SWEET – A Tool for WCET Flow Analysis

Björn Lisper
School of Innovation, Design, and Engineering
Mälardalen University

bjorn.lisper@mdh.se

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Outline

Short introduction to (static) WCET analysis

SWEET:

- Architecture
- Interfaces
- Abstract Execution
- Short demo

WCET

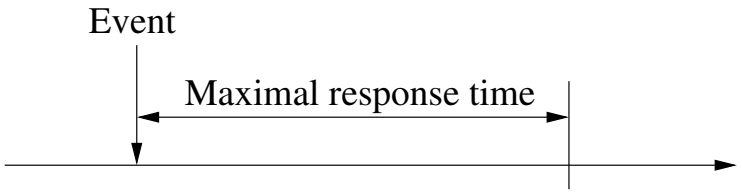
WCET $=$ Worst-Case Execution Time

Definition: $WCET(P) =$ longest time to execute program P uninterrupted on some given hardware

WCET analysis: to estimate or bound the WCET

Why WCET Analysis?

Many systems are *real-time systems*. These have *timing constraints*:



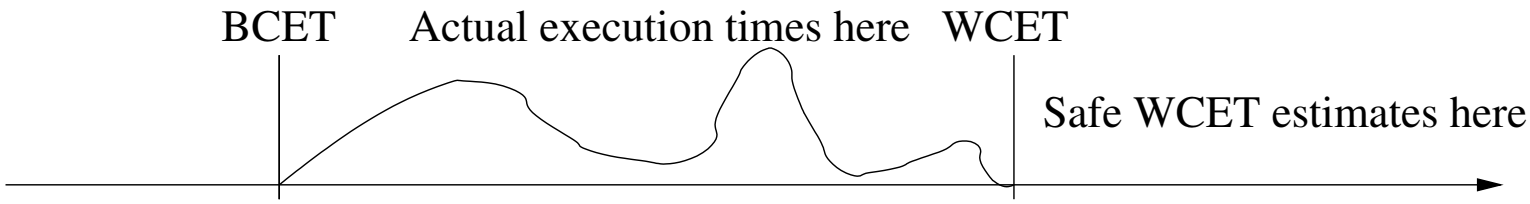
Absolute deadlines, maximum response times, etc.

Two classes:

- *Hard* real-time systems: timing constraints *must* be met
- *Soft* real-time systems: *desirable* that timing constraints are met

WCET Estimation

Safe WCET estimates are needed to safely decide if timing constraints are met:



Safe $=$ will never underestimate real WCET

Static analysis can obtain safe WCET estimates

Important for hard real-time systems

What is Needed for Static WCET Analysis?

- A detailed timing model for the processor, to estimate the execution times of instructions
- Whatever constraints there may be on inputs, initial hardware state, etc.
- Constraints on the possible execution paths through the code (loop iteration bounds, infeasible path constraints, . . .)

Then (in principle) all feasible paths can be explored, and their costs (or upper bounds) decided

(For maximal precision, the linked binary should be analysed)

Making WCET Analysis Feasible

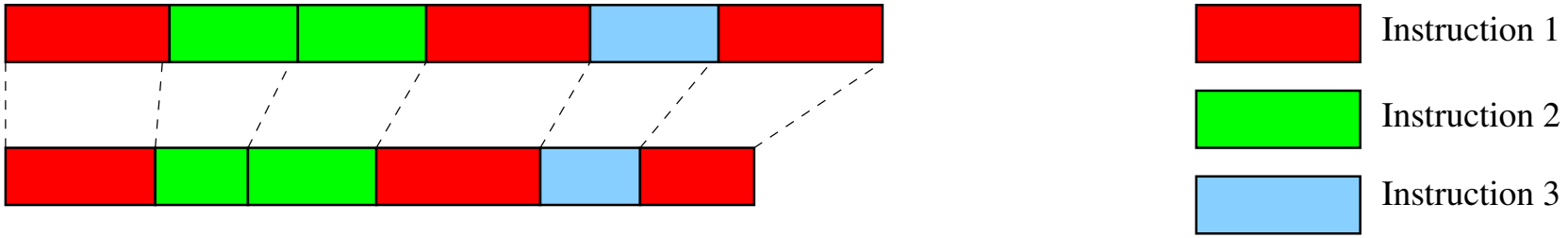
WCET is maximal execution time over all feasible paths. There can be very (exponentially) many paths. How deal with this?

