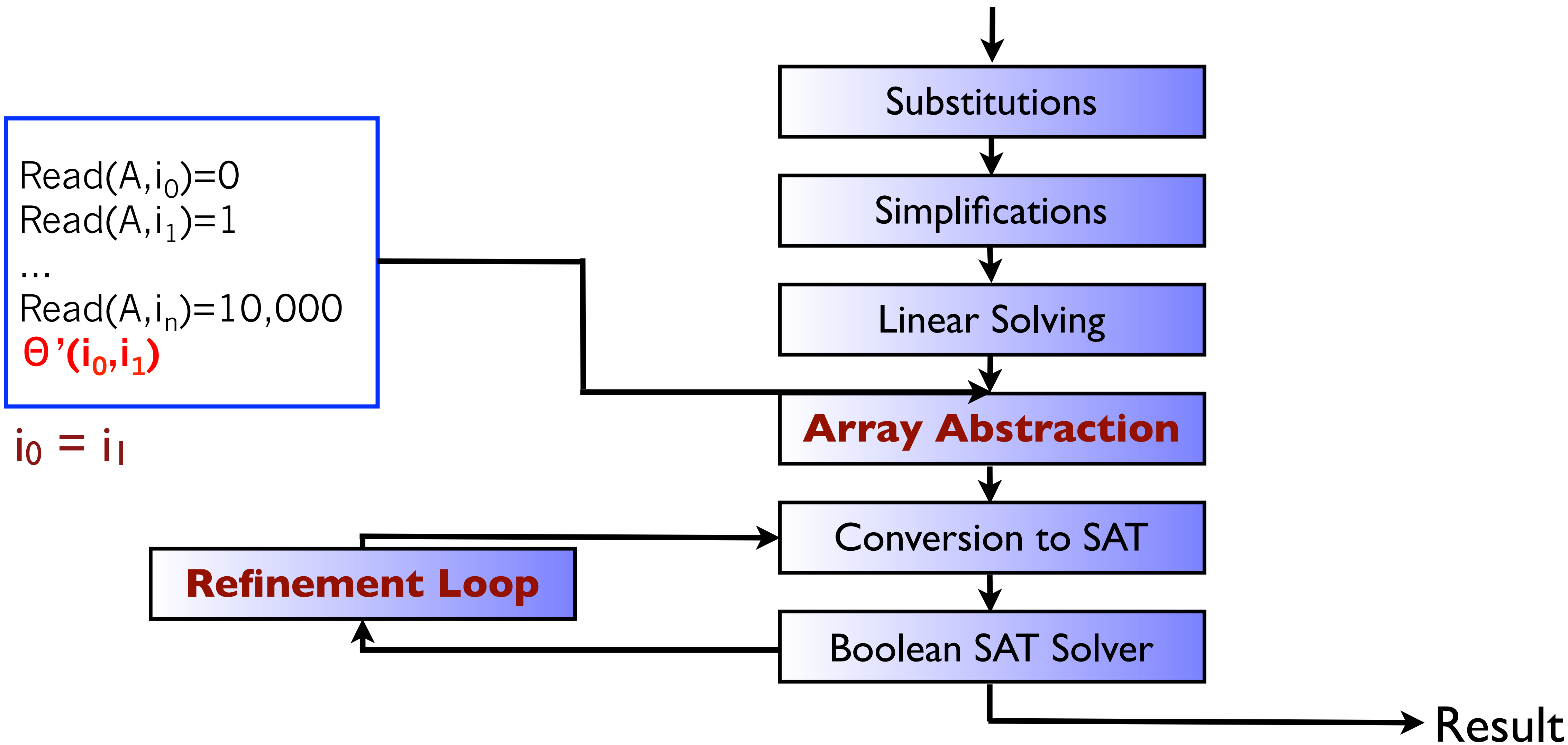
How STP Works

Abstraction-refinement for Array-reads



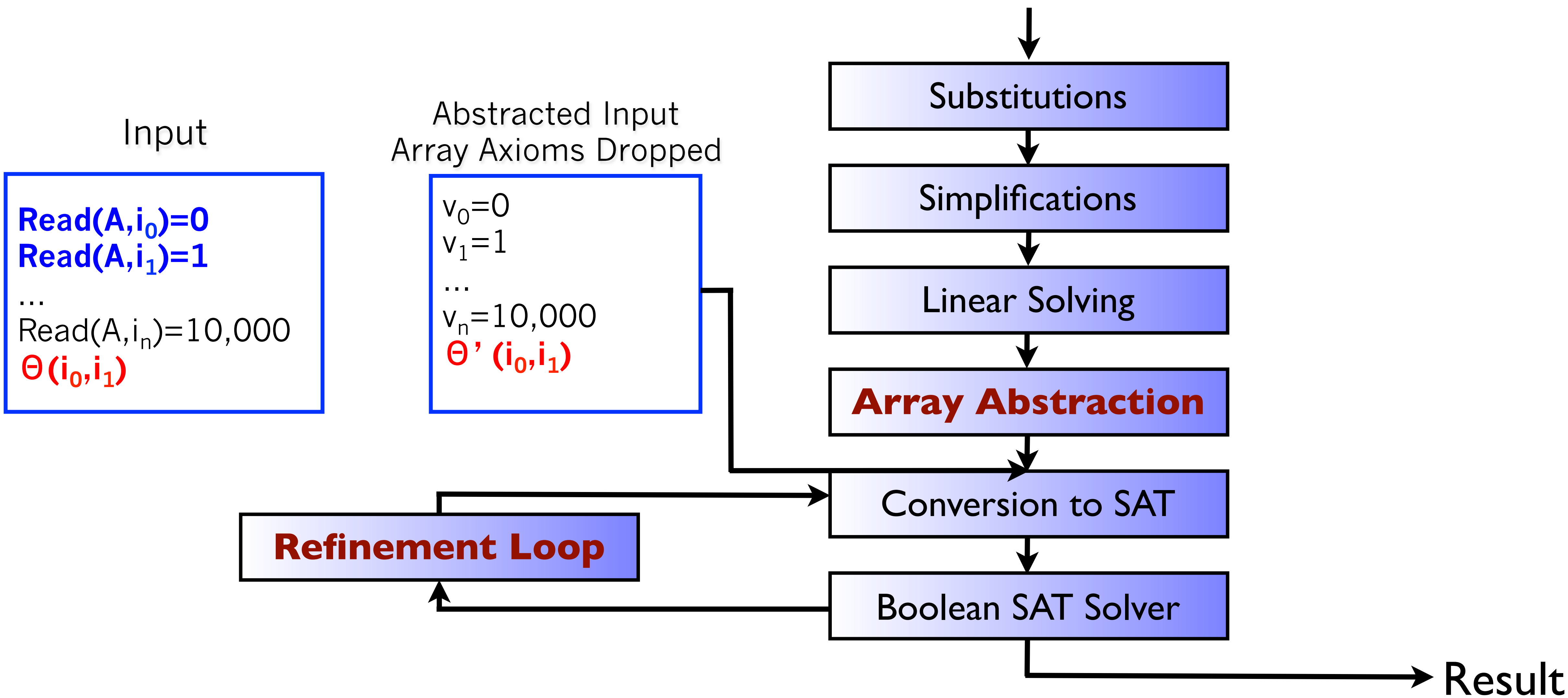
How STP Works

Abstraction-refinement for Array-reads



How STP Works

