Extending the BTOR Language

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extends joint work with Robert Brummayer published at BPR'08

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July 20, 2010

Overview

- overview of the current BTOR language: bit-vectors & arrays

- proposed extensions
  - tables
  - functions
  - quantifiers
  - commands
  - types

- design decisions, related work and conclusions

- BTOR = native language of SMT solver Boolector
  - corresponds to QF_ABV of SMT-LIB — no quantifiers
  - but bit-vectors (BV),
  - arrays (A) and — actually an extensional theory of arrays
  - even a sequential extension for model checking — see BPR'08
- easy to parse, strongly typed, clean BV semantics
  - division by zero is fully defined — undefined in SMT-LIB
- all operators / constructors correspond to API calls of `libboolector.a`
- Boolector recently released under GPL — http://fmv.jku.at/boolector

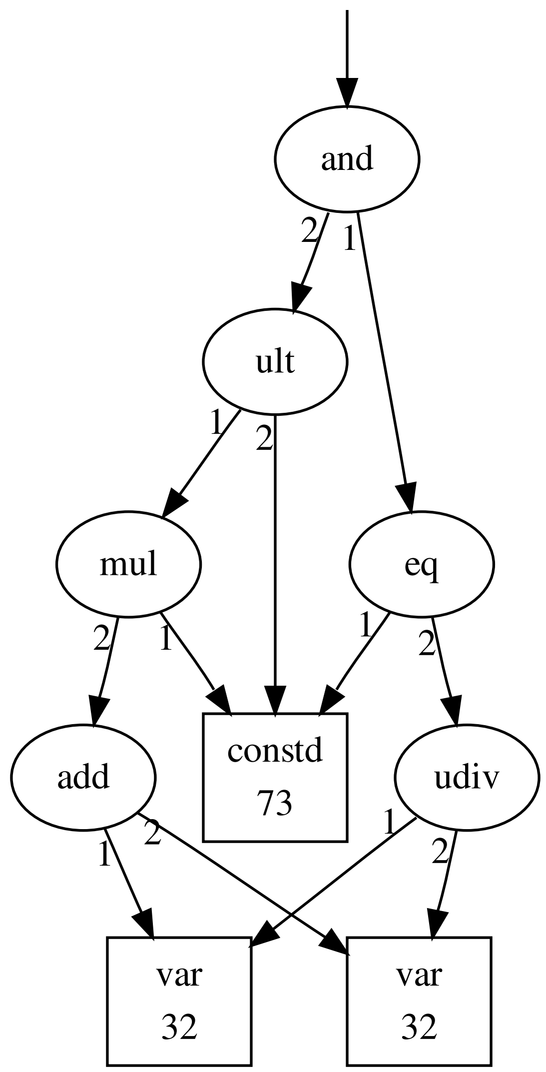
Bit-Vector Example (1/2)

```
1 var 32                 6 add 32 1 2
2 var 32                 7 mul 32 3 6
3 constd 32 73           8 ult 1 7 3
4 udiv 32 1 2            9 and 1 5 8
5 eq 1 3 4              10 root 1 9
```

```
id op bw id_or_num*
```

- first column: id
- second column: operator
- third column: bit-width of result
- other columns: id's of operands, or immediates

Bit-Vector Example (2/2)



Bit-Vector Constructors

- `var` `1 var 16 x`
  - bit-width
  - optional string for back annotation
- `const` for binary constants `2 const 4 1101`
- `constd` for decimal constants `3 constd 4 13`
- `consth` for hexa-decimal constants `3 consth 4 d`

Unary Bit-Vector Operators

class	operators	w_1	w_r
negation	**not**, neg	n	n
reduction	redand, redor, redxor	n	1
arithmetic	inc, dec	n	n

```
1 var 32
2 var 32
3 not 32 1
4 not 32 2
5 or 32 -3 -4
6 and 32 1 2
7 eq 1 5 -6
8 root 1 -7
```

- one's complement `not`
  - can also be expressed by a minus in front of an operand as in AIG's
- two's complement `neg`
- reduction operators from Verilog
- increment and decrement by one

Binary Bit-Vector Operators

class	operators	w_1	w_2	w_r
bitwise	**and**, or, xor, nand, nor, xnor	n	n	n
boolean	implies, iff	1	1	1
arithmetic	**add**, sub, **mul**, **urem**, srem **udiv**, sdiv, [us]mod,	n	n	n
relational	**eq**, ne, **ult**, slt, [us]lte, [us]gt, [us]gte	n	n	1
shift	**sll**, **srl**, sra, ror, rol	n	$log_2 n$	n
overflow	[us]addo, [us]subo, [us]mulo, sdivo	n	n	1
concatenation	**concat**	n_1	n_2	$n_1 + n_2$

