Program verification using Verification-Condition generation

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Outline

- From Programs to SMT formulas
  - Straight line programs
- Annotations
  - Loops and Procedures
- Modeling low-level C programs
- HAVOC toolkit
- Challenges for scalable and automated verification

Program Correctness: Hoare Triple

- **Hoare triple**

  {P} S {Q}

  P, Q : predicates/property

  S : a program

- **From a state satisfying P, if S executes, then either:**
  - **Either S does not terminate, or**
  - **S terminates in a state satisfying Q**

Program verification → Formula

{ b.f = 5 } a.f = 5 { a.f + b.f = 10 }

is valid

iff

Select(f1,b) = 5 $\wedge$ f2 = Store(f1,a,5) $\Rightarrow$ Select(f2,a) + Select(f2,b) = 10

is valid

theory of equality:	f, =
theory of arithmetic:	5, 10, +
theory of arrays:	Select, Store

- [Nelson & Oppen '79]

Satisfiability-Modulo-Theory (SMT)

- Boolean satisfiability solving + theory reasoning
- Ground theories
  - Equality, arithmetic, Select/Store
- NP-complete logics

- Phenomenal progress in the past few years
  - Yices [Dutretre&deMoura'06],
  - Z3 [deMoura&Bjorner'07]

Simple prog. language (BoogiePL)

[Leino et al.'05]

- Commands
  - x := E
    - evaluate E and change x to that value
  - **havoc** x
    - change x to an arbitrary value
  - **assert** E
    - if E holds, terminate; otherwise, go wrong
  - **assume** E
    - if E holds, terminate; otherwise, block
  - S ; T
    - execute S, then T
  - **goto** A **or** B;
    - change point of control to block A or block B, choosing blindly

Variables and Assignments

- **Two types of variables**
  - **Scalar (e.g. int, bool,..)**
  - **Maps (mutable arrays, n-dimensional)**

```
var y: int;
var a: [int] int;        // array variable
start:
     y   :=  10;                    // assignment to scalar
    a[y] := 20;                     // sugar for a   :=  update(a, y, 20) ;
     y   :=  a[10];                 //read from a map
```

Example translation: if-then-else

[[if P then S else T end]]

≅

```
Start:    goto Then or Else

Then:     assume P ;
          [[ S ]] ;
          goto After

Else:     assume ¬P ;
          [[ T ]] ;
          goto After

After:    …
```

Programs → Formulas

- Assume no loops (back-edge gotos)

{P} S {Q}

⇩

assume P; S; assert Q

- Task: Transform a program with assume/assert into a formula
  - Known as *Verification Condition* (VC) generation

Verification-condition generation

1. **passive features: assert, assume, ;**
2. **state changes: :=, havoc**
3. **control flow: goto (no loops)**

Weakest (liberal) precondition

- The ***weakest liberal precondition*** of a statement S with respect to a predicate Q on the post-state of S, denoted **wp(S,Q)**, is the set of pre-states from which execution:
  - does not go wrong (by failing an assert), and
  - if it terminates, terminates in Q

VC generation: passive features

- wp(assert E, Q) =

  $E \wedge Q$

- wp(assume E, Q) =

  $E \Rightarrow Q$

- wp(S; T, Q) =

  wp(S, wp(T, Q))

Eliminate :=, havoc

- Dynamic single assignment (DSA) form
  - There is at most one definition for each variable on each path
  - Replace defs/uses with new incarnations
    - x := x+1 with $x_{n+1} := x_n + 1$
  - At join points unify variable incarnations
- Replace havoc x with new incarnations x_{n+1}
- *Eliminate assignments* by replacing

  x := E ➔ assume x = E

Example

```
assume x = 1;
x := x + 1;

if (x = 0) {
    x := x + 2;
} else {
    x := x + 3;
}
assert x = 5;
```

```
assume x0 = 1;
assume x1 = x0 + 1;

if (x1 = 0) {
    assume x2 = x1 + 2;
    assume x4 = x2;
} else {
    assume x3 = x1 + 3;
    assume x4 = x3;
}
assert x4 = 5;
```

Example

assume $x_0 = 1$;

assume $x_1 = x_0 + 1$;

if ($x_1 = 0$) {

  assume $x_2 = x_1 + 2$;

  assume $x_4 = x_2$;

} else {

  assume $x_3 = x_1 + 3$;

  assume $x_4 = x_3$;

}

assert $x_4 = 5$;

start: assume $x_0 = 1$; goto l_1;

l_1: assume $x_1 = x_0 + 1$; goto l_2, l_3;

l_2: assume $x_1 = 0$;

  assume $x_2 = x_1 + 2$;

  assume $x_4 = x_2$; goto l_4;

l_3: assume $x_1 \neq 0$;

  assume $x_3 = x_1 + 3$;

  assume $x_4 = x_3$; goto l_4;

l_4: assert $x_4 = 5$

Control flow

- Finally, program is a collection of blocks
- Each block is
  - l: $A_1,\ldots,A_m$; goto $l_1,\ldots,l_n$
  - l is block label
  - A is either assume E or assert E
- Distinguished "start" label