Answer: make some controlled approximations to obtain a linear cost model This will allow the use of standard optimization techniques to bound the WCET

The Implicit Path Enumeration Technique (IPET)

Compute local WCETs w_i for code fragments i (typically basic blocks)

For each execution of a code fragment, replace its real execution time with its local WCET:



A relaxation. Some precision is sacrificed in order to get a problem that is less costly to solve

WCET Estimation as Integer Linear Programming

For each code fragment, introduce an *execution counter* counting its # of executions

Then, for any path p, $execution\_time(p) \leq \sum_i x_i w_i$ where the x_i's are the final values of the execution counters for p

Thus, $\max \sum x_i w_i$ over all paths will provide a safe WCET bound

Many program flow constraints can be expressed as *linear constraints* on the x_i's

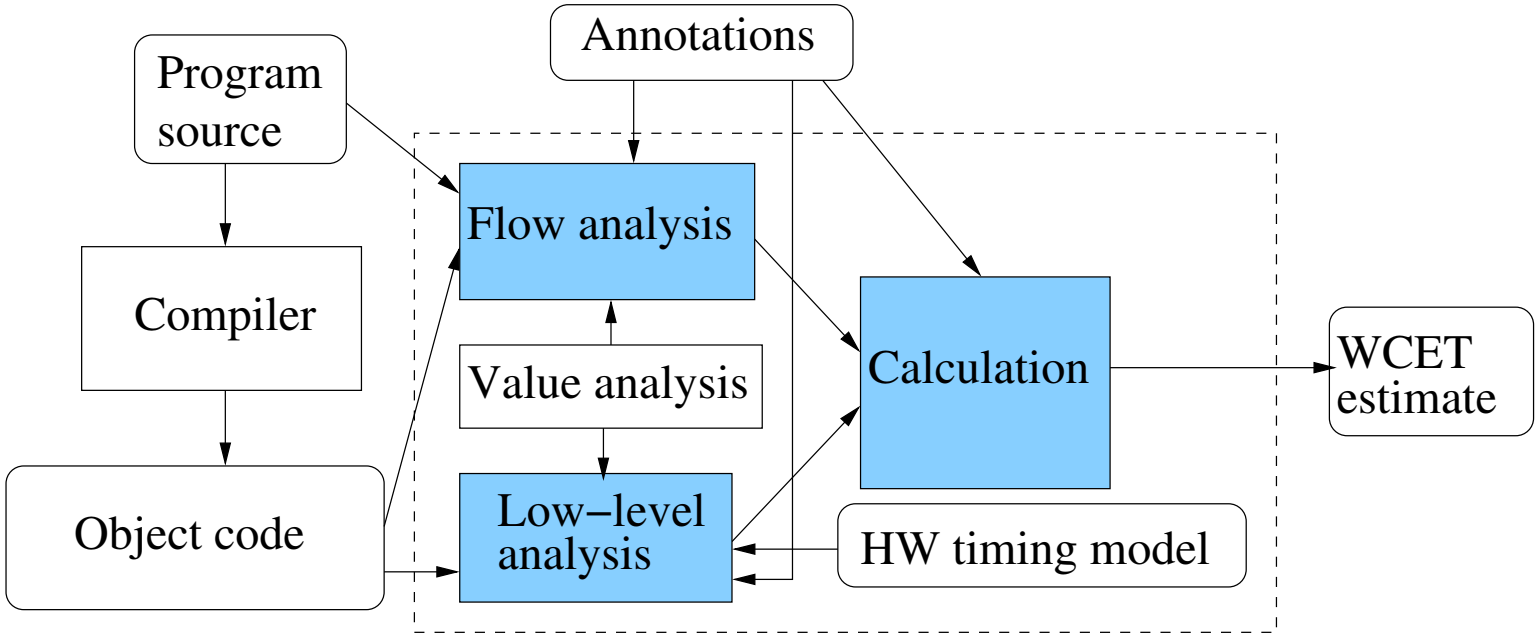
An **integer linear programming problem**. Solution $=$ WCET bound

Linear Flow Constraints ("Flow Facts")