Abstraction-refinement for Array-reads



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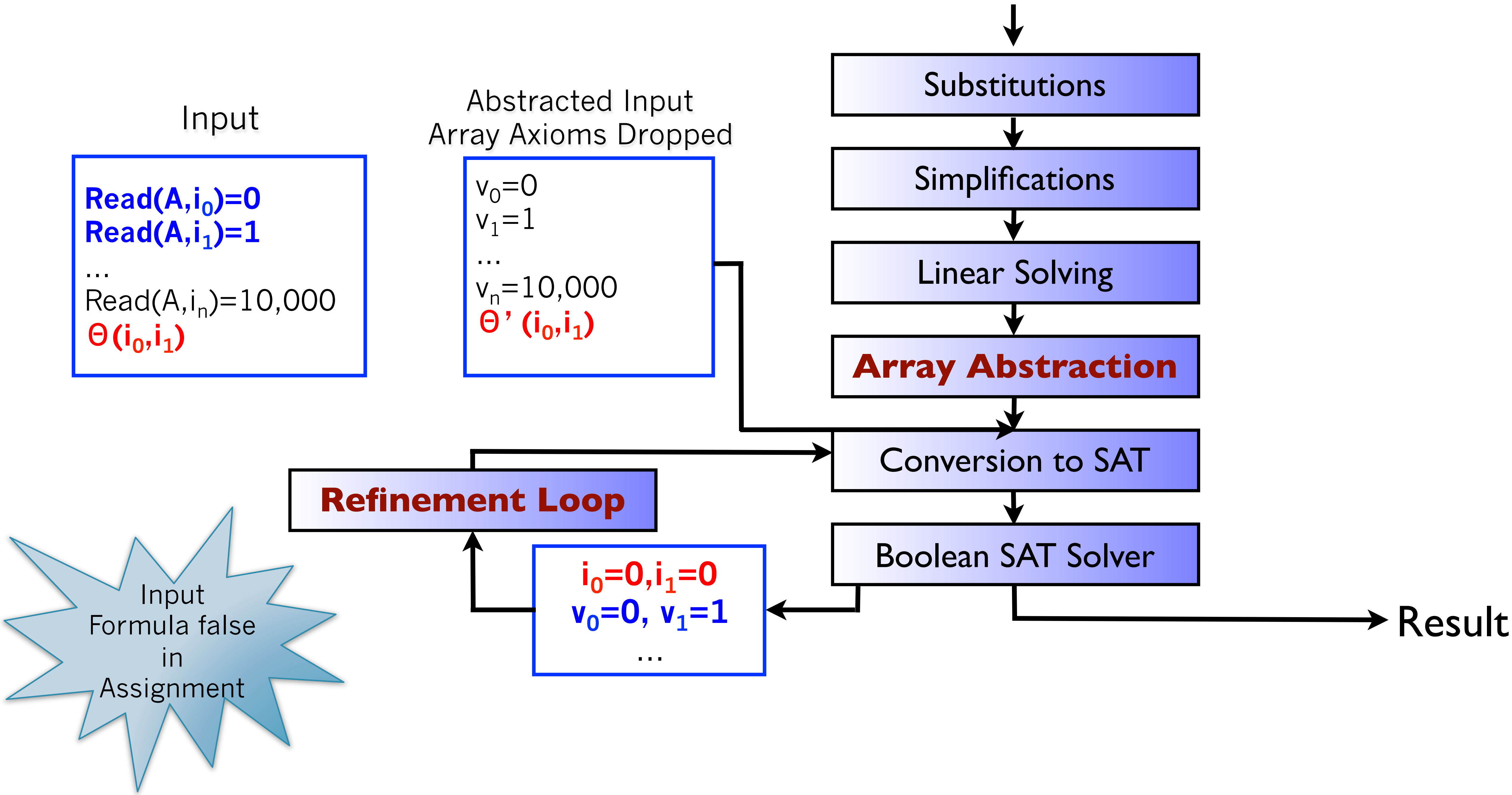
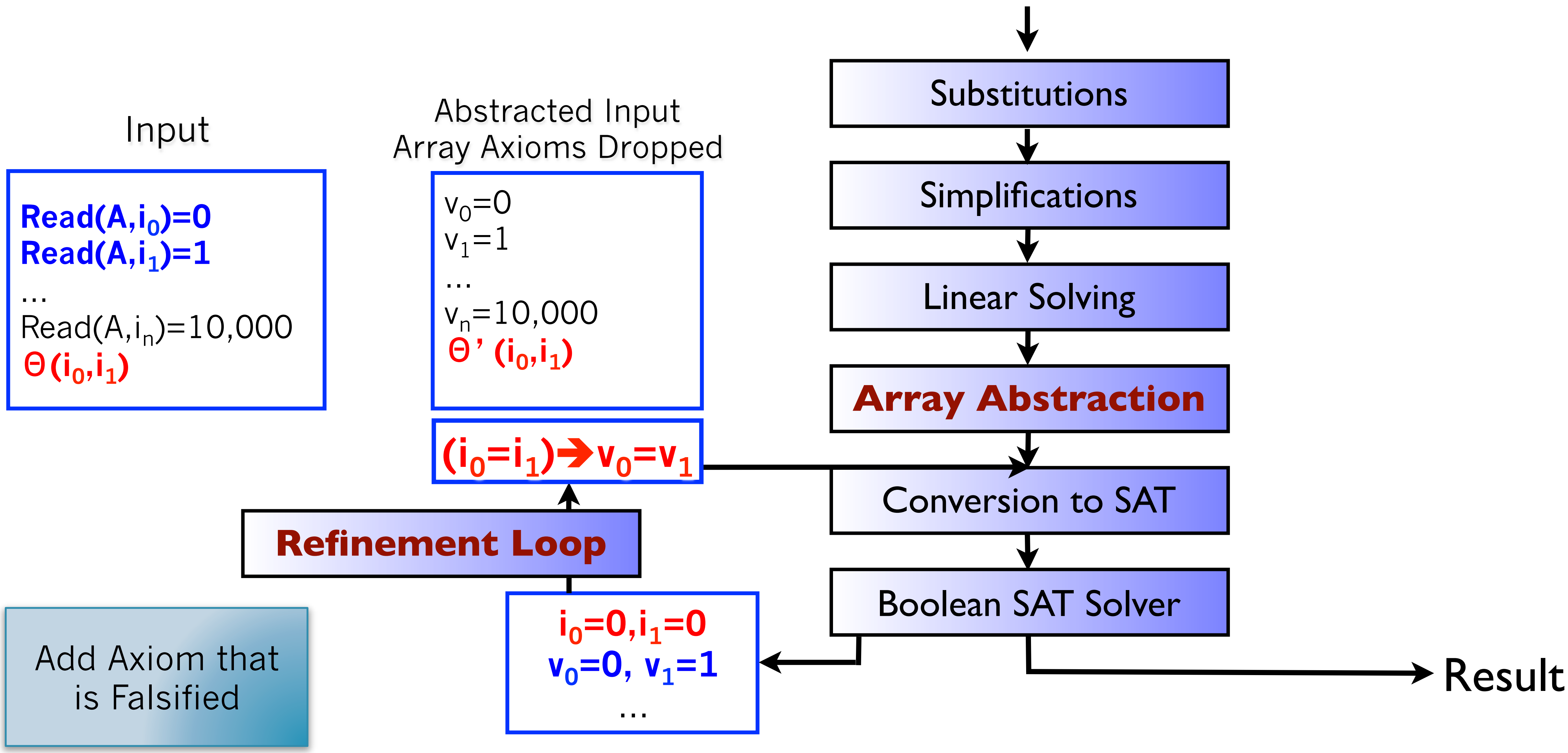
Abstraction-refinement for Array-reads



