Oberseminar WS05/06

Static Detection of Safe Loop Bounds

Christoph Cullmann

Betreuer: Florian Martin

Why Loop Bounds?

- Today:
  many time-critical programs on embedded systems
- We need WCET calculations for them
- Loop bounds are needed to calculate the WCET

Current Situation

- There exists already tools for WCET calculation
- Example: AbsInt's aiT :)
- aiT already includes a loop analysis

How does it work?

- Works on transformed loops
- Cooperates with value analysis iteratively
- To find loop bounds, use:
  - pattern matching
  - slicing
  - dominator/post-dominator analysis

Why multiple Iterations?

- Programs tend to include nested loops
- Inner loops will depend on outer loops in many cases
- Each iteration deals with loops on same nesting depth
- Restart of the value analysis with the computed loop bounds after each round

Why come up with new stuff?

- Current pattern matching needs:
  - manual adoption for each loop type
  - manual adoption for each compiler, even each optimization mode

- It's hard to integrate more complex loops

  e.g. loops with multiple internal alterations of loop counter

What will stay the same?

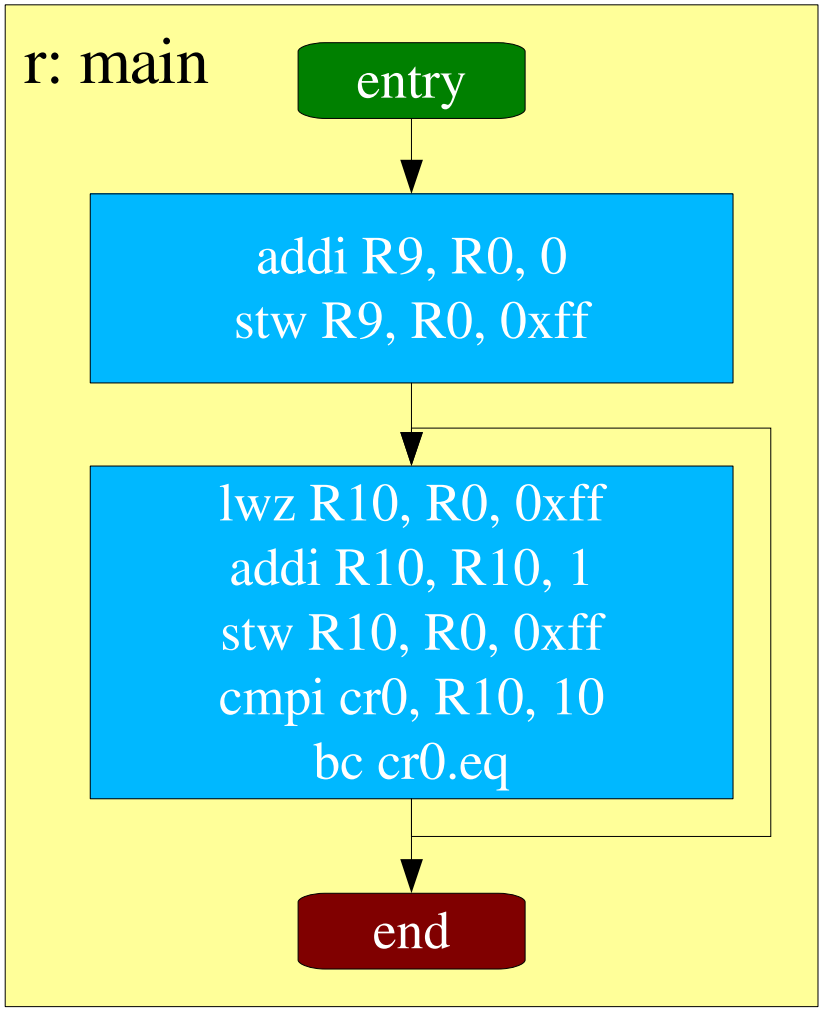
- Works on transformed loops
- Uses dominator analysis & slicing for finding and classifying exits
- Cooperates with existing value analysis
- The iteration scheme stays the same

Where is the innovation hidden?