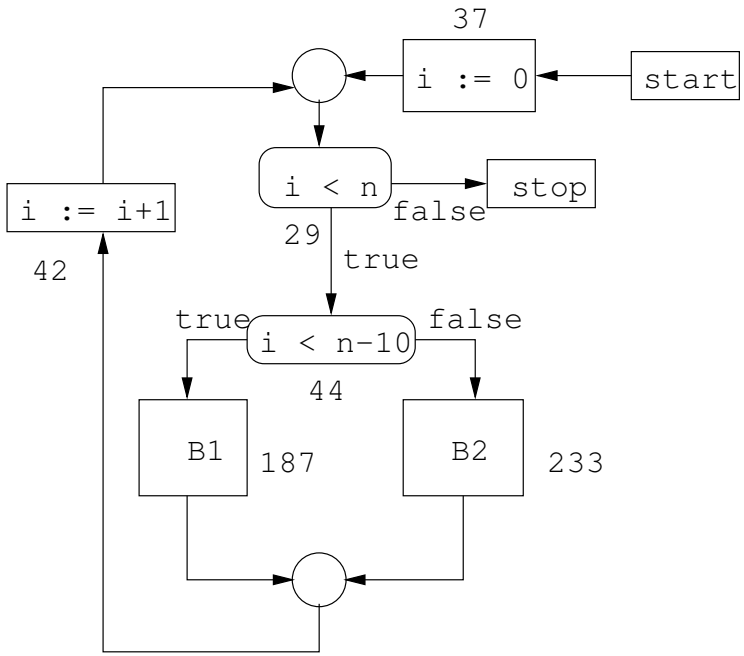
Many flow constraints can indeed be expressed as linear constraints on execution counters:

- $x_i \geq 0$ for all n_i (counters must be non-negative)
- **Structural flow constraints** (from CFG structure, flow preservation):
  - For each node $\neq$ start, stop, $\sum$ input counters $= \sum$ output counters
  - $x_i = 1$ if n_i is the start or stop node of the CFG
- **Semantic constraints**:
  - Loop iteration bounds (capacity bounds): $x_i \leq c$
  - Infeasible paths (mutual exclusivity): $x_i + x_j \leq c$
  - Relative bounds (often in nested loops): $x_i = c \cdot x_j$

Typical Structure of WCET Analysis



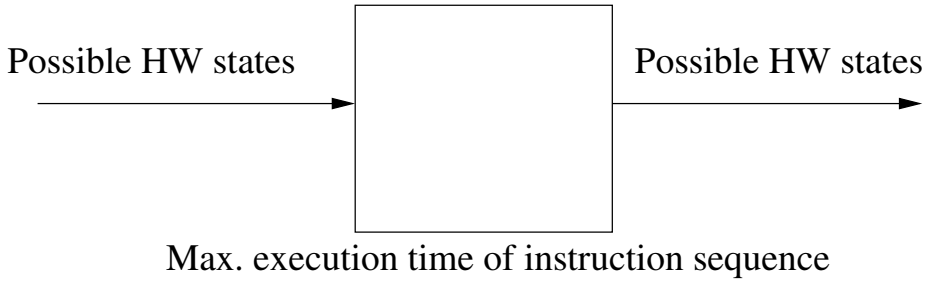
The analysis is typically done on CFG level:



Numbers = local WCET bounds for basic blocks

Low-Level Analysis

Purpose: find local WCETs for code fragments (basic blocks)



Must (1) bound possible hardware states, (2) use this information to bound the execution time of instruction sequences

(1) is often done by abstract interpretation, (2) requires an accurate timing model for the instruction set

Flow Analysis

Purpose: derive safe and tight Flow Facts

Undecidable in general (would solve the Halting Problem)