- unsigned and signed context

- second operand of shift-operations has bit-width $log_2 n$

Ternary and Miscallenous Bit-Vector Operators

class	operators	w_1	w_2	w_3	w_r
conditional	**cond**	1	n	n	n

`cond` as the only ternary operator — if-then-else

class	operators	w_1	upper	lower	w_r
extract	**slice**	n	u	l	$u-l+1$

`slice` extracts bits out of a bit-vector — operands are immediates

Arrays (1/2)

- BTOR supports one-dimensional bit-vector arrays
  - multi-dimensional arrays can be simulated by `concat` of operands

- constructor
  - `array e i`
  - elements have bit-width `e`
  - indices have bit-width `i`, i.e. size is $2^{\mathtt{i}}$

```
1 array 32 8
```

4 GB of memory

- array access
  - `read` — can be used to model uninterpreted functions
  - `write` — updates of arrays / functions

Arrays (2/2)

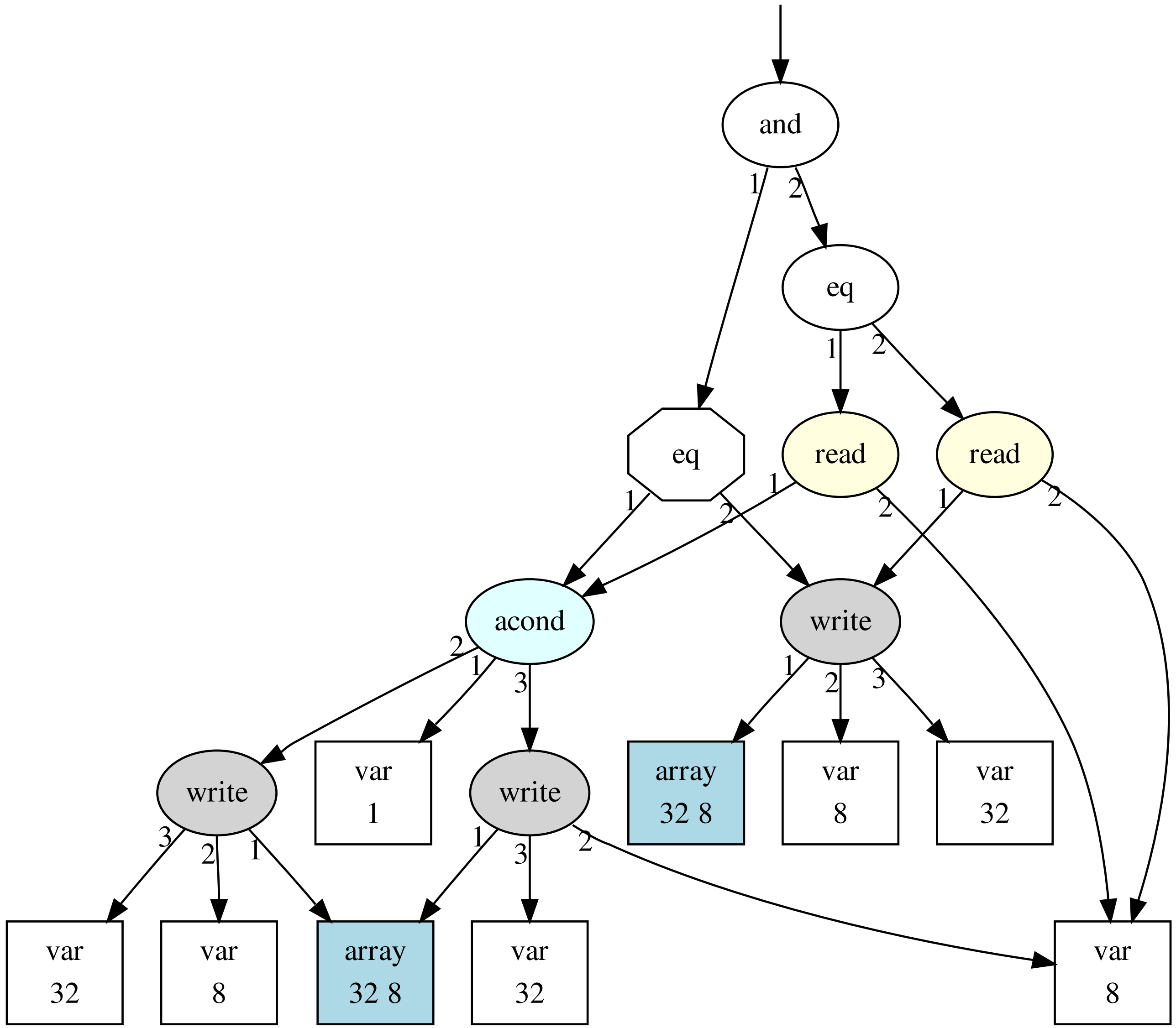
- if-then-else on arrays
  - `id acond ew iw cond then else`
- comparing arrays
  - arrays of the same type can be compared for equality with `eq`
  - two arrays are equal *iff* their elements are equal
- thus we have an extensional theory of arrays
  - can be used for comparing memory “before” and “after”
  - for instance equivalence checking of basic blocks in C with pointers

