From SVC to CVC4

15 Years of Decision Procedures
SAT/SMT Summer School

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Outline

1. From SVC to CVC4
   - SVC
   - CVC
   - CVC Lite
   - CVC3
   - CVC4
2. Verification of Low-Level Code
   - Satisfiability Modulo Theories
   - Processing Packets
   - Memory Models
   - Example

SVC

Motivation for a Validity Checker

- Processor Verification via Symbolic Simulation
- Prove that Abstract Specification Machine matches Implementation
- Burch-Dill Commuting Diagram
- Check equality of two big formulas

Burch-Dill Commuting Diagram

$$
\begin{tikzcd}
Abs(q_i) \arrow[r, "F_s"] & \stackrel{?}{=} \\
q_i \arrow[u, "Abs"] \arrow[r, "F_i"] & F_i(q_i) \arrow[u, "Abs"]
\end{tikzcd}
$$

SVC

SVC

- Stanford Validity Checker [Barrett, Dill, & Levitt '96]
- Authors: Clark Barrett, Jeremy Levitt, Aaron Stump, Robert Jones, David Dill
- First source release: 1998

Innovations

- Theory reasoning based loosely on Shostak's method [Shostak '84, Levitt '98]
- Powerful rewriter/simplifier
- Helpful built-in support for backtracking data structures
- Novel decision procedures (e.g. bit-vectors, arrays, records)
- Modular theory solver design

SVC

Applications

- Processor Verification [Levitt & Olukotun '97]
- Specification Checking [Park et al. '98]
- Theorem prover assistance [Heilmann '99]

Headaches

- Shostak's method - too complicated and restrictive
- Equational solvers required to respect restrictive total order
- Boolean reasoning too primitive
- Software architecture - too entangled

CVC

CVC

- Cooperating Validity Checker [Stump, Barrett, & Dill '02]
- Authors: Aaron Stump, Clark Barrett, David Dill, Sergey Berezin, Vijay Ganesh
- First release: 2002

Innovations

- Use of SAT solver (Chaff) for Boolean reasoning [Barrett, Dill, & Stump '02]
- Theory combination framework based on Nelson-Oppen with features of Shostak [Barrett '03]
- Proof production [Stump, Barrett, & Dill '02]

CVC

Applications

- Predicate Abstraction [Das & Dill '02]
- Software Verification (BLAST tool) [Henzinger et al. '03]
- Compiler Validation [Barrett, Goldberg, & Zuck '03]

Headaches

- Software architecture - too entangled

CVC Lite

CVC Lite

- CVC Lite [Barrett & Berezin '04]
- Authors: Clark Barrett, Sergey Berezin, David Dill, Vijay Ganesh
- Additional Contributors: Cristian Cadar, Jake Donham, Yeting Ge, Deepak Goyal, Ying Hu, Sean McLaughlin, Mehul Trivedi, Michael Veksler, Daniel Wichs, Mark Zavislak, Jim Zhuang
- First release: 2004

Innovations

- Theorem-based computation
- Handling of partial functions via TCC's [Berezin et al. '04]
- Mixed integer-real arithmetic (plus some non-linear reasoning)
- Quantifiers
- Predicate sub-typing

CVC Lite

Applications

- Translation validation for compilers [Goldberg, Zuck, & Barrett '04]
- Trusted theorem prover assistance [McLaughlin, Barrett, & Ge '05]
- Hardware equivalence checking at Calypto Systems

Headaches

- Performance
- Software architecture - too entangled

CVC3

CVC3

- CVC3 [Barrett & Tinelli '07]
- Authors: Clark Barrett, Cesare Tinelli, Chris Conway, Morgan Deters, Alexander Fuchs, Yeting Ge, George Hagen, Mina Jeong, Dejan Jovanović, Tim King
- First release: 2007

Innovations

- Enhanced MiniSat Boolean core with proof capability
- New decision procedures (bit-vectors, data types, quantifiers)
- Improved support for non-linear arithmetic
- Extensive support for SMT-LIB and format translation

CVC3

Applications

- Deductive program verification with Why [Filliâtre & Marché '07]
- Symbolic analysis of software at IBM [Chandra, Fink, & Sridharan '09]
- Static analysis of C programs [Conway & Barrett '10]
- Many more...