Find methods that work well enough on interesting program classes

We'll give an account for a method that is used in SWEET

SWEET

SWEET = SWEdish Execution time Tool

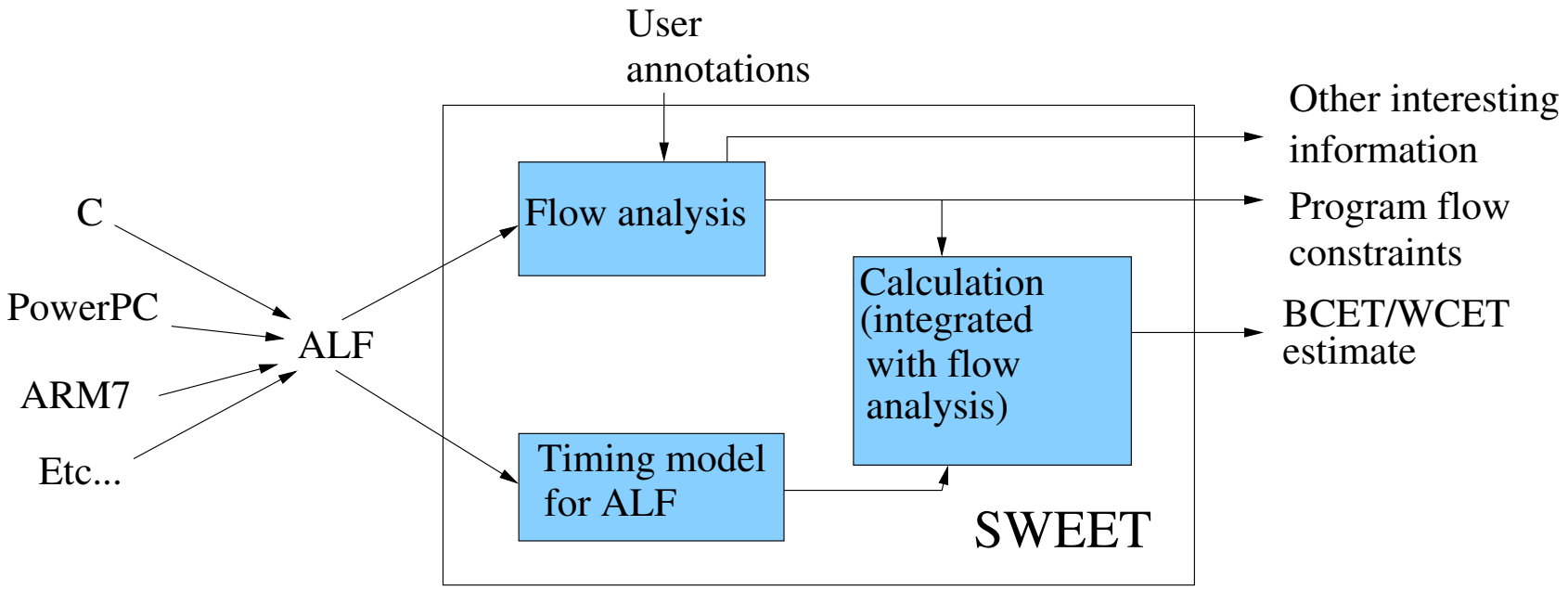
A program flow analysis tool, can generate many types of flow constraints (Flow Facts)

Analyses the “ALF” intermediate format

Can analyse different code formats by translation into ALF

Can compute BCET/WCET estimates for simple ALF level timing models

Structure of SWEET



SWEET's Flow Facts

Upper and lower loop iteration bounds

Various infeasible path constraints (single, pairwise, longer paths)

Can be *context-sensitive* (full call strings)

Given relative to *execution contexts* ("scopes"): main (global), function calls, loops

FOREACH Flow Fact: valid for *each individual execution* of the scope (execution counters reset at each entry)

FORALL Flow Fact: valid for *all executions together* of the scope (execution counters not reset)

(IPET Flow Facts are relative to the "main" scope)

Some Examples

```
: main : [] : bb4 <= 46 ;
```

A global loop bound: in scope `main` the basic block `bb4` is executed at most 46 times in total

```
: main : [] : bb17 + bb19 <= 412 ;
```

An infeasible path constraint stating that `bb17` and `bb19` can be taken together at most 412 times in total

```
((main,BB1),baz) ((baz,BB7),bar) : bar : [] : bb9 <= 4
```

A bound on `bb9`, in scope `bar`, when `bar` is called from `baz` at `BB7` which in turn is called from `BB1` in `main`

Flow Fact Formats

SWEET can generate Flow Facts in different formats:

- It's own native Flow Fact format (the most expressive format)
- The AIS annotation format for aiT
- The RapiTime annotation format

Allows SWEET to pass Flow Facts to the commercial WCET analysis tools aiT and RapiTime

Input Annotations

Can specify the ranges for variables in different program points

Typically used to constrain values of global variables, or function arguments, at entry

Can declare variables as *volatile* – for them, nothing more can be assumed than being in the specified range

Input annotations really specify the environment in which the program executes

Input Annotation Examples

```
PROG_ENTRY ASSIGN "a" TOP_INT || "b" TOP_INT ;
```

Program variables `a` and `b` can have any (int) value at program entry

```
PROG_ENTRY ASSIGN "a" INT 0 30 || "b" INT 0 100 ;
```

At program entry the value of `a` is in the range $[0 \ldots 30]$ and value of `b` is in the range $[0 \ldots 100]$

```
VOLATILE ASSIGN k INT 66 68 ;
```

The variable `k` is volatile, and will always have its value in the range $[66 \ldots 68]$

ALF

SWEET analyses the language ALF

ALF is an intermediate code format

Designed to represent both high- and low-level code faithfully (C as well as machine code)

Low-level constructs (load, store, arithmetic/logic operations, dynamic jumps) as well high-level constructs (function call/return etc.)