VC Generation for Unstructured Control Flow

For each block $A \cong l: S; \text{goto } l_1,..,l_n$

1. Introduce a boolean variable A_{ok}
   - A_{ok} holds iff all executions starting at A do not end in a failed assertion
2. Introduce a Block Equation for each block A:

$$BE_A \;\cong\; A_{ok} \Leftrightarrow VC(S, \bigwedge_{B \in Succ(A)} B_{ok})$$

VC of entire program:

$$(\bigwedge_A BE_A) \Rightarrow Start_{ok}$$

VC Generation

A { start: assume $x_0 = 1$; goto l_1;

B { l_1: assume $x_1 = x_0 + 1$; goto l_2, l_3;

C { l_2: assume $x_1 = 0$;
assume $x_2 = x_1 + 2$;
assume $x_4 = x_2$; goto l_4;

D { l_3: assume $x_1 \neq 0$;
assume $x_3 = x_1 + 3$;
assume $x_4 = x_3$; goto l_4;

E { l_4: assert $x_4 = 5$

$$A_{ok} \Leftrightarrow (x_0 = 1 \Rightarrow B_{ok}) \quad \wedge$$

$$B_{ok} \Leftrightarrow (x_0 = 1 \Rightarrow C_{ok} \wedge D_{ok}) \quad \wedge$$

$$C_{ok} \Leftrightarrow (x_1 = 0 \Rightarrow (x_2 = x_1 + 2 \Rightarrow (x_4 = x_2 \Rightarrow E_{ok}))) \quad \wedge$$

$$D_{ok} \Leftrightarrow (x_1 \neq 0 \Rightarrow (x_2 = x_1 + 2 \Rightarrow (x_4 = x_3 \Rightarrow E_{ok}))) \quad \wedge$$

$$E_{ok} \Leftrightarrow (x_4 = 5 \wedge \text{true})$$

$$\Rightarrow A_{ok}$$

VC Generation

Formula over Arithmetic, Equality, and Boolean connectives

Can be solved by a SMT solver

$$A_{ok} \Leftrightarrow (x_0 = 1 \Rightarrow B_{ok}) \quad \wedge$$

$$B_{ok} \Leftrightarrow (x_0 = 1 \Rightarrow C_{ok} \wedge D_{ok}) \quad \wedge$$

$$C_{ok} \Leftrightarrow (x_1 = 0 \Rightarrow (x_2 = x_1 + 2 \Rightarrow (x_4 = x_2 \Rightarrow E_{ok}))) \quad \wedge$$

$$D_{ok} \Leftrightarrow (x_1 \neq 0 \Rightarrow (x_2 = x_1 + 2 \Rightarrow (x_4 = x_3 \Rightarrow E_{ok}))) \quad \wedge$$

$$E_{ok} \Leftrightarrow (x_4 = 5 \wedge \text{true})$$

$$\Rightarrow A_{ok}$$

Summary: VC Generation

- **From programs → logical formulas**
- **Efficient VC generation**
  - **A formula that is *linear* in the size of the (loop-free and call-free) program**
- **Language of assertion determines the logical theories for the VC**

Loops and procedure calls

- **Transform loops to loop-free programs**
  - **With *loop-invariants***
- **Transform procedure calls into asserts and assumes**
  - **With *preconditions* and *postconditions***