Headaches

- Performance
- Incompleteness due to non-stably-infinite theories
- Software architecture - too entangled

CVC4

CVC4

- CVC4 [Barrett et al. '11]
- Designers and Authors: Kshitij Bansal, Clark Barrett, Christopher Conway, Morgan Deters, Liana Hadarean, Tim King, Dejan Jovanović, Andrew Reynolds, Cesare Tinelli
- First release: 2011

Innovations

- New efficient expression package
- Decentralized and more powerful theory combination techniques (polite theories, care functions) [Jovanović & Barrett '10]
- New state-of-the-art theory implementations (uninterpreted functions, real arithmetic, arrays, bit-vectors)
- Performance-neutral proof production
- Designed to be easily parallelizable

CVC4

Applications

- BMC of Hybrid Systems [King & Barrett '11]
- More to come...

Headaches

- Trying to keep the software architecture from becoming too entangled

CVC4

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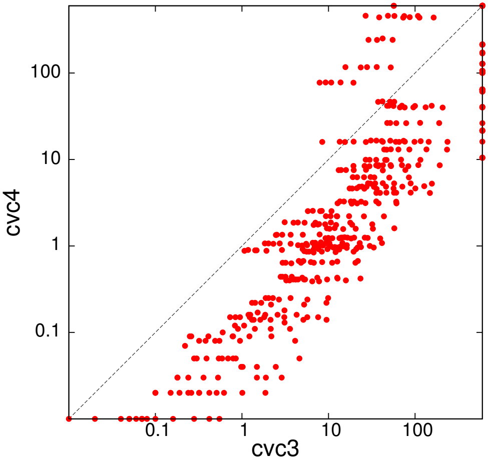
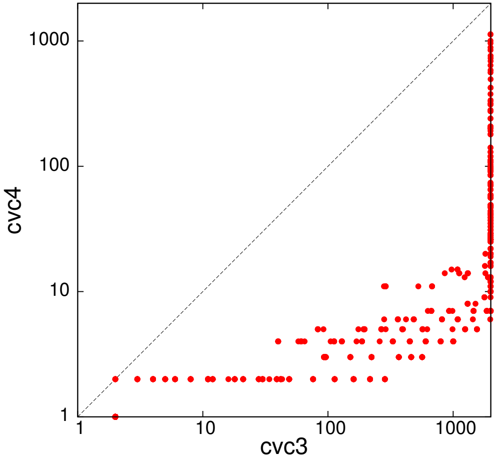
A Sneak Peek at CVC4

- CVC4 vs CVC3 (time and memory)
- CVC4 vs other solvers (time and memory)

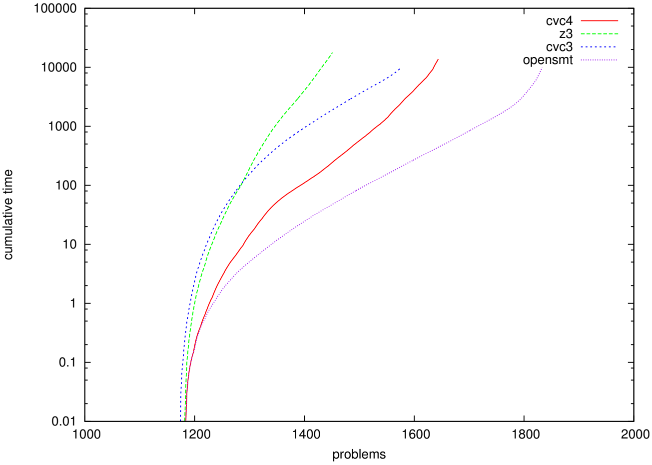
CVC4 vs CVC3 (time)