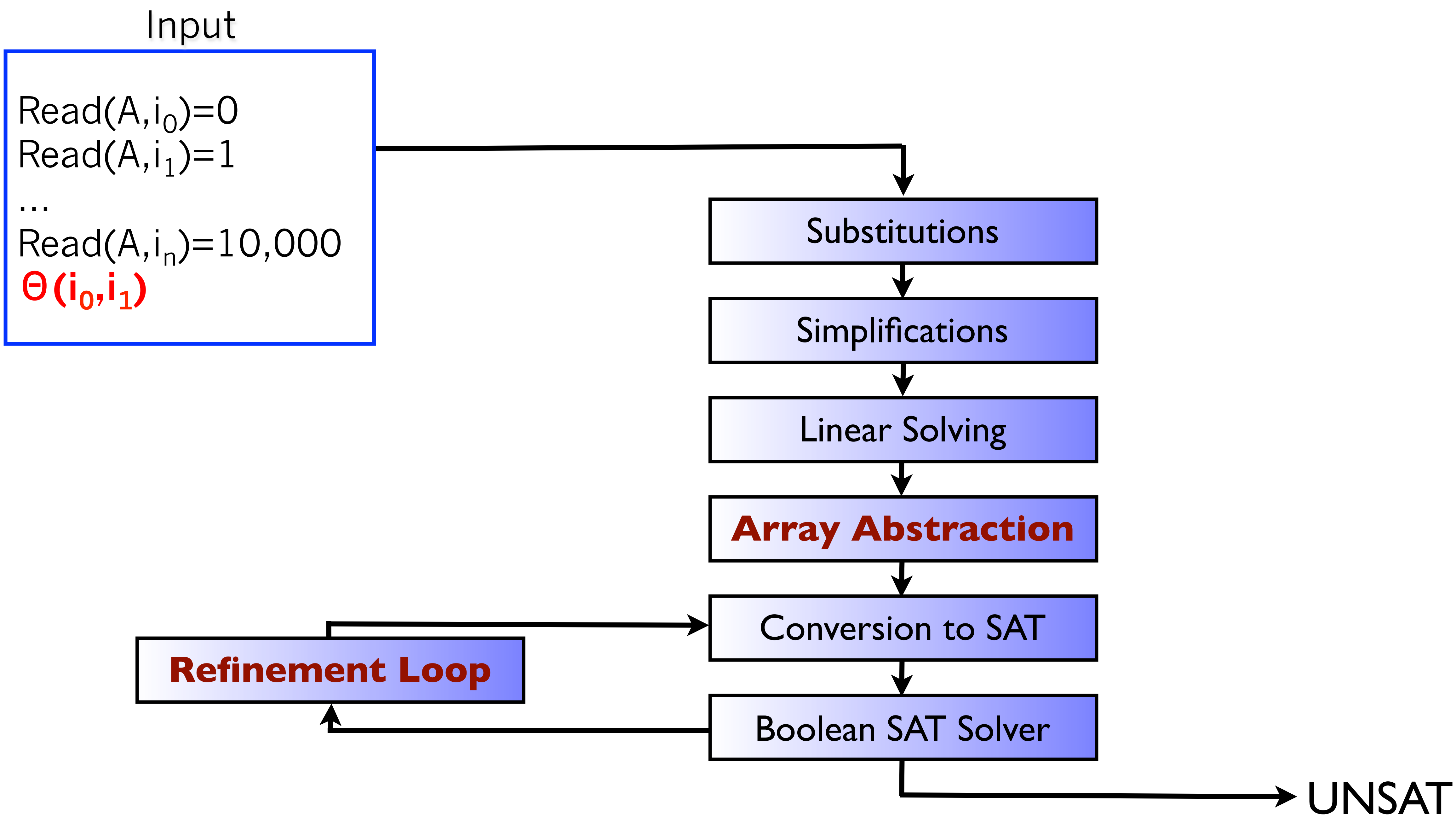
How STP Works

Abstraction-refinement for Array-reads



How STP Works

Abstraction-refinement for Array-reads

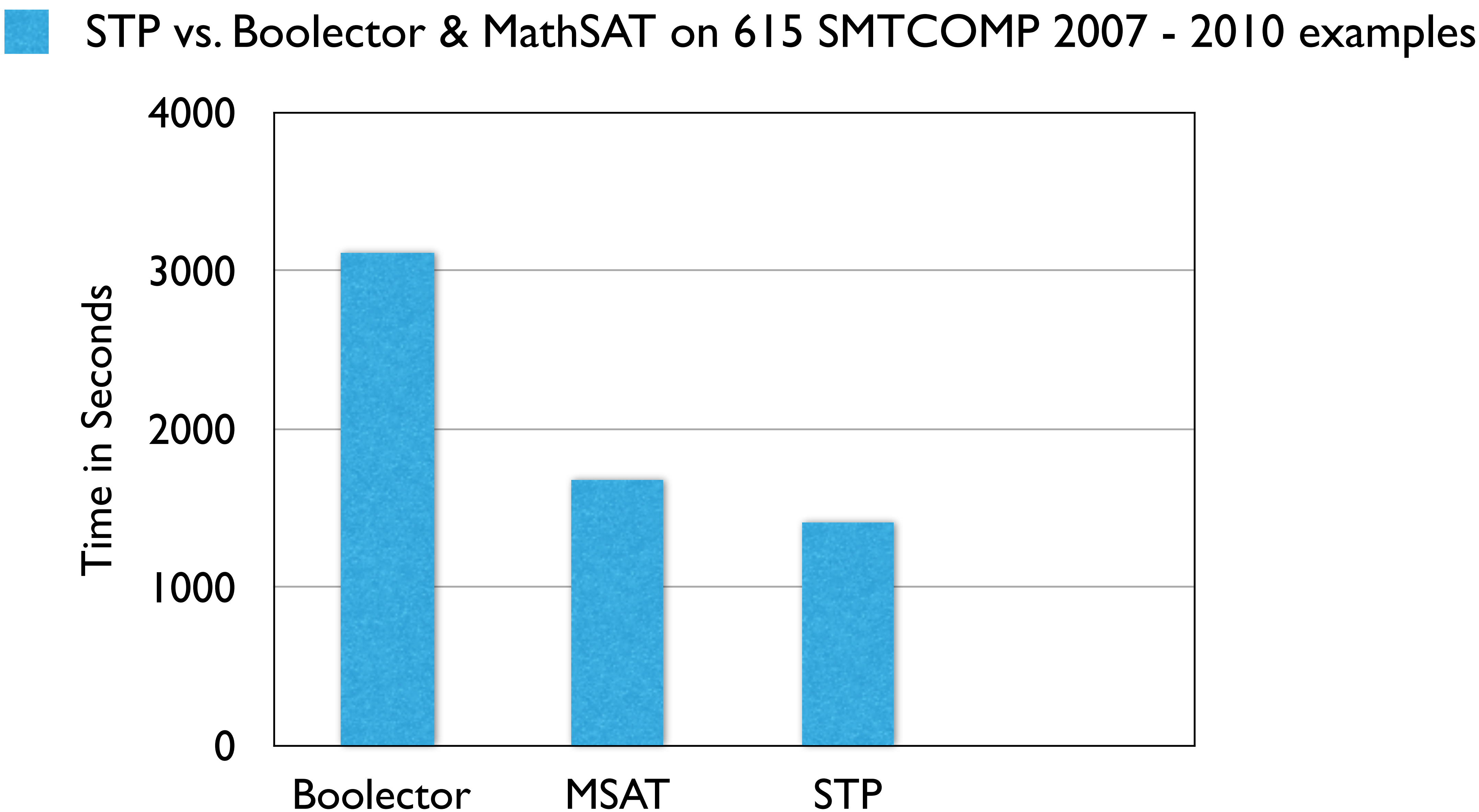


STP vs. Other Solvers

Testcase (Formula Size)	Result	Z3 (sec)	Yices (sec)	STP (sec)
610dd9c (~15K)	SAT	TimeOut	MemOut	37
Grep65 (~60K)	UNSAT	0.3	TimeOut	4
Grep84 (~69K)	SAT	176	TimeOut	18
Grep106 (~69K)	SAT	130	TimeOut	227
Blaster4 (~262K)	UNSAT	MemOut	MemOut	10
Testcase20 (~1.2M)	SAT	MemOut	MemOut	56
Testcase21 (~1.2M)	SAT	MemOut	MemOut	43

* All experiments on 3.2 GHz, 512 Kb cache
* MemOut: 3.2 GB (Memory used by STP much smaller), TimeOut: 1800 seconds
* Examples obtained from Dawn Song at Berkeley, David Molnar at Berkeley and Dawson Engler at Stanford
* Experiments conducted in 2007

STP vs. Other Leading Solvers



* All experiments on 2.4 GHz, 1 GB RAM
* Timeout: 500 seconds/example

Impact of STP

- Enabled existing SE technologies to scale
  - Bounded model checkers, e.g., Chang and Dill

- Easier to engineer SE technologies
  - Formal tools (ACL2+STP) for verifying Crypto, Smith & Dill

- Enabled new SE technologies
  - Concolic testing (EXE,Klee,...) by Engler et al., Binary Analysis by Song et al.

Impact of STP: Notable Projects

- Enabled Concolic Testing
- 100+ reliability and security projects

Category	**Research Project**	**Project Leader/Institution**
Formal Methods	ACL2 Theorem Prover + STP Verification-aware Design Checker Java PathFinder Model Checker	Eric Smith & David Dill/Stanford Jacob Chang & David Dill/Stanford Mehlitz & Pasareanu/NASA
Program Analysis	BitBlaze & WebBlaze BAP	Dawn Song et al./Berkeley David Brumley/CMU
Automatic Testing Security	Klee, EXE SmartFuzz Kudzu	Engler & Cadar/Stanford Molnar & Wagner/Berkeley Saxena & Song/Berkeley
Hardware Bounded Model-cheking (BMC)	Blue-spec BMC BMC	Katelman & Dave/MIT Haimed/NVIDIA

Impact of STP

http://www.metafuzz.com

Program Name	Lines of Code	Number of Bugs Found	Team
Mplayer	~900,000	Hundreds	David Molnar/Berkeley & Microsoft Research
Evince	~90,000	Hundreds	David Molnar/Berkeley & Microsoft Research
Unix Utilities	1000s	Dozens	Dawson Engler et al./Stanford
Crypto Hash Implementations	1000s	Verified	Eric Smith & David Dill/Stanford

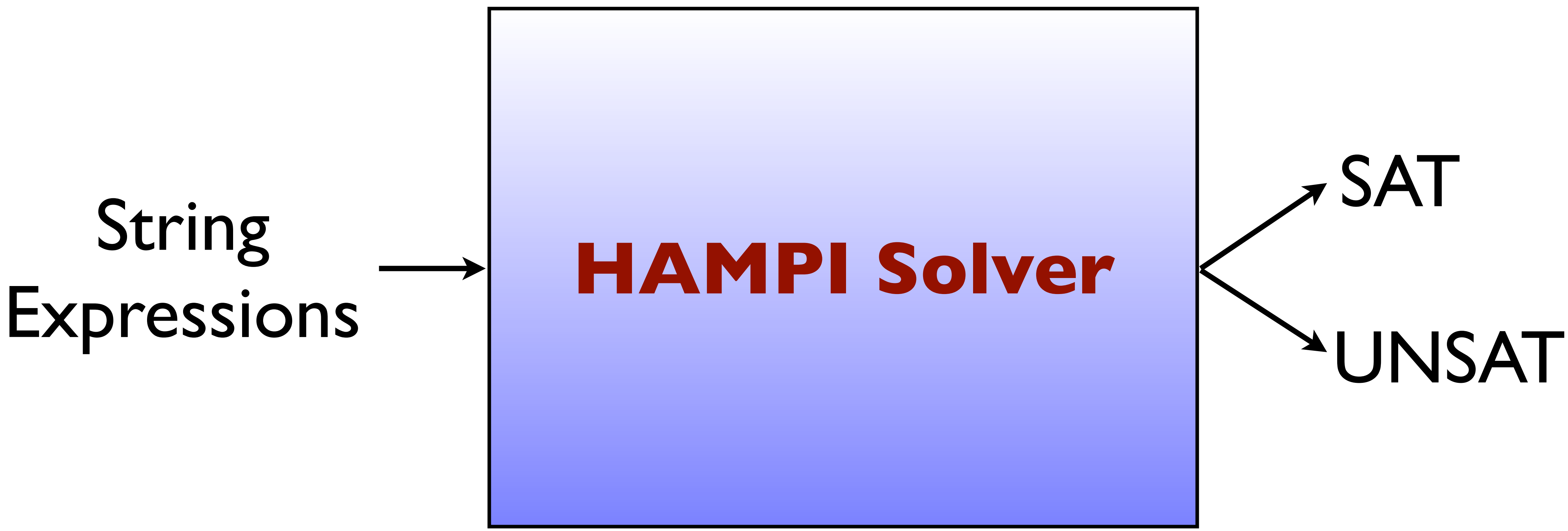
Rest of the Talk

- STP Bit-vector and Array Solver
  - Why Bit-vectors and Arrays?
  - How does STP scale: Abstraction-refinement
  - Impact: Concolic testing
  - Experimental Results

- HAMPI String Solver
  - Why Strings?
  - How does HAMPI scale: Bounding
  - Impact: String-based program analysis
  - Experimental Results

- Future Work
  - Multicore SAT
  - SAT-based Languages

HAMPI String Solver



- X = concat(“SELECT...”,v) AND (X $\in$ SQL_grammar)
- JavaScript and PHP Expressions
- Web applications, SQL queries
- NP-complete

What is the theory of Strings?