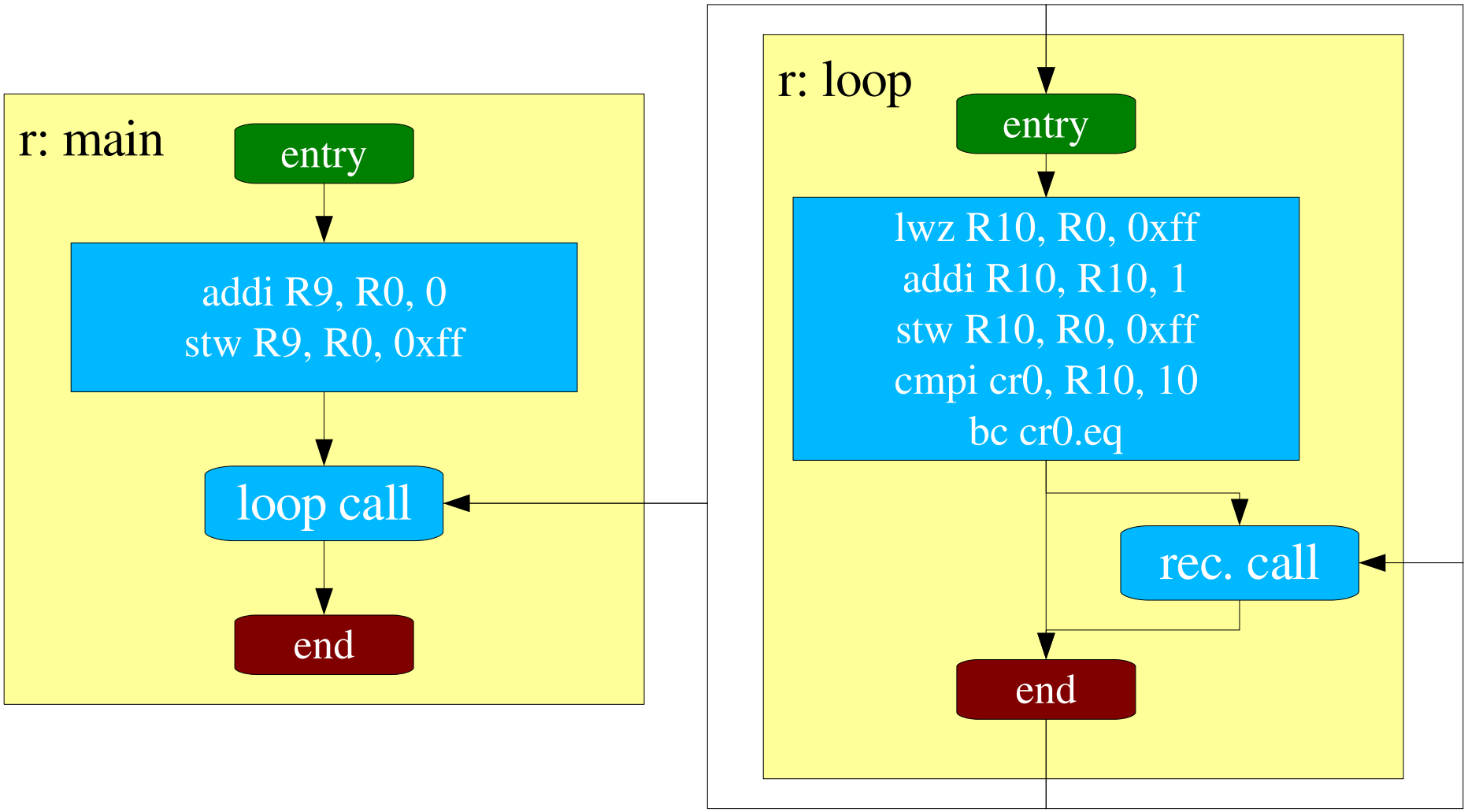
- The main difference:
  it uses a new data-flow analysis to generate equations for the loop counters