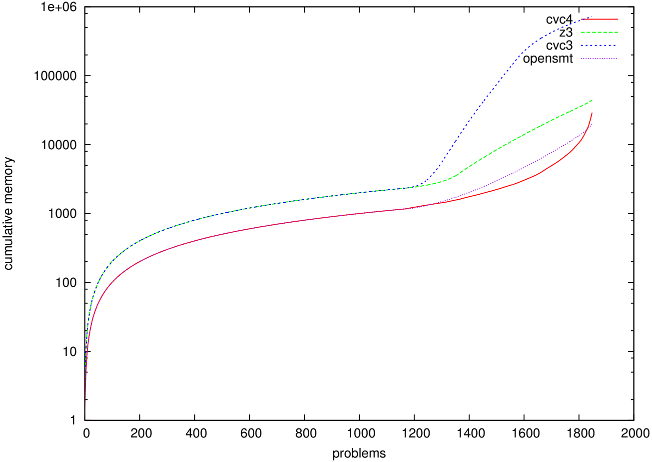
CVC4 vs CVC3 (memory)



Cumulative Time Cactus Plot



Cumulative Memory Cactus Plot



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   - Memory Models
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Satisfiability Modulo Theories

For a theory T, the T*-satisfiability problem* consists of deciding whether there exists a model $\mathcal{A}$ and variable assignment α such that $(\mathcal{A}, \alpha) \models T \cup \varphi$ for a given formula φ.

Theories of Inductive Data Types

An *inductive data type* (IDT) defines one or more *constructors*, and possibly also *selectors* and *testers*.

Example: *list* **of** *int*

- Constructors: $cons : (int, list) \rightarrow list$, $null : list$
- Selectors: $car : list \rightarrow int$, $cdr : list \rightarrow list$
- Testers: is_cons, is_null

The *first order theory* of a inductive data type associates a function symbol with each constructor and selector and a predicate symbol with each tester.

Example: $\forall\, x : list.\, (x = null \vee \exists\, y : int, z : list.\, x = cons(y, z))$

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For IDTs with a single constructor, a conjunction of literals is decidable in polynomial time [Oppen '80].

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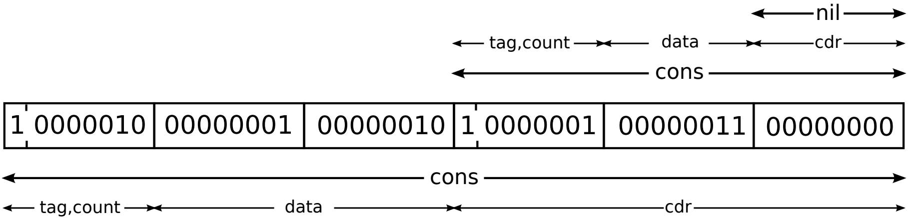
Example: $\forall\, x : list.\, (x = null \vee \exists\, y : int, z : list.\, x = cons(y, z))$

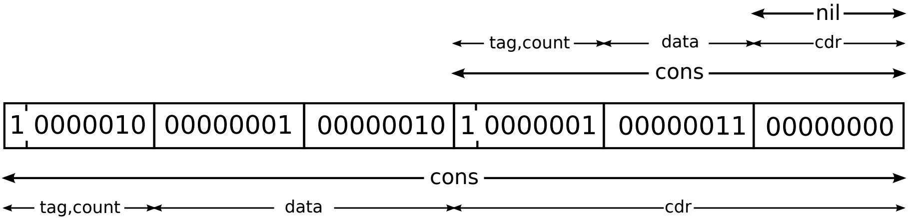
For more general IDTs, the problem is NP complete, but reasonbly efficient algorithms exist in practice [Barrett et al. '07].