- Capture String Expressions in PHP, JavaScript, Perl, C/C++/Java
- Support symbolic execution/program analysis

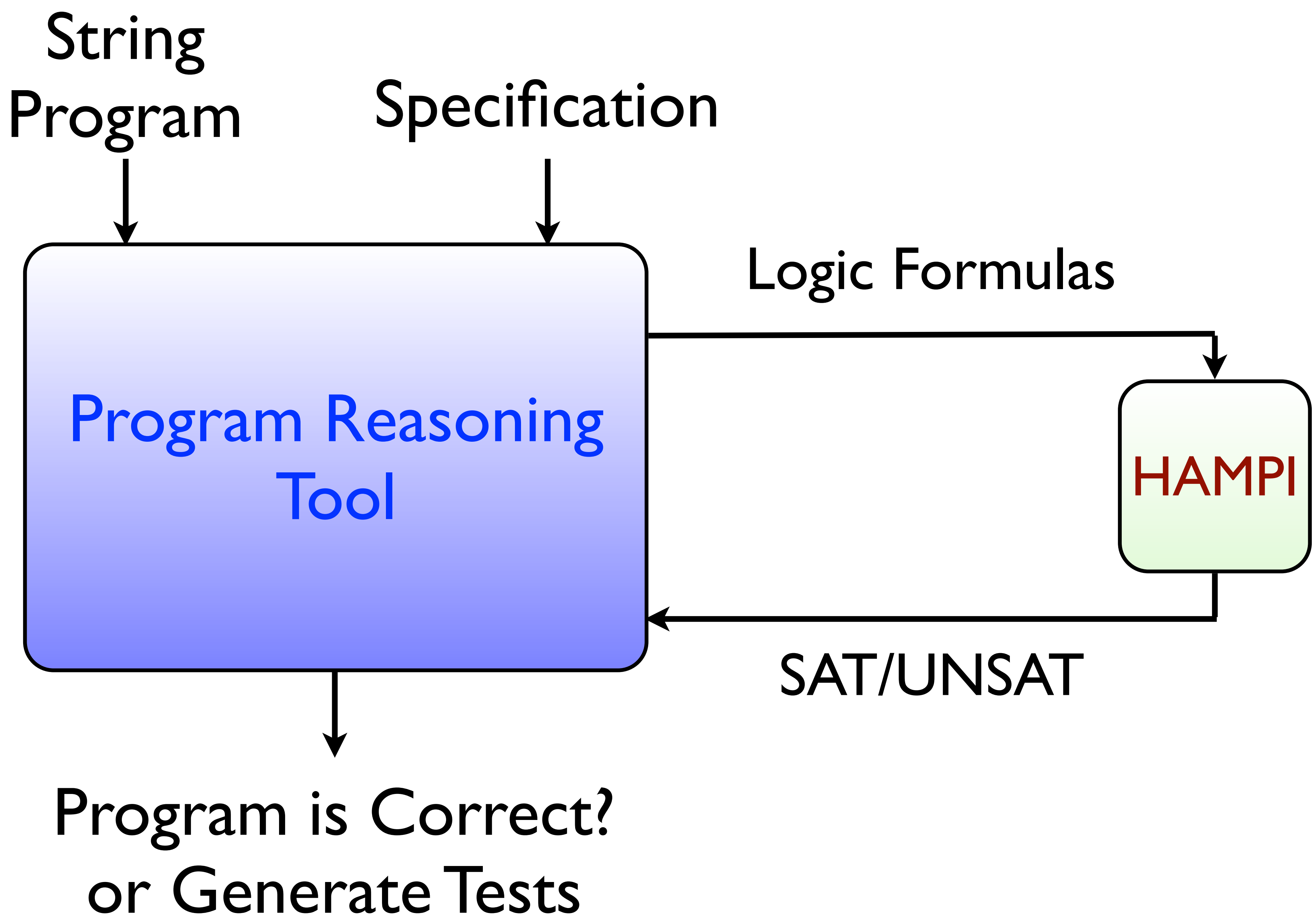
PHP/JavaScript/C++...	Theory of Strings

Var a;
$a = 'name'
	Var a : 12; //String variable of bounded-size
	a = 'name'

a." is "	Concat(a," is ");
substr(a,1,3)	sub-string extraction
assignments/strcmp a = string_expr;	equality a = string_expr;
Sanity check using regular expression RE Expression in a suitable Language (e.g., SQL)	a in RE a in SQL

Hampi Use-case

String Operations in PHP, JavaScript,...



Hampi Use-case

SQL Injection Vulnerabilities

Buggy PHP/
JavaScript

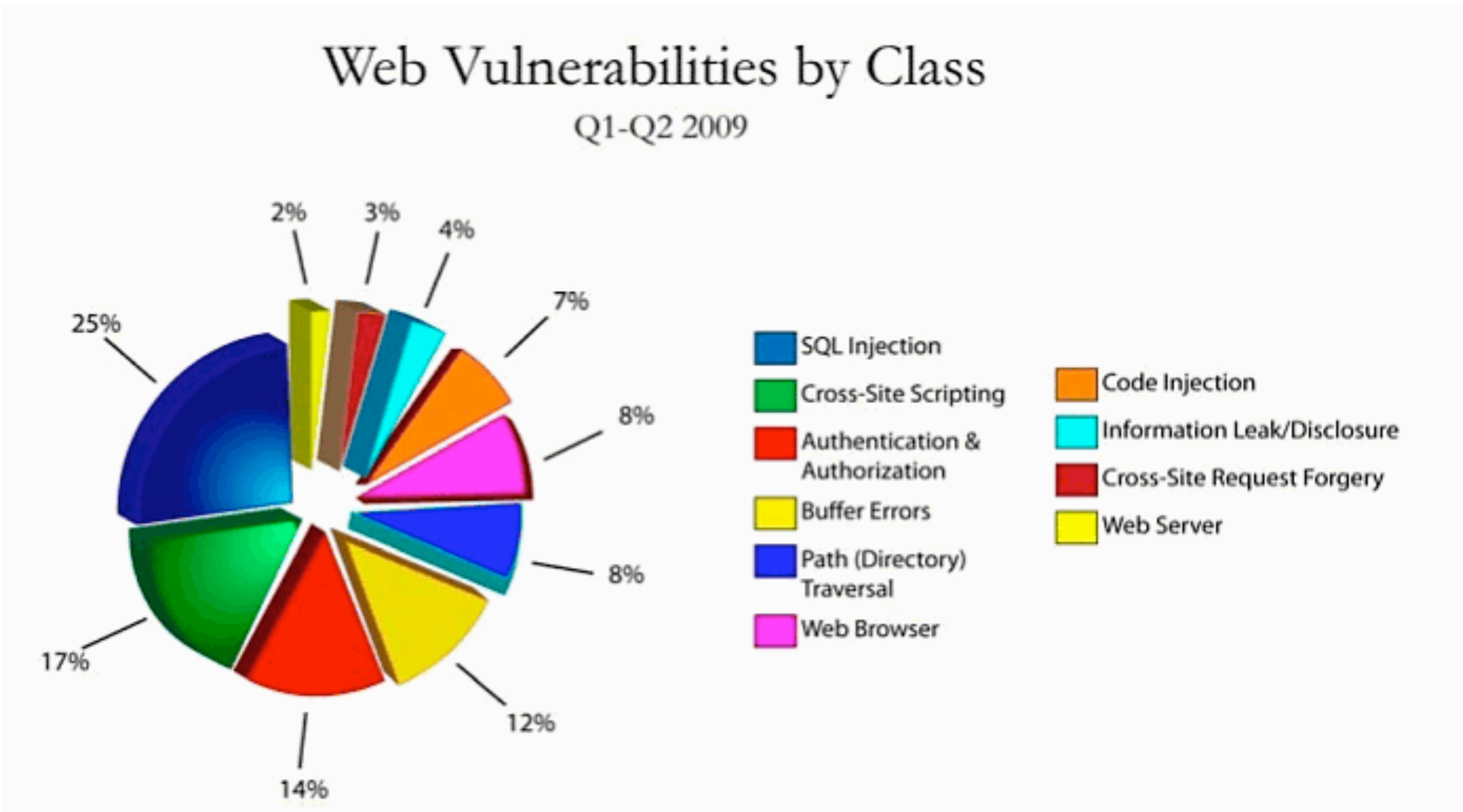
Malicious SQL Query

Unauthorized
Database Results

Backend
DataBase

Hampi Use-case

SQL Injection Vulnerabilities



Hampi Use-case
SQL Injection Vulnerabilities

Buggy Script

```
if (input in regexp("[0-9]+"))
   query := "SELECT m FROM messages WHERE id=' " + input + " ' ")
```