Array Example (1/2)

```
1 array 32 8
2 array 32 8
3 var 8
4 var 32
5 var 8
6 var 32
7 var 8
8 var 32
9 var 1
10 write 32 8 1 3 4
11 write 32 8 1 5 6
12 acond 32 8 9 10 11
13 write 32 8 2 7 8
14 eq 1 12 13
15 read 32 12 5
16 read 32 13 5
17 eq 1 15 16
18 and 1 14 17
19 root 1 18
```

- `write` and `acond` return an array of type `32 8`
- `read` returns a bit-vector of bit-width `32`

Array Example (2/2)



Design Decisions

- easy to parse
  - numerical ids, thus no symbol table   variable names can be added
  - simple single pass parser: read line by line
  - no yacc/lex, no recursive decent necessary
- also not hard to write / print, since there is no need for pretty printing
  - as in parsing: simple non-recursive implementation
- easy to script

```
awk '{a[$2]++}END{for(k in a)printf "%-7s%d\n", k, a[k]}' | sort -n -k 2
```

- strongly typed + fixed precise semantics

```
1 table 3 8
00000000
00000001
00000011
00000010
00000110
00000111
00000101
00000100
```

```
1 array 3 3
2 const 3 000
3 const 8 00000000
4 write 3 8 1 2 3
5 const 3 001
6 const 8 00000001
7 write 3 8 4 5 6
8 const 3 010
9 const 8 00000010
10 write 3 8 7 8 9
...
```

- initialization of constant memory — 3-bit gray code in the example
  - used to model lookup-tables in programs
  - *will also be useful as internal operator*

- related zero initialized memory: `1 zarray 32 8`

Functions

- functions on bit-vectors are simply arrays without updates / `write`

- adding uninterpreted functions is a matter of syntatic sugar

```
1 fun 32 8              1 array 32 8
2 var 32                2 var 32
3 apply 8 1 2           3 read 8 1 2
```

- functions and arrays should be allowed to have multiple arguments

```
1 fun 32 1 8            1 array 32 1 8
2 var 32                2 var 32
3 var 1                 3 var 1
4 apply 8 1 2 3         4 read 8 1 2 3
```

- same applies to other associative operators
  - `concat`, `and`, ...

Quantifiers

- many verification (if not most) only need bit-vectors + arrays + quantifiers

  example: $\forall i, j[0 \leq i \leq j < n \rightarrow a[i] \leq a[j]]$

- first consider quantifiers over indices: $\forall x[\exists y[x = y]$ over 32-bit

```
1 var 32 x
2 var 32 y
3 eq 1 1 2
4 exists 1 3 2
3 forall 1 1 4
```

- methods for quantification
  - bit-blasting to QBF — needs (more) efficient QBF solvers
  - template based matching — yesterday's talk by Leonardo de Moura

- “ASCII API” to make Boolector “scriptable”

- add all current API functions to BTOR format

  - `assert`, `assume`, `sat`, `deref`, ...

- add new features to API and BTOR

  - `push`, `pop`, `failed`, `core`, `proof`, ...

- API is mostly the same as for plain SAT solvers such as PicoSAT

Types

- basic types
  - `bool`, `term`, `int`, `real`, ...
- constructors
  - `bv`, `array`, `fun`, ...
- replace bit-with argument at 3rd column by type id
- also merges “`acond`” and “`cond`” etc.

- DIMACS, AIGER
  - based on the same similar principles as BTOR, e.g. only numeric id's
  - DIMACS = CNF, AIGER = AIG's
- Simplify, CVC, Z3, Spear native input formats
  - compromise between easy to read Simplify / CVC and
  - compact / easy to parse Z3 / Spear
- SMT-LIB, TPTP
  - extensible human-readable LISP/Prolog like syntax
  - SMT-LIB 2.0 is "scriptable", i.e. specifies "commands"

Conclusion

- BTOR is a clean and simple format for BV with arrays
- extensions needed in applications
  - without changing expressiveness: tables + functions + scripts
  - theory extensions: quantifiers + types
- could be a starting point for a compact SMT format
  - maybe even a binary format
- finally we need to extend Boolector to support all this