Processing Packets



Network packets are highly structured

Processing Packets



Network packets are highly structured
but usually processed with low-level bit-twiddling code

```
while( (n = *p++) & 0x80 ) {
    p += n & 0x7f;
}
```

Processing Packets

One solution: packet-processing DSLs
(e.g., binpac, Melange, Morpheus, Prolac)

```
type List =
  cons {
    tag:1 = 0b1,
    count: 7,
    data: u_char[count],
    cdr: List
  }
| nil {
    tag:8 = 0x00
  }
```

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- High level
- Type safe

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```

- High level
- Type safe
- Slower than C
- Need to rewrite existing code

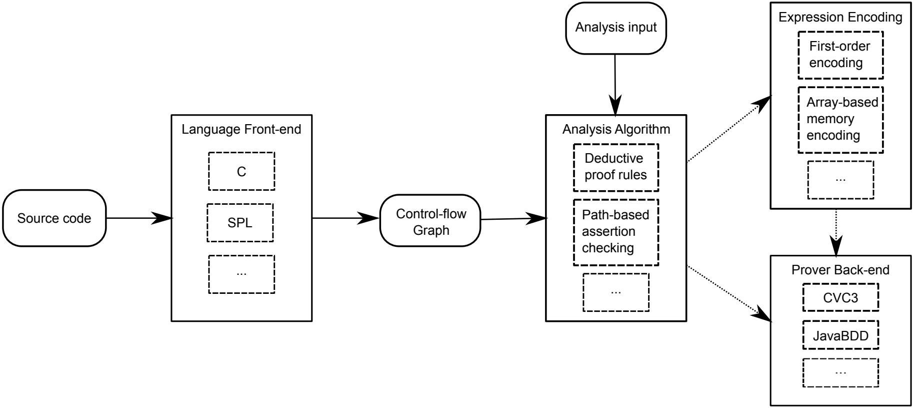
Packet Types as Specification

Instead of synthesizing a performant implementation,
let's use packet types as the basis of a specification

```
while( (n = *p++) & 0x80 ) {
    assert( isCons(prev(p)) );
    p += n & 0x7f;
    assert( p == cdr(prev(p)) );
}
```

We can use bit-precise reasoning to prove that the code satisfies the assertions using CASCADE.

Cascade Verification Framework



Cascade/C

- High-precision verification of program paths
- Intended for use in a *multi-stage analysis*
- Path is defined and assertions are injected using an XML control file

Cascade/C

swap.ctrl:

```
<controlFile>
  <sourceFile name="swap.c" id="1" />
  <run>
    <startPosition fileId="1" line="1" />
    <endPosition fileId="1" line="5">
      <assert><![CDATA[
         orig(*x)==*y && orig(*y)==*x
      ]]></assert>
    </endPosition>
  </run>
</controlFile>
```

swap.c:

```
void swap(int*x, int*y) {
  *x = *x + *y;
  *y = *x - *y;
  *x = *x - *y;
}
```

```
*x = *x + *y;
*y = *x - *y;
*x = *x - *y;
assert( orig(*x)==*y && orig(*y)==*x );
```

CVC3 Encoding

- Encode verification conditions as SMT instances
- Use CVC3 SMT solver to decide validity
- CVC3 includes theories for:
  - Arrays
  - Uninterpreted functions
  - Bit vectors
  - Inductive datatypes
- Connect the high-level assertions and the low-level code by generating:
  - An inductive datatype
  - Functions mapping datatype values to arrays of bytes
  - Encode program semantics using bit vectors

CVC3 Encoding

```
type List =
  cons {
    tag:1 = 0b1,
    count: 7,
    data: u_char[count],
    cdr: List
  }
| nil {
    tag:8 = 0x00
  }
```

CVC3 Encoding

```
ptrType : BITVECTOR(N);
byteType : BITVECTOR(8);
memType : ARRAY ptrType OF byteType;

DATATYPE
List =
  cons( tag: BITVECTOR(1),
        len: BITVECTOR(7),
        data: memType,
        cdr: List )
| nil( tag: BITVECTOR(8) )
| undefined;
END;

toList : (memType, ptrType) -> List;

∀ m:memType, i:ptrType.
  isNil(toList(m,i)) ⟺ m[i] = 0;
∀ m: memType, i: ptrType.
  isCons(toList(m,i)) ⟺ m[i][7] = 1;
∀ m: memType, i: ptrType.
  isCons(toList(m, i)) ⟹
      cdr(toList(m,i)) = toList(m,i+len(toList(m,i))+1);
etc...
```