- This leads to:
  - being more generic
  - being more flexible
  - but has problems with special cases :)

Running Example



After Loop Transformation



Overview: One Analysis Iteration

- Sorting of loops by nesting depth
- Classification of loops based on value analysis
- Collection of possible loop counters & start values
- Building of equations via data-flow analysis
- Inspecting all exits and calculating min/max iterations using found start values, equations and exit informations

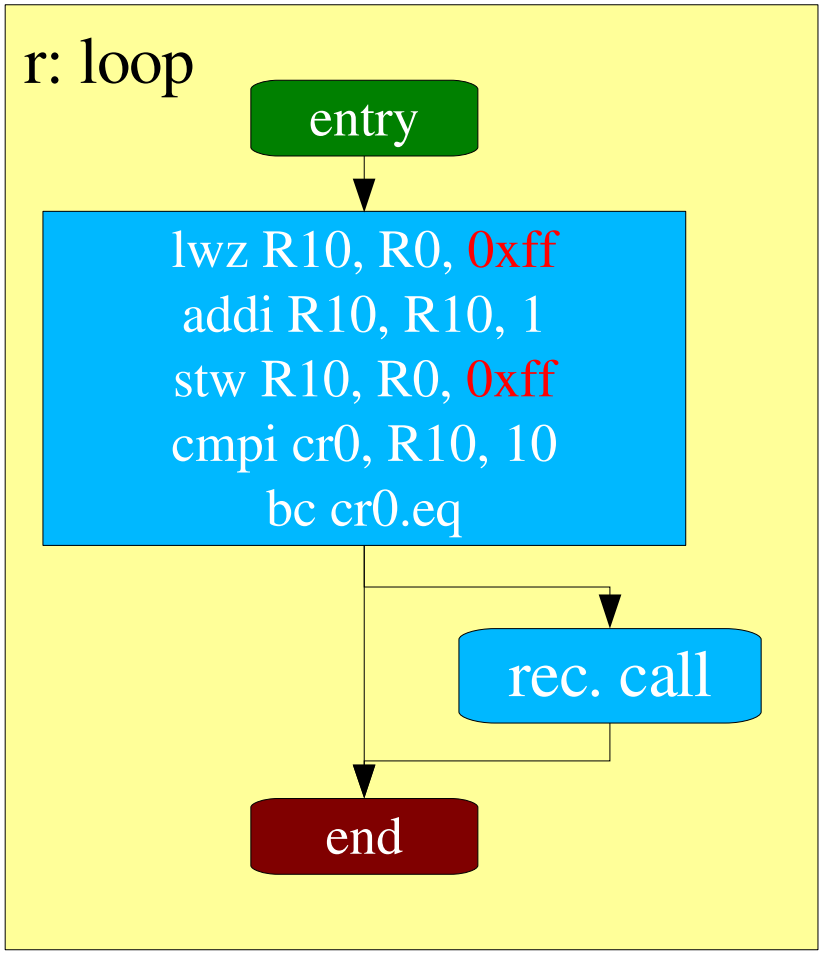
Loop Classification

- Classification in this types:
  - never reached loops
  - loops for which the recursive call is never reached
  - loops for which return node for the loop call is never reached
  - other loops: these ones will be analyzed more in detail

Detection of Loop Counters

- Candidates for loop counters:
  - registers accessed in the loop routine
  - memory cells accessed in the loop routine
- Simple analysis on the control graph, using value analysis results for memory access
- Ask value analysis for start values
- Only keep registers/memory cells with known start values

Results for example



- Loop routine accesses only memory cell 0xff:4 and register R10
- start value for 0xff:4 known, thanks to value analysis, not for R10
- Possible loop counters:
  - 0xff:4, with start [0,0]

Overview: Data Flow Analysis

- Covers all loops in the current nesting depth
- Is started with equations for found possible loop counters at first call
- Will result in equations for possible loop counters annotated to all edges in the loop routine
- This equations:
  show alteration of counter in one loop iteration

Properties of the Flow Problem

- Data flow value:
  set of equations

- Each equations contains:
  - destination variable
  - set of all possible values

- Important:
  - a variable on the right side stands symbolic for the start-value of this variable at the loop entry

Variables? Values?