- input passes validation (regular expression check)
- query is syntactically-valid SQL
- query can potentially contain an attack substring (e.g., 1' OR '1' = '1)

Hampi Use-case
SQL Injection Vulnerabilities

Should be: “^[0-9]+$”

Buggy Script

```
if (input in regexp(“[0-9]+”))
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- input passes validation (regular expression check)
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Hampi Use-case
SQL Injection Vulnerabilities

Input String
```
Var v : 12;
```

SQL Grammar

cfg *SqlSmall* := "SELECT ” [a-z]+ " FROM ” [a-z]+ " WHERE " *Cond*;

cfg *Cond* := *Val* "=" *Val* | *Cond* " OR " *Cond*;

cfg *Val* := [a-z]+ | "’” [a-z0-9]* "’" | [0-9]+;

SQL Query

val q := concat("SELECT msg FROM messages WHERE topicid='", v, "'");

SQLI attack conditions

assert v in [0-9]+;

assert q in *SqlSmall*;

“q is a valid SQL query”

assert q contains "OR ‘1'=‘1'";

“q contains an attack vector”

Hampi finds an attack input: v ≔ 1’ OR ‘1’ = ‘1

SELECT msg FROM messages WHERE topicid=1’ OR ‘1’=‘1’

Hampi Key Contribution: Bounded Logics

Testing, Vulnerability Detection,...

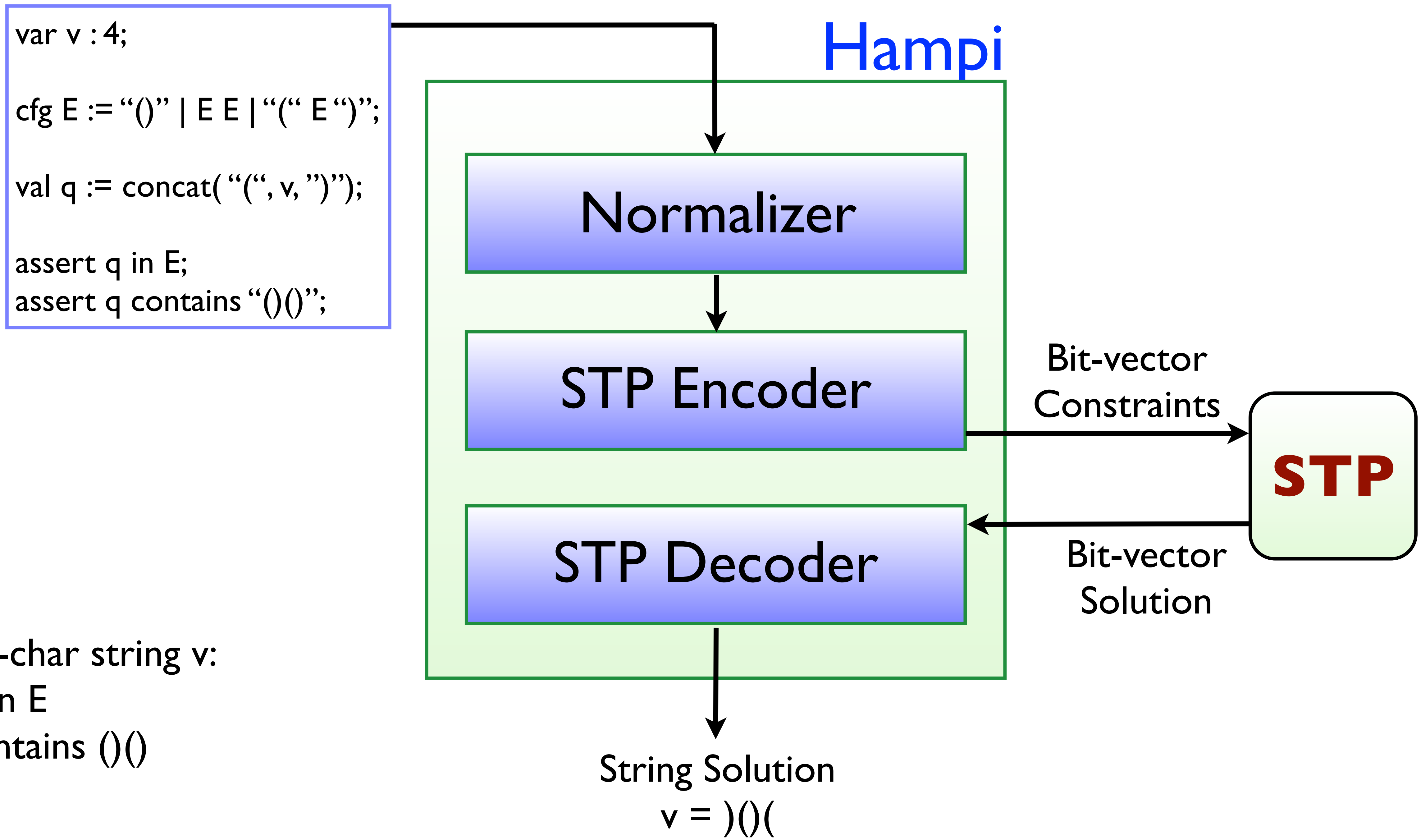
- Finding satisfying assignment is key
- Short assignments are sufficient