Verification Condition Generation

```
n = *p++;
assume( (n & 0x80) != 0 );
assert( isCons(prev(p)) );
```

becomes

$$\frac{\begin{array}{c} m_1 = m_0[\&\mathrm{n} \mapsto m_0[m_0[\&\mathrm{p}]]] \\ m_2 = m_1[\&\mathrm{p} \mapsto m_1[\&\mathrm{p}] + 1] \\ m_2[\&\mathrm{n}] \ \& \ 0\mathrm{x}80 \neq 0\mathrm{x}00 \end{array}}{\mathit{isCons}(\mathit{toList}(m_2, m_0[\&\mathrm{p}]))}$$

Memory Models

- "Flat" memory model
  - Memory is one big array:

$$m_1 = m_0[\&\mathrm{n} \mapsto m_0[m_0[\&\mathrm{p}]]]$$
$$m_2 = m_1[\&\mathrm{p} \mapsto m_1[\&\mathrm{p}] + 1]$$

  - No "frame rule" is implied.
    - E.g., the following isn't necessarily valid:

```
{ toList(q)==cdr(p) }
  i++
{ toList(q)==cdr(p) }
```

    - We can't rule out `&i` being reachable if `toList` is unrolled enough times.
  - Detailed non-aliasing assumptions have to be added by hand

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    - We can't rule out `&i` being reachable if `toList` is unrolled enough times.
  - Detailed non-aliasing assumptions have to be added by hand
  - And they don't help much

Memory Models

- Burstall model [Burstall '72, Bornat '00]
  - A separate memory array for each static type:

$$
\begin{aligned}
m'_{char} &= m_{char}[\&\mathrm{n} \mapsto m_{char}[m_{char*}[\&\mathrm{p}]]] \\
m'_{char*} &= m_{char*}[\&\mathrm{p} \mapsto m_{char*}[\&\mathrm{p}] + 1]
\end{aligned}
$$

  - Can't handle safe dynamic casts
  - Can't handle promiscuous pointer manipulation

Memory Models

- Burstall model [Burstall '72, Bornat '00]
  - A separate memory array for each static type:

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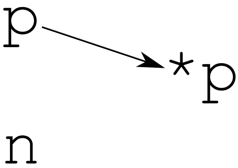
$$m'_{char*} = m_{char*}[\&\mathrm{p} \mapsto m_{char*}[\&\mathrm{p}] + 1]$$

  - Can't handle safe dynamic casts
  - Can't handle promiscuous pointer manipulation
  - Which is exactly what packet processing is

Partitioning the Heap

An "in between" model, based on separation analysis
[Hubert & Marché '07, Rakamaric & Hu '09]

- Memory is partitioned into disjoint *regions*.
- Every pointer expression is associated with a region



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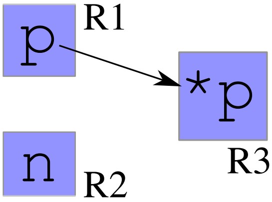

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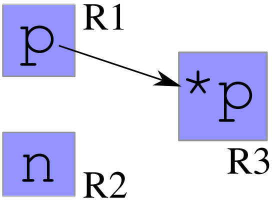

- Each region can be represented by a separate "memory"

Partitioning the Heap

Flat:

$$\frac{\begin{array}{c} m_1 = m_0[\texttt{\&n} \mapsto m_0[m_0[\texttt{\&p}]]] \\ m_2 = m_1[\texttt{\&p} \mapsto m_1[\texttt{\&p}] + 1] \\ m_2[\texttt{\&n}] \ \texttt{\&} \ \texttt{0x80} \neq \texttt{0x00} \end{array}}{\mathit{isCons}(\mathit{toList}(m_2, m_0(\texttt{\&p})))}$$