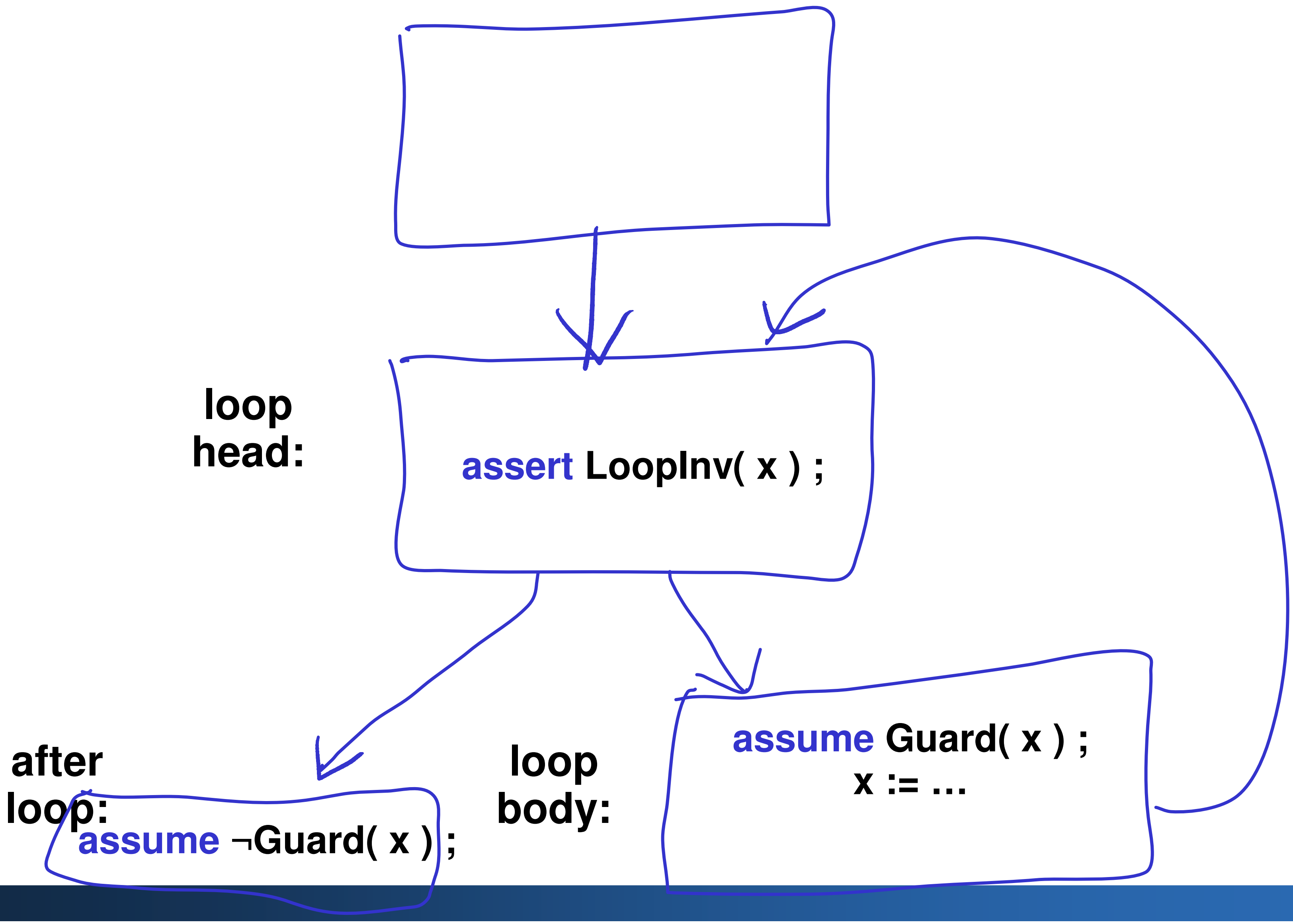
Example translation: loop

[[while { invariant J } B do S end]]

≅

```
LoopHead:     assert J ;
              goto LoopBody or AfterLoop
LoopBody:     assume B ;
              [[ S ]] ;
              goto LoopHead
AfterLoop:    assume ¬B ;
              …
```

Transforming loops



Transforming loops

assert P
=
assert P ; assume P

loop head:

assert LoopInv(x) ;
assume LoopInv(x);

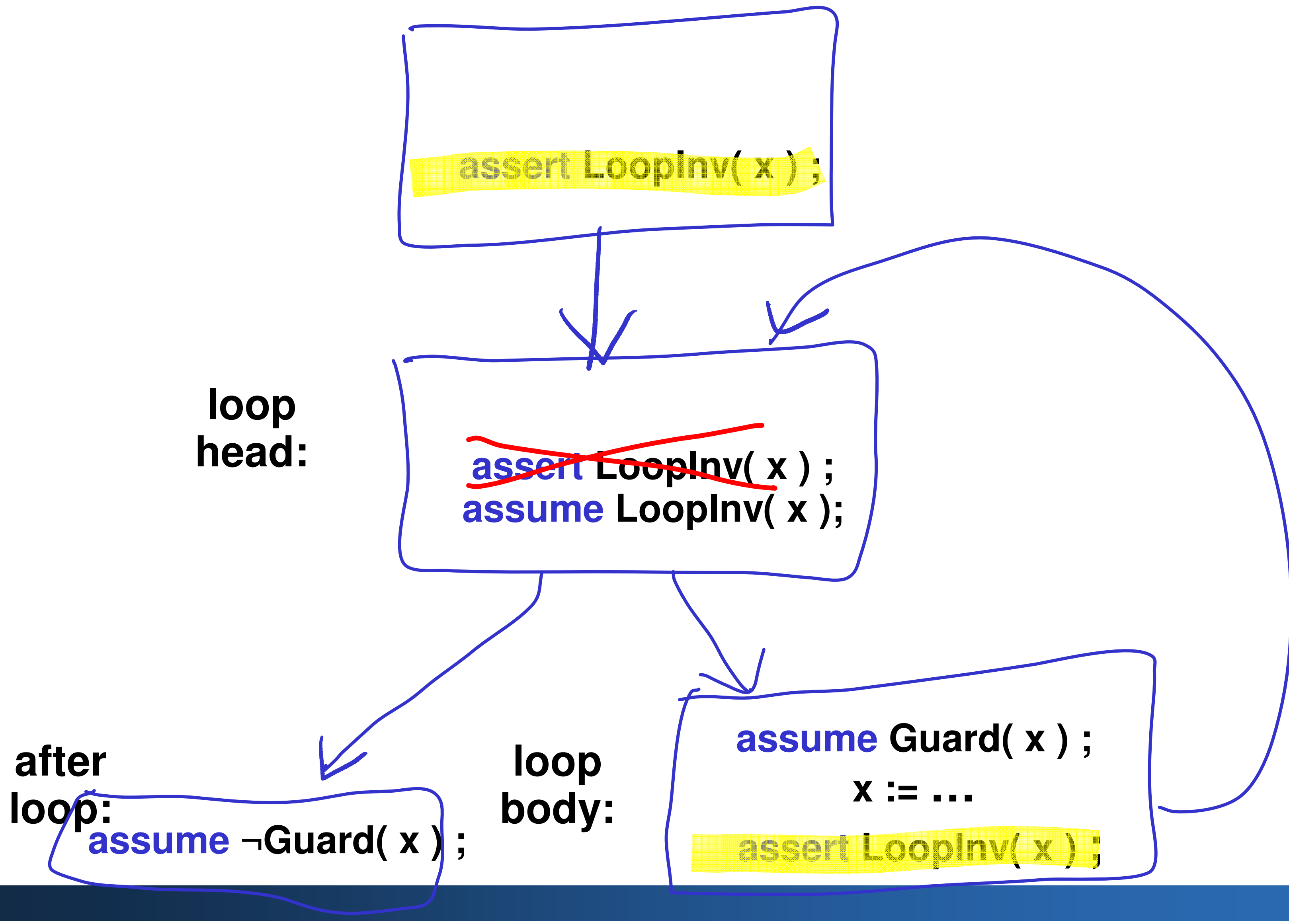
after loop:

assume ¬Guard(x) ;

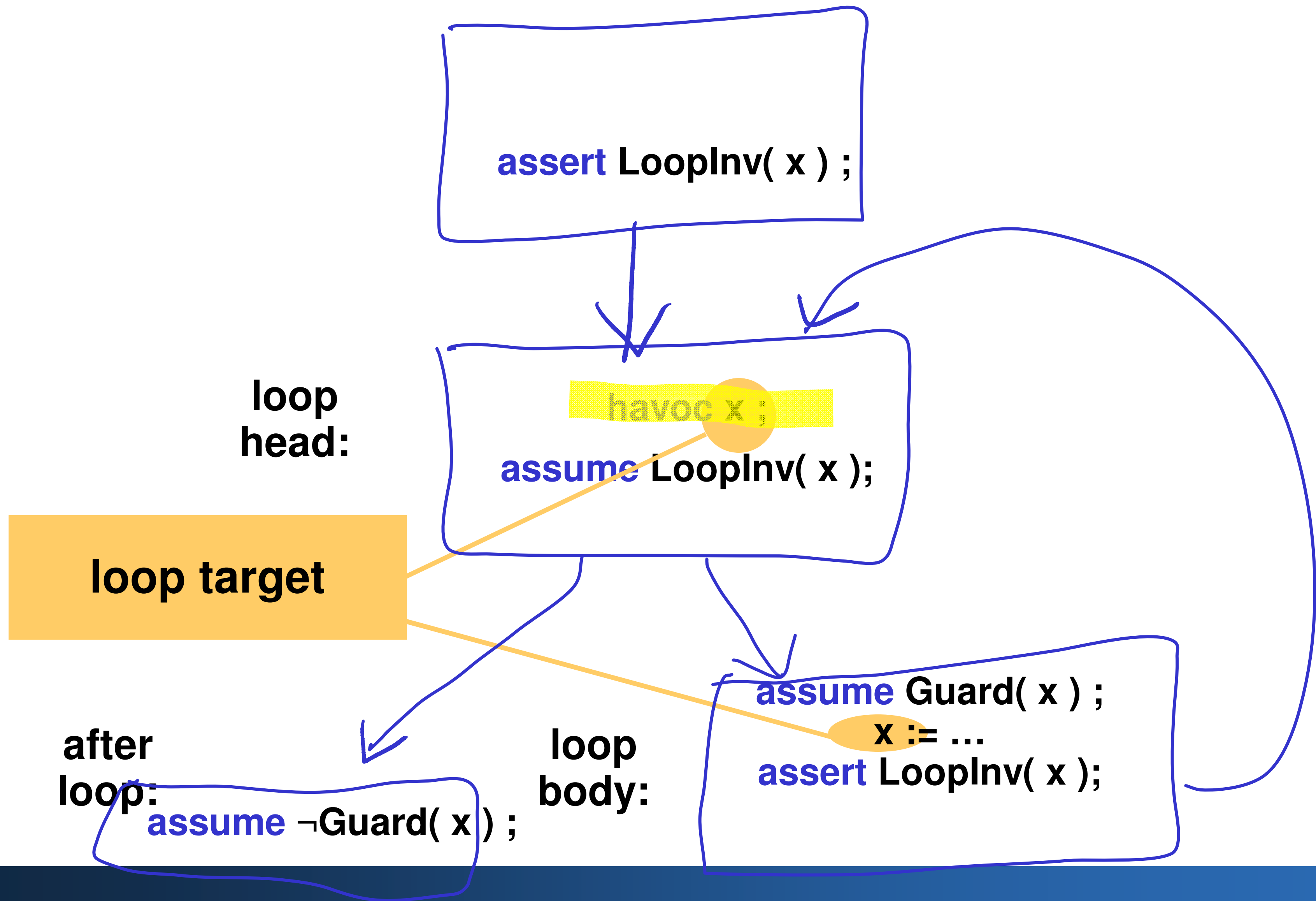
loop body:

assume Guard(x) ;
x := …

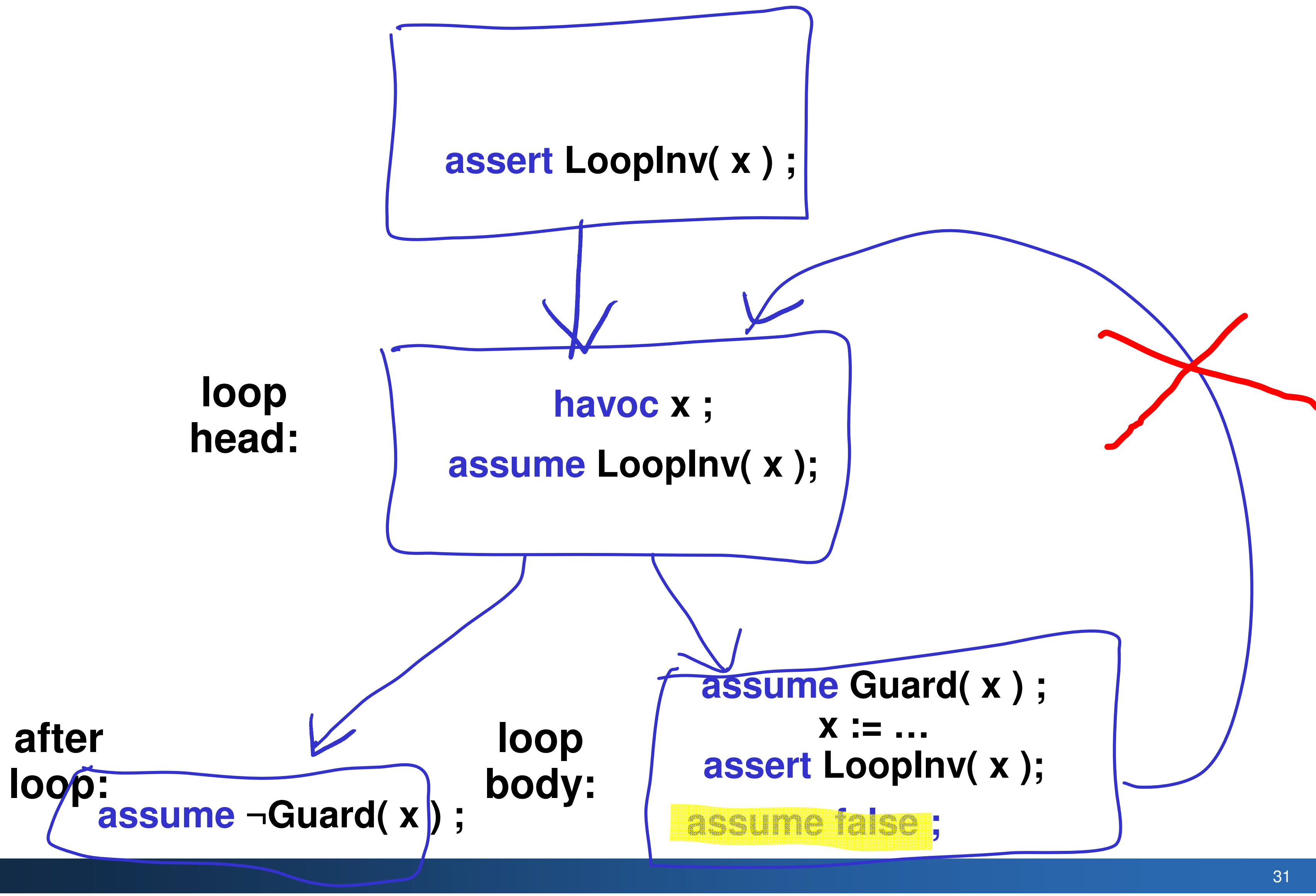
Transforming loops



Transforming loops



Transforming loops



What about procedure calls?

- Each procedure verified separately
- Procedure calls replaced with their specifications

```
procedure Foo();
requires  pre;
ensures  post;
modifies M;
```

- precondition
- postcondition
- set of locations possibly modified in Foo

```
call Foo();
```

→

```
assert pre;
havoc M;
assume post;
```

Example of loop invariant + procedure contract

```
int x, y;  //globals

void main(){

    x := y := 0;
    Foo(4);
    assert (x  =  5); // should fail
    assert (x  = 4); //should pass

}
```

```
requires n >= 0;
ensures x = n;
modifies x;
void Foo(int n){
   x := 0; y := n;

   invariant( y >= 0 ∧  x + y  = n)
    while(y  > 0) {
        x++;
        y—;
     }
}
```

Summary

- VC generation
  - Generates a SMT formula from loop/call free code
- Loop invariants
  - Transform loops to loop-free code
- Procedure contracts
  - Transform procedure calls to call-free code

Modeling C

- Convert C to BoogiePL
  - A memory model to model C's operations
  - Using the HAVOC toolkit

- Generate formulas using Boogie VC generator

C language

C types

- Scalars (int, long, char, short)
- Pointers (int*, struct T*, ..)
- Nested structs and unions
- Array (struct T a[10];)
- Function pointers
- Void *

Difficult to establish type safety in presence of pointer arithmetic, casts

C language (cont.)