Memory consists of *frames* – memory areas with a name and size. Similar to unlinked code

Translators to ALF from C, PowerPC & NEC V850 binaries (experimental)

An Example

This C code:

```
if(x > y) z = 42;
```

can be translated into the following ALF code:

```
{ switch
  { s_le 32 { load 32 { addr 32 { fref 32 x } { dec_unsigned 32 0 } } }
            { load 32 { addr 32 { fref 32 y } { dec_unsigned 32 0 } } }
  }
  { target { dec_unsigned 1 1 }
  { label 32 { lref 32 exit } { dec_unsigned 32 0 } } }
}
{ store { addr 32 { fref 32 z } { dec_unsigned 32 0 } }
  with { dec_signed 32 42 } }
{ label 32 { lref 32 exit } { dec_unsigned 32 0 } }
```

Abstract Execution

SWEET computes Flow Facts through a kind of symbolic execution – “abstract execution” (AE)

AE executes the program with *abstract states*, representing sets of real (“concrete”) states

Can be seen as a value analysis (abstract interpretation)

Each abstract state transition corresponds to many possible concrete state transitions

SWEET currently uses intervals to represent sets of (numerical) values

Abstract Execution (II)

AE can be seen as a very context-sensitive value analysis (differing between loop iterations)

Contrary to a conventional value analysis, it does not compute an abstract state for each program point: it's more similar to a real execution with a concrete state

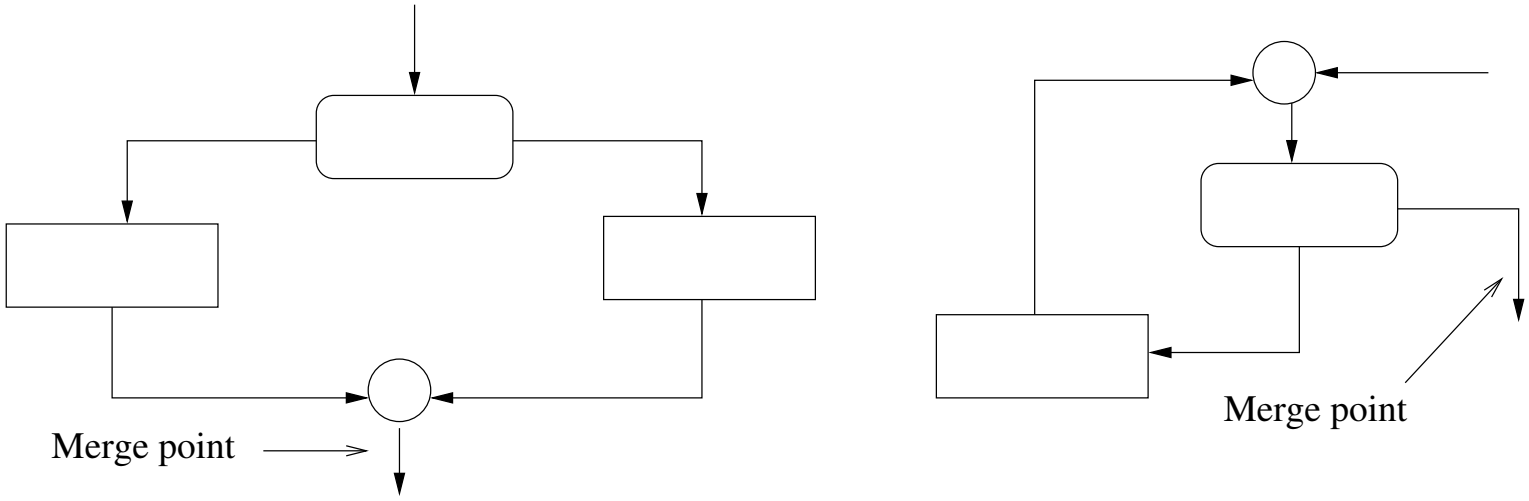
Uses a scheme to successively collect constraints on execution counters during AE of loops