- Hence, bounding strings is sufficient
- Bounded logics are easier to decide

Hampi Key Conceptual Contribution

Bounding, expressiveness and efficiency

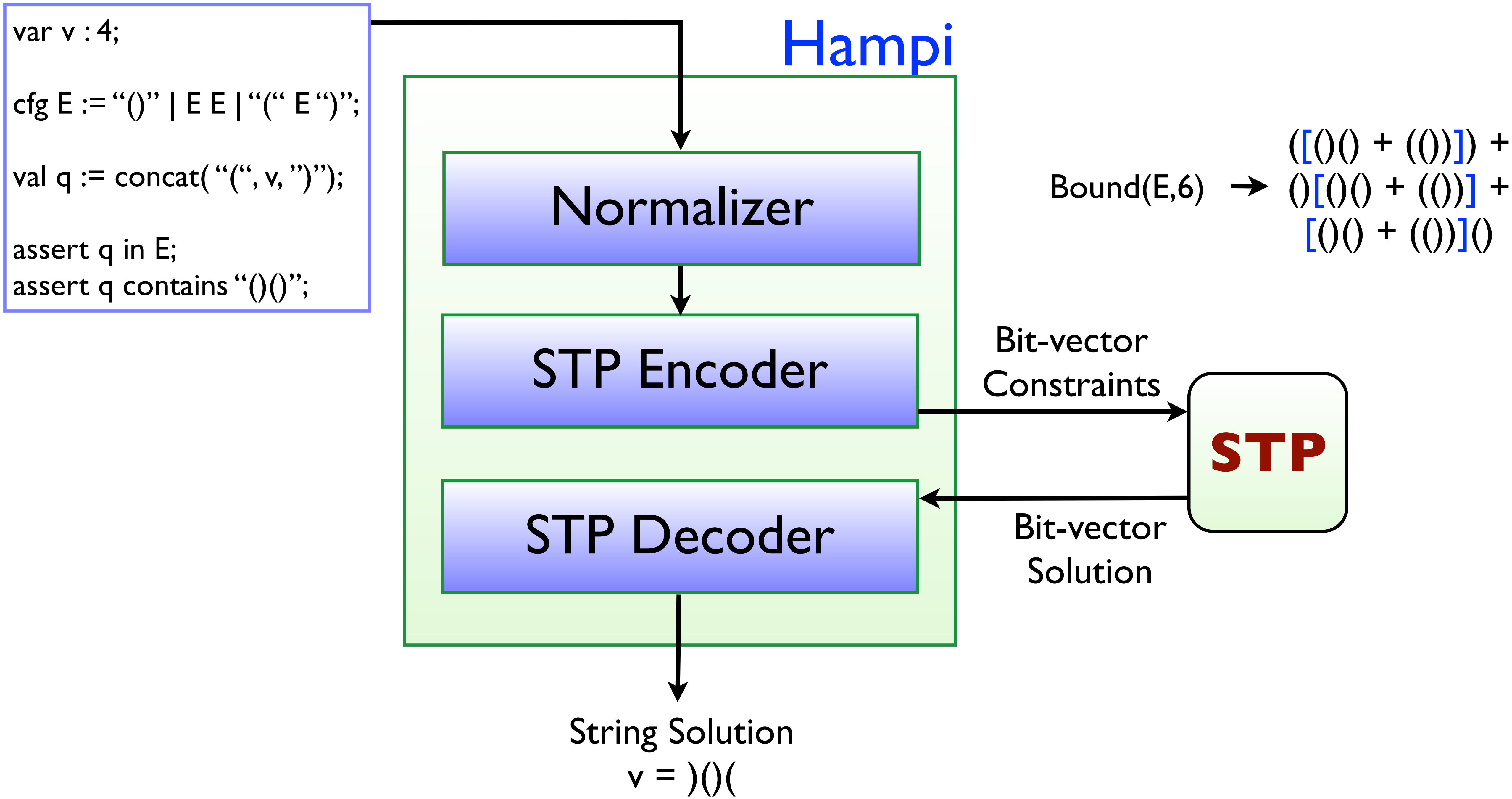
L_i	Complexity of $\emptyset = L_1 \cap \ldots \cap L_n$	Current Solvers
Context-free	Undecidable	n/a
Regular	PSPACE-complete	Quantified Boolean Logic
Bounded	NP-complete	SAT Efficient in practice

How Hampi Works
Bird’s Eye View: Strings into Bit-vectors



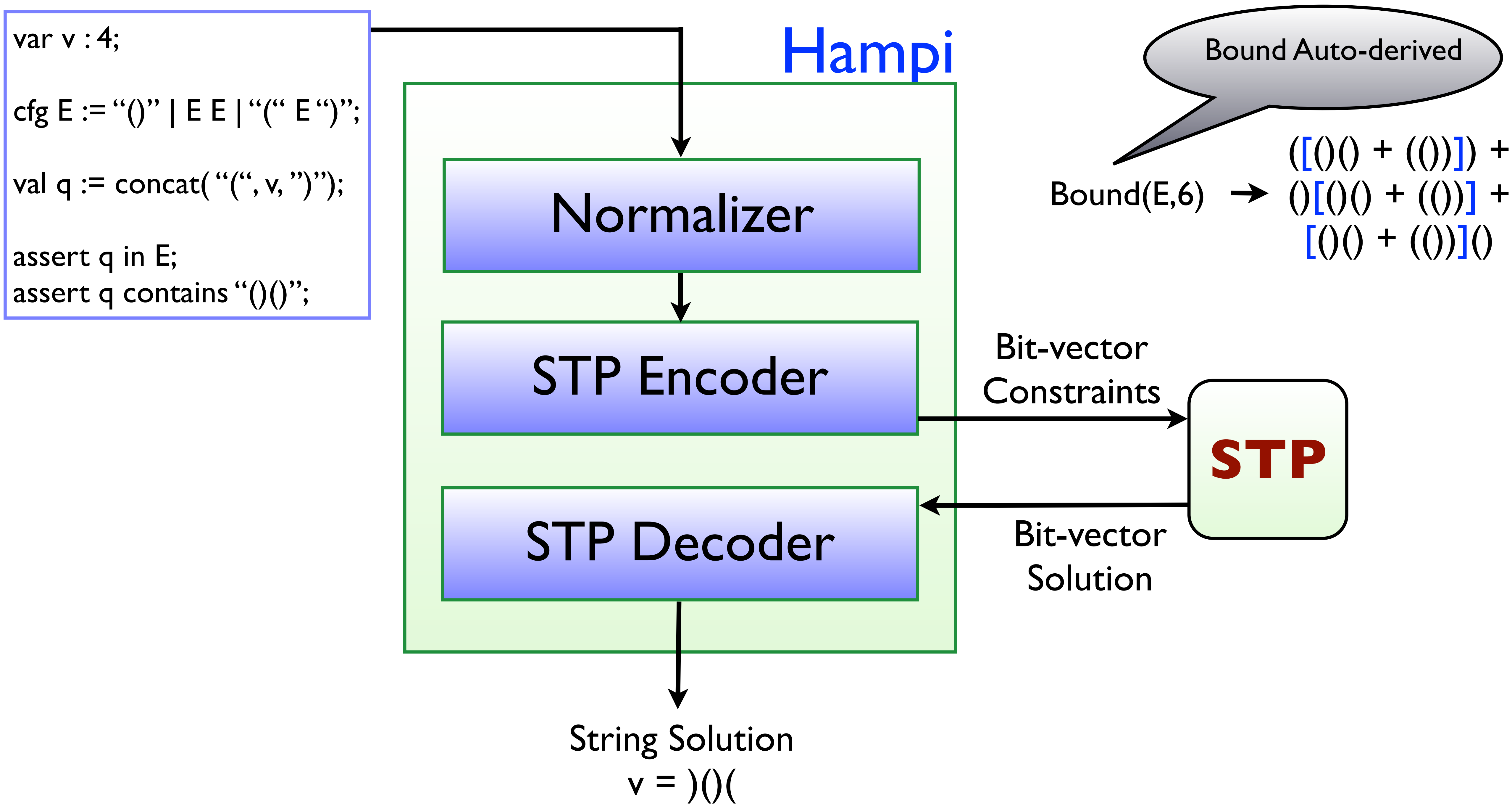
Find a 4-char string v:
- (v) is in E
- (v) contains ()()

How Hampi Works
Unroll Bounded CFGs into Regular Exp.



How Hampi Works

Unroll Bounded CFGs into Regular Exp.



How Hampi Works

Converting Regular Exp. into Bit-vectors

Encode regular expressions recursively

- Alphabet { (,) } → 0, 1
- constant → bit-vector constant
- union + → disjunction $\vee$
- concatenation → conjunction $\wedge$
- Kleene star * → conjunction $\wedge$
- Membership, equality → equality

(v) ∈ ()[()() + (())] + [()() + (())]() + ([()() + (())])

Formula Φ_1 $\vee$ Formula Φ_2 $\vee$ Formula Φ_3

$B[0]=0 \wedge B[1]=1 \wedge \{B[2]=0 \wedge B[3]=1 \wedge B[4]=0 \wedge B[5]=1 \vee \ldots$

How Hampi Works

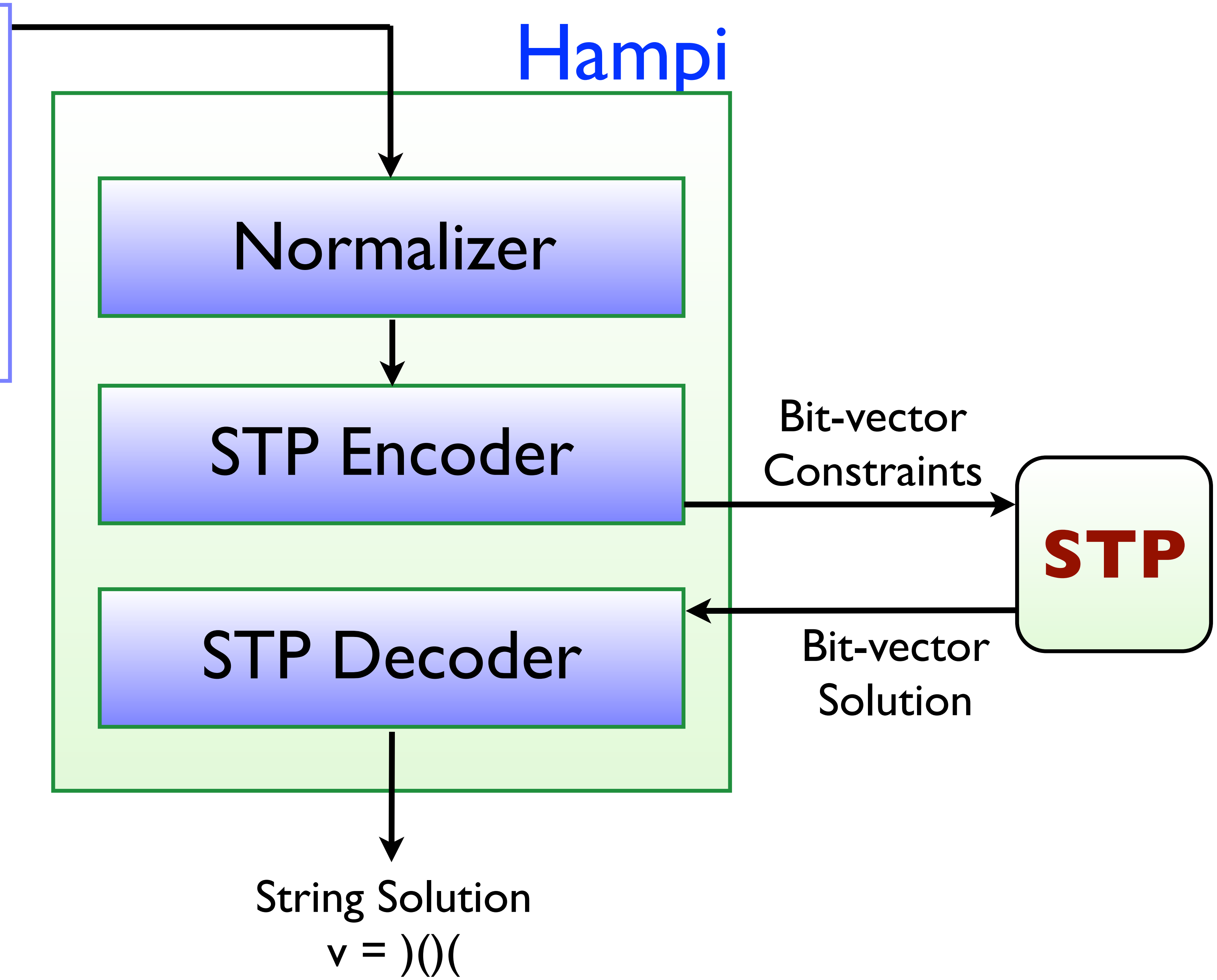
Decoder converts Bit-vectors to Strings