Operations

- Arithmetic and Relational (+, -, ≤, =..)
- Pointer arithmetic ((T*) x ++)
- Address-of (&) operation
  - Allows taking address of fields and nested structures
- Allocate and free
- Casts

Memory Model in HAVOC

- **Every pointer (address or value) is an integer**
- **Pointer dereference modeled as lookups/updates to a map Mem**
- **Accounts for pointer arithmetic, internal pointers, address-of operations, arrays, casts, …**

Memory model

- **Maps (in BoogiePL) for memory model**

  // Mutable

  Mem: int → int

  Alloc: int → {UNALLOCATED, ALLOCATED, FREED}

  // Immutable

  Base: int → int //base address of each pointer

  Type: int → type //type of each pointer

C Variable → Boogie Variable

- Variables are *usually* allocated in the heap/Mem
  - To account for the address of a variable (e.g. y = &x)
  - To deal with structure/union variables
    - struct T { int f; int g;} x;
  - All globals are allocated on the heap (make the translation modular)
- Only scalar locals and parameters whose addresses haven't been taken are mapped to BoogiePL variables

C → BoogiePL

```c
typedef struct {
 int g[10]; int f;} DATA;

DATA *create() {
   int a;

   DATA *d = (DATA*)
   malloc(sizeof(DATA));
   init(d->g, 10, &a);

   d->f = a;
   d->g[1] = 2;

   return d;
}
```

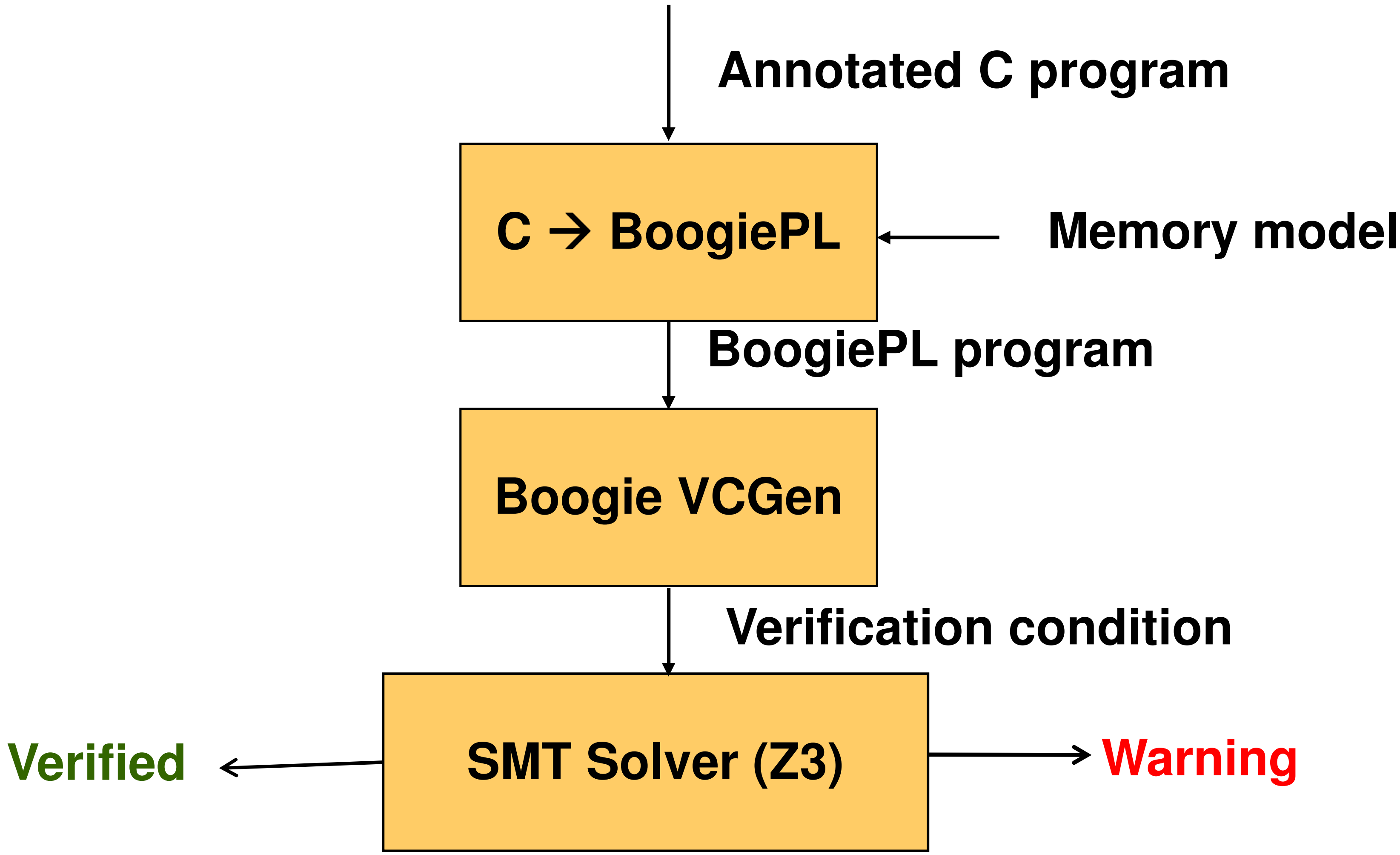
```
function f_DATA: int -> int;
forall u: int::  f_DATA(u) = u + 40;

procedure create() returns d:int{
   var @a: int;
   @a := malloc(4);
   d := call malloc(44);

   call init(g_DATA(d),10, @a);

   Mem[f_DATA(d)] := Mem[@a];
   Mem[g_DATA(d) + 1*4]:=2;
   free(@a);
   return;
}
```

HAVOC

Assertion checker for low-level (C) systems programs (kernel, device drivers, etc.)