Abstract states can be *split* at conditions. This can result in many states

To counter this, abstract states can be *merged*. *Merge points* can be placed in the CFG. Merging can affect the precision, though

Merging Abstract States

Merge $=$ take least upper bound, $\sqcup$



Common merge points: after join nodes, at loop exit edges

Example

```
i=INPUT; // i=[1..4]
#p=0;
while (i < 10) {
    // point p
    #p=#p + 1;
    ...
    i=i+2;
}
// point q
```

(a) Code example

p	i at p	i at q
1	[1..4]	impossible
2	[3..6]	impossible
3	[5..8]	impossible
4	[7..9]	[10..10]
5	[9..9]	[10..11]
6	impossible	[11..11]

(b) Analysis

min.
#p: 3

max.
#p: 5

(c) Result

(`#p` is the execution counter for program point `p`)

Discussion

Note how we collected information about lower and upper bound of `#p` during the AE of the loop

This scheme can be extended to record a number of more complex flow constraints, including infeasible nodes, infeasible pairs of nodes, and more general infeasible paths

After the AE of the loop, three abstract states reside at `q`

If a merge point is placed at the loop exit, then these states are merged into a single state

BCET/WCET Estimation with SWEET

SWEET has a simple mechanism to estimate BCET and WCET

Each basic block i can be given a constant cost c_i

We add a variable T that stands for time

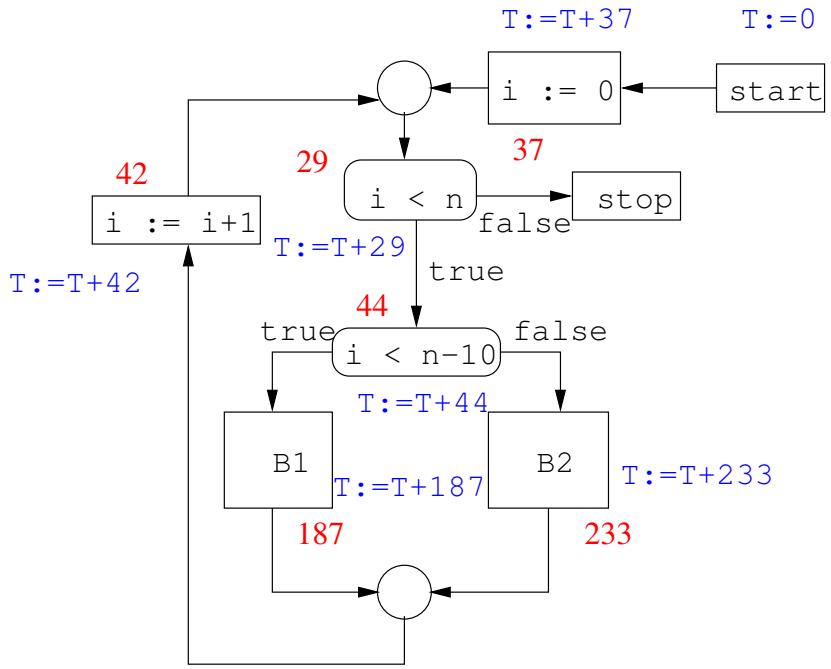
T is incremented with c_i for each executed basic block i

AE now computes an interval for T

The final interval at end yields bounds for BCET and WCET

(Crude estimates, typically neither exact nor safe. But can still be useful to get a grip on what BCET and WCET is)

An Example


T:=T+37
T:=0
i := 0
start
37
29
42
i < n
stop
false
i := i+1
T:=T+29
T:=T+42
true
44
true
false
i < n-10
T:=T+44
B1
B2
T:=T+187
T:=T+233
187
233

Other Analyses

SWEET can also make other analyses, like;

- A conventional value analysis
- data flow analysis (reaching definitions)
- program slicing

So it's also becoming a general program analysis tool

More SWEET Stuff

Extensive online documentation at

`http://www.mrtc.mdh.se/projects/wcet/sweet/`

Includes instructions for how to obtain the tool (it's open source)

Conclusions

A tool for generating Flow Facts

Also: crude BCET/WCET estimation, value analysis, . . .

Can interface with WCET analysis tools that do precise low-level analysis

Things to improve (future work):

- Better handling of failure to bound loops
- More expressive input annotations
- A larger assortment of abstract domains for value analysis
- A lightweight relational domain for AE
- More X-to-ALF translators
- . . .