```
var v : 4;

cfg E := “()” | E E | “(“ E “)”;

val q := concat( “(“, v, ”)”);

assert q in E;
assert q contains “()()”;
```



Find a 4-char string v:
- (v) is in E
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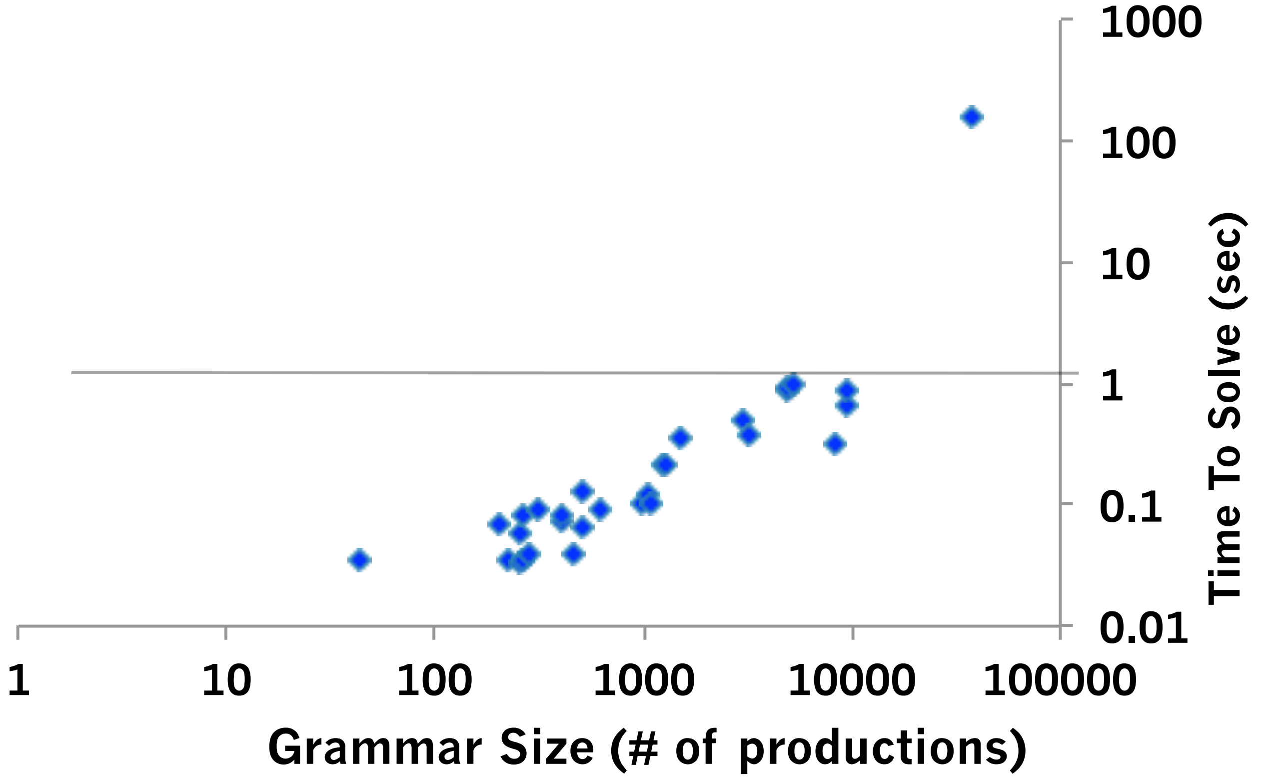
HAMPI: Result 1

Static SQL Injection Analysis



- 1367 string constraints from Wasserman & Su [PLDI'07]
- Hampi scales to large grammars
- Hampi solved 99.7% of constraints in < 1sec
- All solvable constraints had short solutions

Monday, May 2, 2011

HAMPI: Result 2
Security Testing

- Hampi used to build Ardilla security tester [Kiezun et al., ICSE'09]

- 60 new vulnerabilities on 5 PHP applications (300+ kLOC)
  - 23 SQL injection
  - 37 cross-site scripting (XSS)

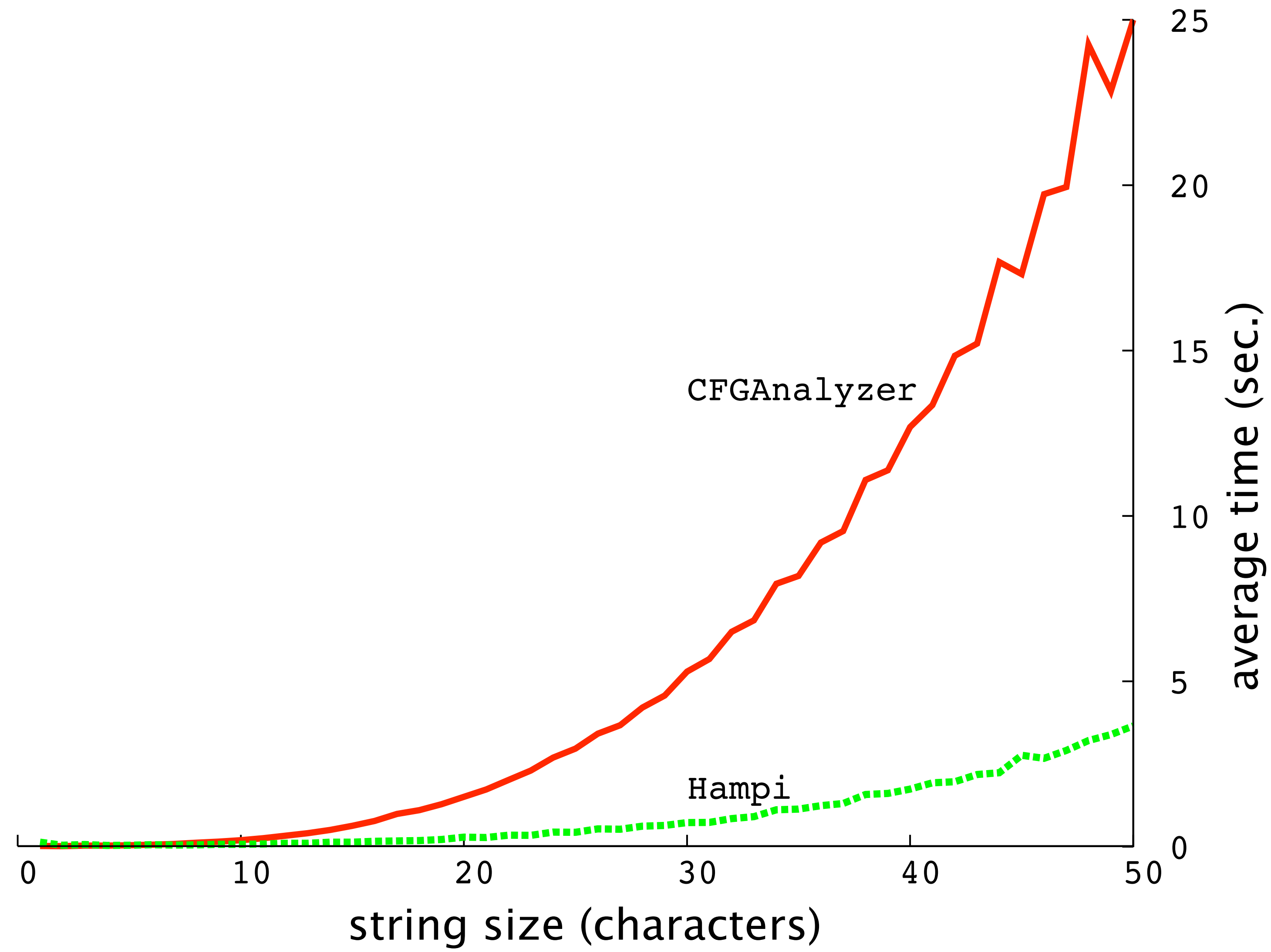
5 added to
US National Vulnerability DB

- 46% of constraints solved in < 1 second per constraint

- 100% of constraints solved in <10 seconds per constraint

HAMPI: Result 3

Comparison with Competing Tools



- HAMPI vs. CFGAnalyzer (U. Munich): HAMPI ~7x faster for strings of size 50+
- HAMPI vs. Rex (Microsoft Research): HAMPI ~100x faster for strings of size 100+
- HAMPI vs. DPRLE (U.Virginia): HAMPI ~1000x faster for strings of size 100+

Impact of Hampi: Notable Projects

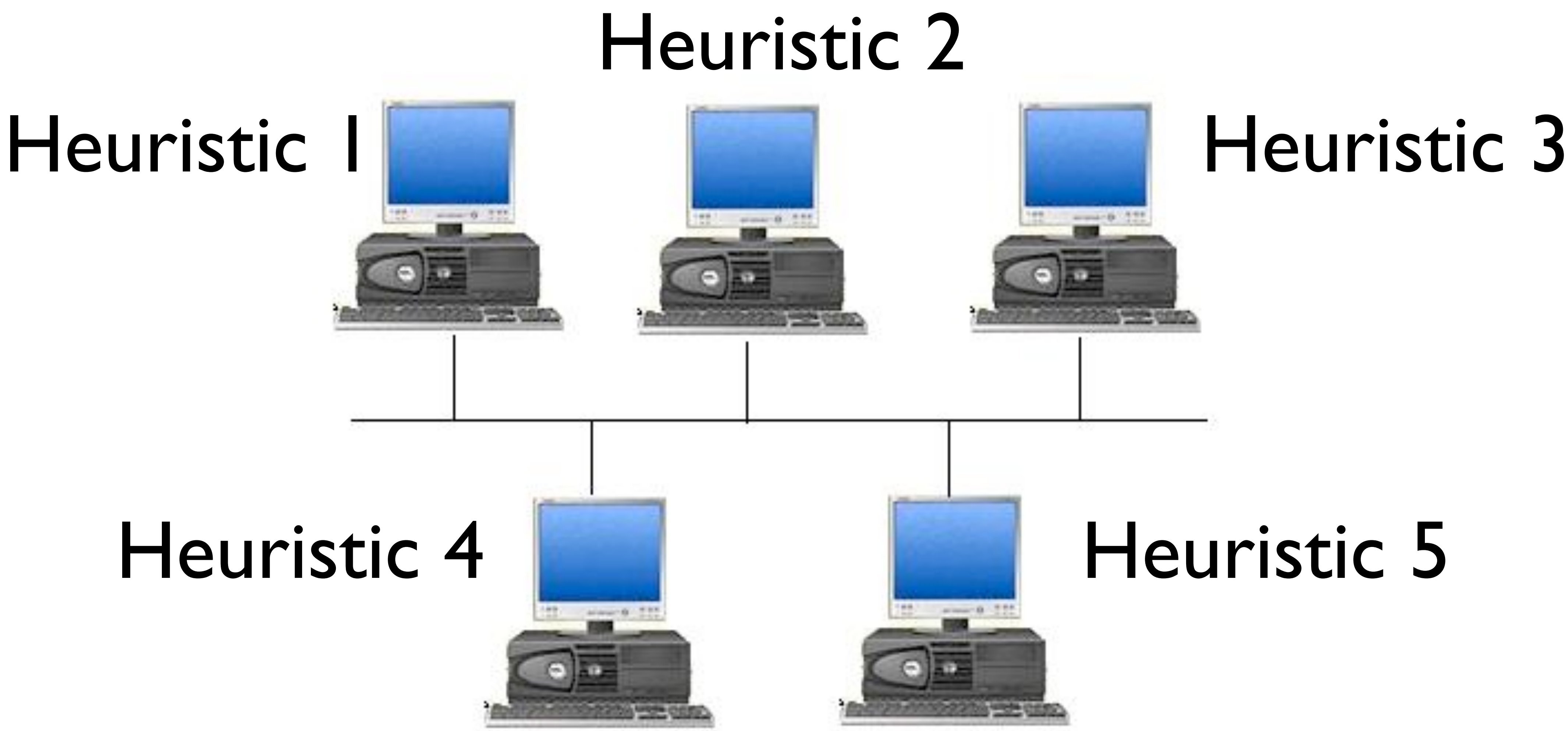
Category	Research Project	Project Leader/Institution
Static Analysis	SQL-injection vulnerabilities	Wasserman & Su/UC, Davis
Security Testing	Ardilla for PHP (SQL injections, cross-site scripting)	Kiezun & Ernst/MIT
Concolic Testing	Klee SAGE Kudzu NoTamper	Engler & Cadar/Stanford Godefroid/Microsoft Research Saxena & Song/Berkeley Bisht & Venkatakrishnan/U Chicago
New Solvers	Kaluza	Saxena & Song/Berkeley

Rest of the Talk

- STP Bit-vector and Array Solver
  - Why Bit-vectors and Arrays?
  - How does STP scale: Abstraction-refinement
  - Impact: Concolic testing
  - Experimental Results
- HAMPI String Solver
  - Why Strings?
  - How does HAMPI scale: Bounding
  - Impact: String-based program analysis
  - Experimental Results
- Future Work
  - Multicore SAT
  - SAT-based Languages

Current Parallel SAT Approaches
Won't Scale with more Nodes

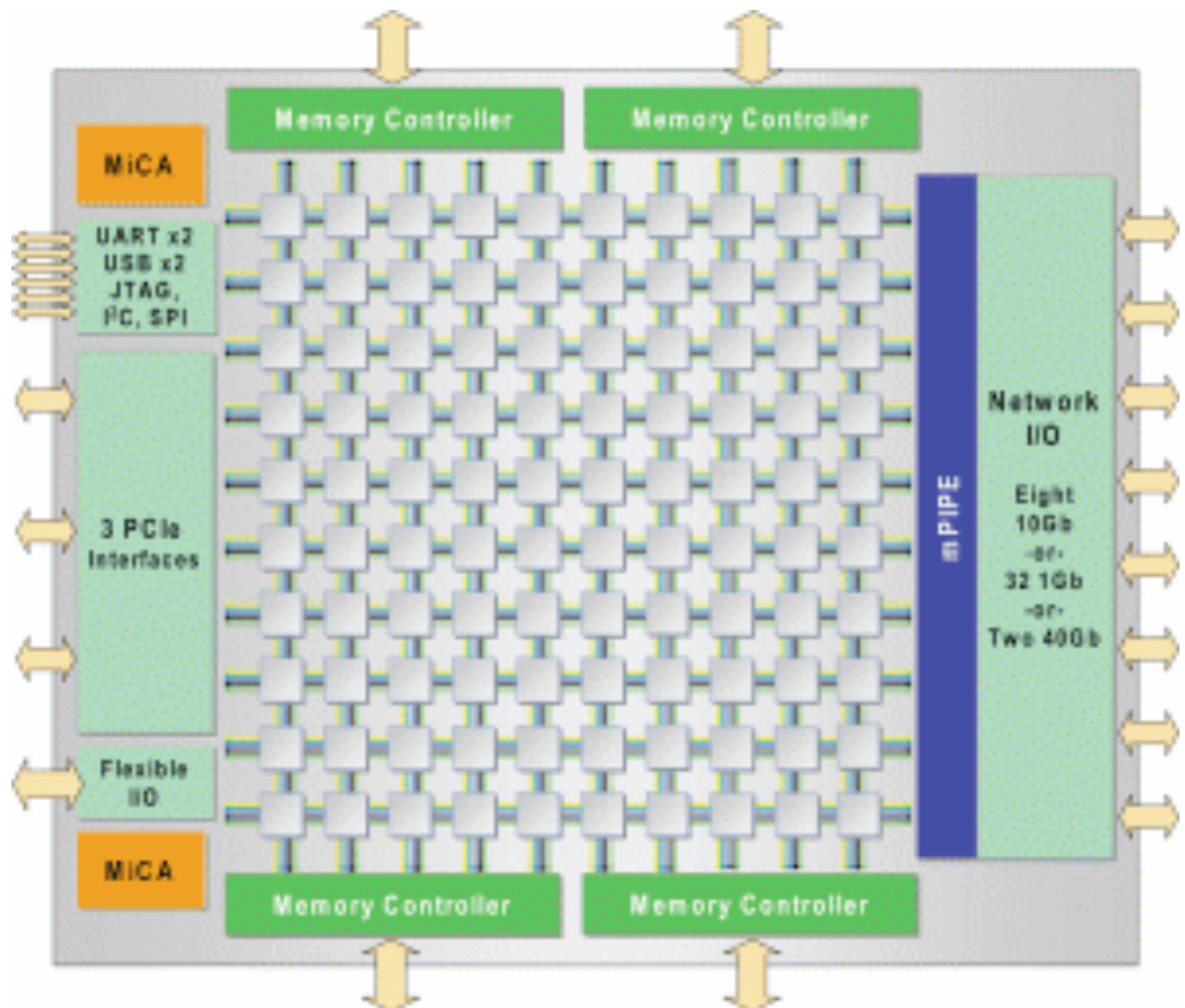