1. **Precise modeling of the heap**
   - **Internal pointers, pointer arithmetic, casts, lists, arrays, ..**
2. **Expressive annotation language for C**
   1. **Deal with linked lists, arrays, types**
3. **Automated and efficient reasoning using SMT solvers + decision procedures for heap**

HAVOC Flow


Annotated C program
C → BoogiePL
Memory model
BoogiePL program
Boogie VCGen
Verification condition
Verified
SMT Solver (Z3)
Warning

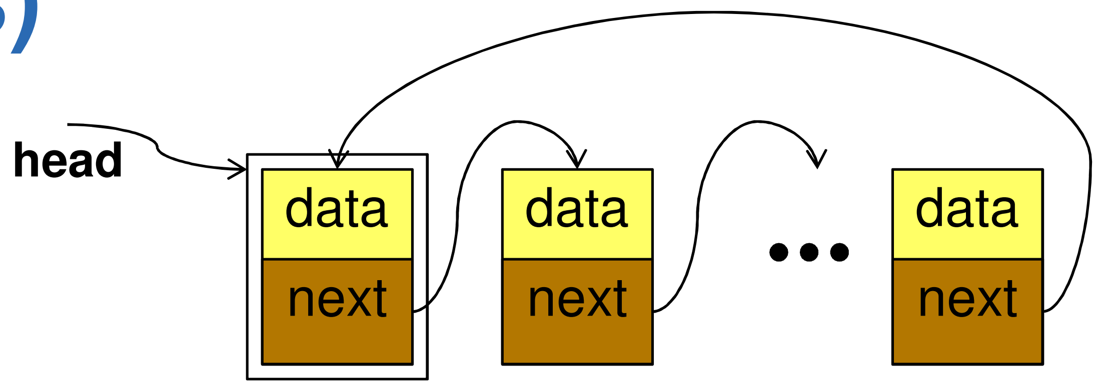
Challenges

- **Expressive yet efficient logic to specify properties**
  - **Properties about lists, arrays,**
  - **Yet amenable to automated SMT solvers**

- **Annotation inference**
  - **Infer procedure contracts and loop invariants**

Example (lists)

```
typedef struct _DATA {
  int data;
  struct _DATA *next;
} DATA, *PDATA;
```



Possible null dereference !!

Need to understand lists

```
void InitializeList(PDATA head) {

  PDATA iter;
   iter = head->next;

while (iter != head) {
   iter->data = 5;
   iter = iter->next;
 }
}
```

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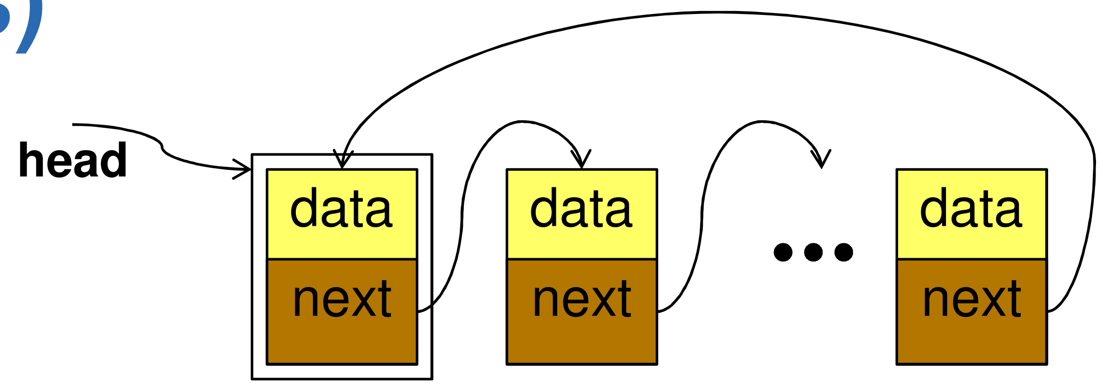
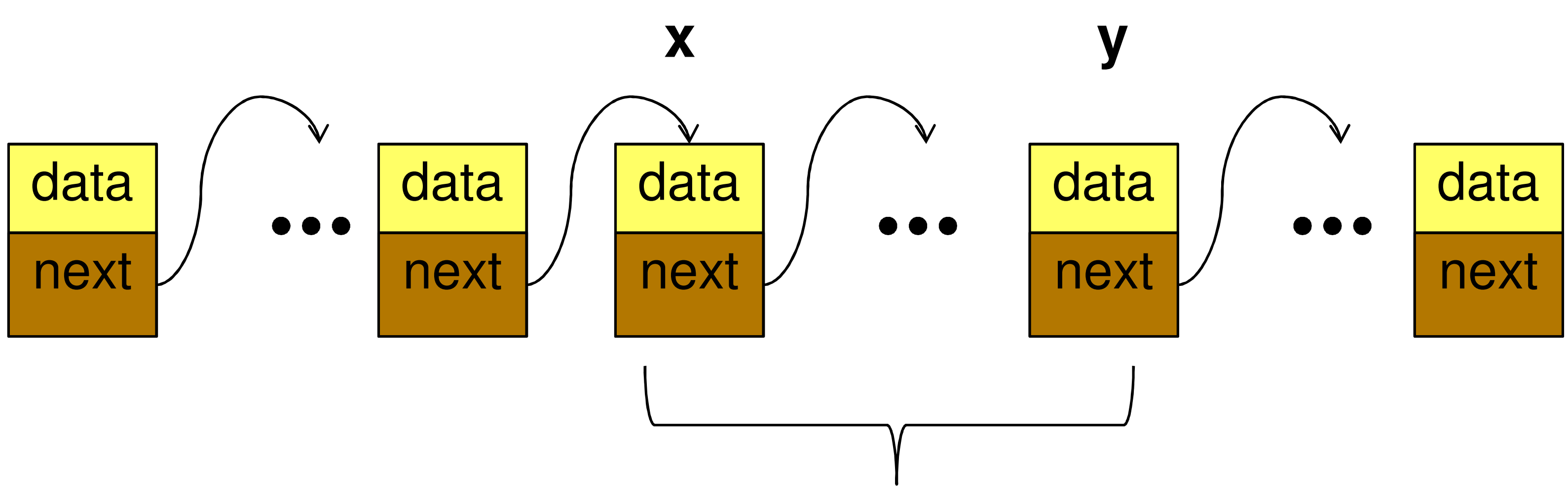
Example (lists)

```
typedef struct _DATA {
  int data;
  struct _DATA *next;
} DATA, *PDATA;
```