Partitioning the Heap

Partitioned:

$$\frac{\begin{array}{c} m'_{\mathrm{n}} = m_{\mathrm{n}}[\&\mathrm{n} \mapsto m_{*\mathrm{p}}[m_{\mathrm{p}}[\&\mathrm{p}]]] \\ m'_{\mathrm{p}} = m_{\mathrm{p}}[\&\mathrm{p} \mapsto m_{\mathrm{p}}[\&\mathrm{p}] + 1] \\ m'_{\mathrm{n}}[\&\mathrm{n}]\ \&\ \mathtt{0x80} \neq \mathtt{0x00} \end{array}}{\mathit{isCons}(\mathit{toList}(m_{*\mathrm{p}}, m_{\mathrm{p}}[\&\mathrm{p}]))}$$

Partitioning the Heap

Partitioned:

$$\frac{\begin{array}{c} m'_{\mathrm{n}} = m_{\mathrm{n}}[\&\mathrm{n} \mapsto m_{*\mathrm{p}}[m_{\mathrm{p}}[\&\mathrm{p}]]] \\ m'_{\mathrm{p}} = m_{\mathrm{p}}[\&\mathrm{p} \mapsto m_{\mathrm{p}}[\&\mathrm{p}] + 1] \\ m'_{\mathrm{n}}[\&\mathrm{n}] \ \& \ 0\mathrm{x}80 \neq 0\mathrm{x}00 \end{array}}{\mathit{isCons}(\mathit{toList}(m_{*\mathrm{p}}, m_{\mathrm{p}}[\&\mathrm{p}]))}$$

- Separation creates a "frame" around datatype values
- Makes hard problems easy and easy problems trivial
- The verification condition is sound if the partition is sound

"Real World" Example: Encoded Domain Name

```
type Dn =
  label {
    tag:2 = 0b00,
    len:6 != 0b000000,
    name:u_char[len],
    rest:Dn
  }
| indirect {
    tag:2 = 0b11,
    offset:14
  }
| nullt {
    tag:8 = 0x00
  }
```

```
#define NS_CMPRSFLAGS (0xc0)
int ns_name_skip(const u_char **ptrptr, const u_char *eom) {
  { allocated(*ptrptr, eom) }
  const u_char *cp; u_int n;
  cp = *ptrptr;
  { @invariant: cp <= eom =>
                cp + sizeOfDn(cp) = init(cp) + sizeOfDn(init(cp)) }
  while (cp < eom && (n = *cp++) != 0) {
    switch (n & NS_CMPRSFLGS) {
      case 0: /* normal case, n == len */
        { isLabel(prev(cp)) }
        cp += n;
        { rest(prev(cp)) = toDn(cp) }
        continue;
      case NS_CMPRSFLGS: /* indirection */
        { isIndirect(prev(cp)) }
        cp++; break;
      default: /* illegal type */
        __set_errno (EMSGSIZE); return (-1);
    }
    break;
  }
  if (cp > eom) { __set_errno (EMSGSIZE); return (-1); }
  { cp = eom _ cp = init(cp) + sizeOfDn(init(cp)) }
  *ptrptr = cp;
  return (0);
}
```

Experimental results

- Verification times for `ns_name_skip`.
- 30 LOC, 4 assertions + a loop invariant

Name	Lines	Time (seconds) Flat	Part.
Init	5–12	0.34	0.03
Case 0 (1)	12-16	13.94	0.05
Case 0 (2)	12-28	33.42	0.06
Case 0 (3)	12-19	*	0.12
Case 0xc0 (1)	12–14, 20–21	6.14	0.04
Case 0xc0 (2)	12–14, 20–23, 30, 34	*	0.07
Term (1)	12, 30, 34	0.63	0.06
Term (2)	12, 30, 34	*	0.05

Final Thoughts

15 years of checking formulas

- SMT has come a long way in last 15 years
- Dramatic advances in theory and practice
- Explosion of application areas

Lessons

- Balancing high-performance and software flexibility is a challenge
- Modularity and solid theoretical foundations can help
- But in a rapidly advancing area, may have to reimplement every few years anyway

CVC4 is coming

- Goals: open source, high-performance, full-featured SMT solver
- Contributions and collaborations welcome after first release

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