- Portfolio or search-space split approach (ManySAT, pLingeling,...)
- Works ok on clusters
- Confirmed thru' experimentation:
  - 12x speedup on a 128 node cluster
  - Not close to linear speedup



PSAT: Parallel SAT Approach

Partition SAT-Input into k Pieces

- Didn't work on clusters; much better prospects with multicore
- Latency much better on multicore than cluster
- Software engineering instances partition well
- Heuristics to minimize communication overhead



Imperative Language With SAT-based Declarative Primitives

- Motivation:
  - Declarative can be more robust
  - Delegating the "how" to runtime
- Combine imperative and SAT-based declarative language
  - Efficient solvers evaluate and search
  - Solvers leverage multicores
- Examples
  - Squander by Milicevic, Rayside and Daniel Jackson (MIT)

Related Work

- Model Checking:
  - Abstraction-refinement (Ed Clarke et al.)
  - Bounding (Ed Clarke, Daniel Jackson et al.)
- Other SMT solvers
  - Unsat core based approximations (Randy Bryant et al.)
  - Z3, CVC3, Boolector, BAT....
- DPLL(T)
  - Tinelli, Nieuwenhuis and Oliviera

Conclusions

- Logic formulas can capture meta-properties of software
  - The right logical abstraction (bit-vector and arrays, strings,...)
- Exploit meta-properties in solving formulas efficiently
  - Locality, modularity,...
- The more SMT solving, the less program analysis
  - Automation, ease-of-use,...

Questions?

Contributions at a Glance	Future Work
• STP* & HAMPI* (CAV 2007, TISSEC 2008, ISSTA 2009)	• Parallel SAT
• Decidability/Undecidability results for strings (under submission)	• SAT-based programming languages
• BuzzFuzz: Directed Whitebox Fuzzing (ICSE 2009)	• Program hardening
• Concolic testers (JFuzz: NFM 2009)	• Solvers for rich theories (attribute grammars, floating-point)
• Solvers for integer linear arithmetic (FMCAD 2002, TACAS 2003)	• Auto-tuning SAT solvers
• Retargetable compilers (DATE 1999)	• Advice-based SAT solvers
	• Unsound and incomplete solvers
	• Solver-based concurrency bug-finding

* 100+ research projects use STP and HAMPI (NSF funding $600,000.00)
* STP won the SMTCOMP 2006 and 2010 competitions for bit-vector solvers
* HAMPI paper won ACM Best Paper Award 2009