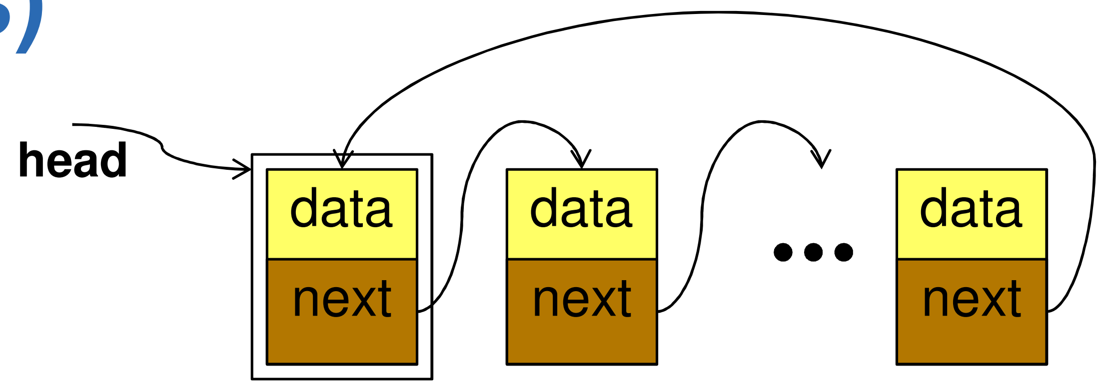




Btwn(next, x, y)

Example (lists)

```
typedef struct _DATA {
  int data;
  struct _DATA *next;
} DATA, *PDATA;
```




```
requires (head ∈ Btwn(next, head->next, head))
void InitializeList(PDATA head) {

  PDATA iter;
   iter = head->next;

invariant(iter ∈ Btwn(next, head->next, head))
while (iter != head) {
    iter->data = 5;
    iter = iter->next;
  }
}
```

Possible null dereference !!

Need to understand lists

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Annotation inference

- **Currently semi-automatic**
  - **Can infer simple annotations**
  - **Needs user to provide complex annotations**

- **Houdini algorithm (from ESC/JAVA) [Flanagan&Leino '01]**
  - **User "guesses" a candidate annotation for all the procedures in a module**
    - **Parameters non-null**
    - **Locks are unheld on entry and exit**
  - **The tool prunes away the annotations that may be violated using an SMT solver**
    - **More examples on HAVOC webpage**

Applications of HAVOC

- Functional correctness of medium sized programs with lists and arrays (e.g. custom allocators)
  - POPL'08
- Complex synchronization properties of a core Windows component
  - ~300KLOC, ~1500 procedure
  - 40+ bugs found with only 600L of manual annotations
  - Annotations allow documentation and incremental checking
- Type checking of low-level C code
  - Device drivers ~1KLOC,

HAVOC is available

- **Download:**
  - **http://research.microsoft.com/projects/HAVOC**
- **Has more details**
  - **How to check properties of linked lists and arrays**
  - **Type checking for C using SMT solvers**
  - **Case studies**

Summary

- Pros
  - **Scalable**: Modular checking (one procedure at a time)
  - **Precision**: Abstract only at procedure/loop boundaries
  - **Expressive:** Easy to encode new properties
- Cons
  - Requires annotations
- [Research] Need to automate more for a given class of properties
  - E.g. SALINFER [Hacket et al.06] tool for inferring buffer annotations for buffer overrun checking at Microsoft

Next parts: automated techniques

- Loop invariant generation
  - Abstract interpretation
  - Predicate-abstraction with refinement
- Bounded model checking
  - Sacrifice soundness for automation
  - Does not require loop invariants/procedure contracts

Questions?