- A variable is a triple of:
  - type: register, memory
  - address: register number or memory address
  - it's width in bytes

- A value is a quadruple of:
  - source variable (none indicates constant)
  - additive constant
  - minimal width in bytes we operate on
  - signedness: are we sign extended or not?

Applied to Example?

- Initial equations for our example on first call of the loop in main would consist only of:

  ((memory, 0xff, 4),
  [((memory, 0xff, 4), [0,0], 4, not extended)])

- In words:

  memory cell 0xff:4 = memory cell 0xff:4
  on loop start

Transfer function

- Forward problem
- Transfer function, different handling for:
  - normal blocks with instruction
  - recursive loop call of loops
  - returns from loops
  - others: identity
- Other interesting parts:
  Combination & Widening

Transfer: for Instructions

- Two phases:
  - remove all equations for variables which are modified by this instruction
  - add new equations you can derive out of the semantics of the instruction

Why two phases?

- First phase easy to implement for all instructions in a generic way, using only value analysis
- This leads already to conservative generation of equations, **we are on the safe side!**
- Second phase only needed for a few instructions:
  - constant addition
  - load/store
  - masking/sign extension
  - ...

Example: addi R10, R10, 1

- incoming flow: { R10 = <0xff:4> }
- First phase: kill equation for R10
- Second phase:
  - search for equation of R10 in incoming flow
  - alteration of the values found in this equation (add 1 to each additive constant)
- outgoing flow: { R10 = <0xff:4> + [1, 1] }

Transfer: for a recursive loop call

- We want to find invariants for one iteration
- Consequence:
  we don't want to propagate the flow from the last iteration to the next one
- Solution:
  we discard the flow-input and add again the initial equations of the loop to the call edge

Transfer: for loop return

- We don't want (and need) to propagate flow outside of loops in the current nesting
- Solution: discard input, propagate empty set of equations

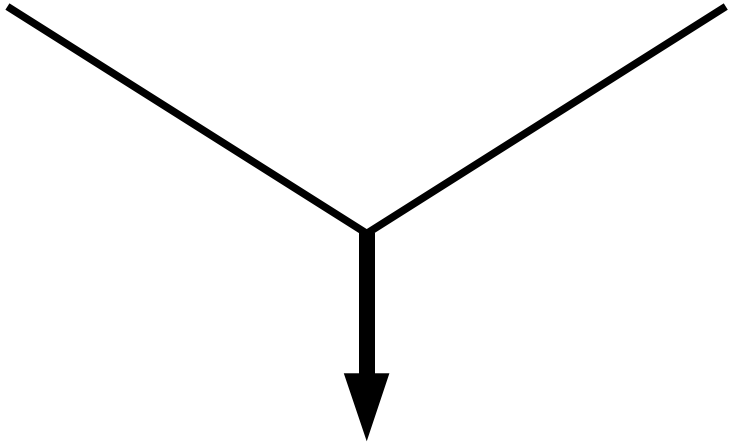
Combination Function

- We aim for safe results, therefor result will only contain:
  - equations for destination variable for which in both given sets already equations existed
  - merged value lists

A Combining Example

{ R10 = <0xff:4> + [1,1],
<0xff:4> = <0xff:4> }

{ R10 = <0xff:4>,
<0xff:4> = <0xff:4>,
R13 = [1,1] }



{ R10 = <0xff:4> + [0,1], <0xff:4> = <0xff:4> }

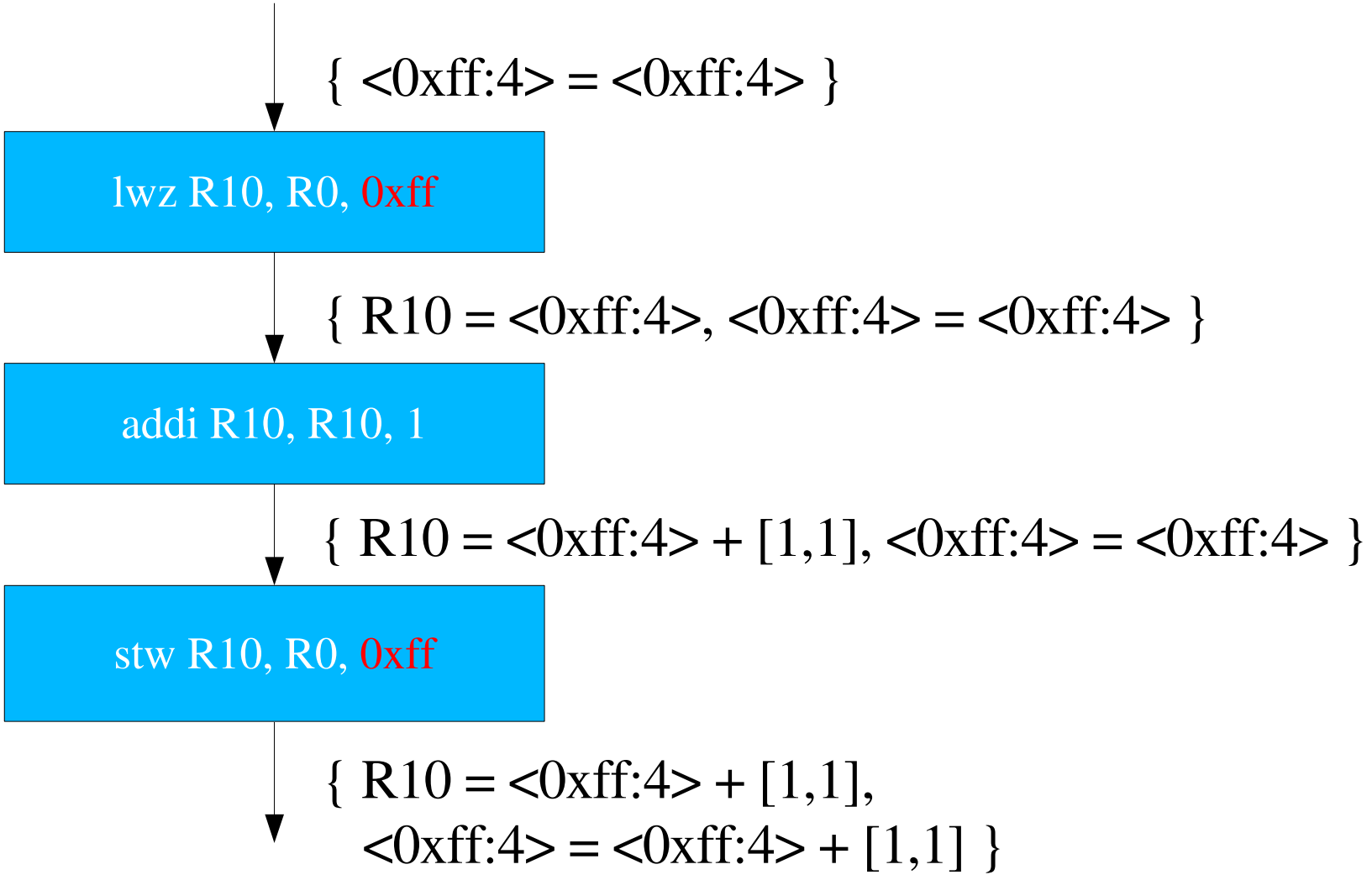
Widening

- Good news:
  - Transfer function monotone
  - Only finite count of destination variables possible
- Problem:
  - the constants in the values can change per iteration
  - only bound by range of integer
- Solution:
  - Kill all equations which changed since last iteration, but existed there already

Widening Example

- Previous iteration:
  { R10 = <0xff:4> + [0,1],
  R12 =R12 + [0,1] }
- Current iteration:
  { R10 = <0xff:4> + [0,2],
  R12 =R12 + [0,1],
  R13 = [1,1] }
- Widening Result:
  { R12 =R12 + [0,1], R13 = [1,1] }

Applied to Part of Example



Evaluation of all exits

- First: classification of exit:
  - always reached in a iteration?
  - only reached sometimes?
    this is done by a dominator analysis

- Only always reached exits can give information about maximal iteration count

- All exits can give information about minimal iteration count

What to do for each exit?

- Exits are conditional branches
- Two cases implemented for the PPC platform:
  - slice backwards to cmp/cmpi/cmpl/cmpli
  - “zero overhead loop” branch
    (decrement counter & branch on zero)
- Identify variables/constants used in the compare
- Identify the condition: =, <, >, ...

Back to example

- Only one exit in the loop, always used:

```
....
cmpi cr0, R10, 10
bc cr0.eq
```

- slice backwards to cmpi

- Used variables: R10
- Used constants: 10
- Condition: =

Now: Use the equations

- Get the equations for the variables used in the compare
- Check if the variable value depends only of one variable + additive constant
- Check if this variable is a loop counter
  (use the equations for this variable which reach the recursive loop call)

Applied to Example

- variable used in compare: R10
- equations for R10 at the compare:
  R10 = <0xff:4> + [1,1]
- base variable of R10: <0xff:4>
- equations for <0xff:4> at recursive call:
  <0xff:4> = <0xff:4> + [1,1]

Derive the loop count

- Use the equations we have now
- We get:
  - increment per iteration
  - increment before the compare
  - possible assignment of constant to counter
- If we have equations not matching this pattern, discard the exit, no computation possible in the current implementation

Once more: Example

- Remember:
  before compare: R10 = <0xff:4> + [1,1]
  per iteration: <0xff:4> = <0xff:4> + [1,1]

- increment per iteration:
  [1, 1]

- increment before compare:
  [1,1]

What's still needed?

- Get the start value of the loop counter:
  - Ask the value analysis!
- Use the knowledge of the width of the variables
  - Do we work in 8, 16 or 32 bit range?
- Use the knowledge of the signedness
  - Does the compare type match our variable type?

Our loved Example

- Start value:
  [0,0]
- Range: 32 bit
- Signedness: signed

Solve the problem

- We have now:
  - start value: [0, 0]
  - end value: [10, 10]
  - increment per iteration: [1,1]
  - increment before compare: [1,1]
- Solution: possible iterations: [10, 10]

Combine the bounds

- For each loop: calculate bound for each exit this way
- Combine the results to conservative bounds for the whole loop
- In our example, that would result in:
  bounds for “loop”: [10, 10]

What we do now?

- Write out all loop bounds for all contexts
- Let value analysis read them in, to refine their results
- Start the next iteration of our analysis, if needed
- Otherwise: We are done :)

That's it!

- We use now a data flow analysis to get loop invariants
- It is more generic, no fixed patterns
- It provides a portable solution
- First practical tests show that it's speed is usable

Future work

- Possible Extensions:
  - applying the method to other platforms:
    ARM, ...
  - Refining the implementation for:
    - more complex exit checks
    - dealing with loops with multiple first calls
  - allow constant multiplication in the equations
  - use a more powerful equation solver (omega, ...)

Thanks & Bon Apetite

Questions?