53. Interprocedural Abstract Interpretation with PAG

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Obligatory Literature

- Alt, Martin, Martin, Florian, Generation of efficient interprocedural analyzers with PAG. In: Mycroft, Alan, Static Analysis. Lecture Notes in Computer Science, 1995. Springer Berlin / Heidelberg
  - http://www.springerlink.com/content/y583778583740462/
- Martin, Florian. PAG – an efficient program analyzer generator. International Journal on Software Tools for Technology Transfer (STTT), Volume 2, Number 1, 46-67, DOI: 10.1007/s100090050017, Special section on program analysis tools
  - http://www.springerlink.com/content/1pb55yv4mq4emywl/
- Auch Technischer Bericht der U Saarbrücken:
  - http://scidok.sulb.uni-saarland.de/volltexte/2004/203/

Ressources

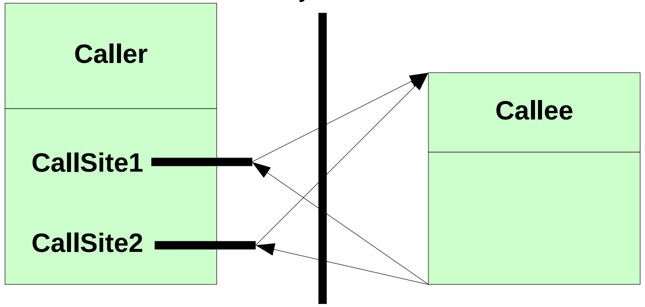
- F. Martin. PAG - an efficient program analyser generator. Software Tools for Technology Transfer STTT 1998, 2:46-67, Springer
- www.absint.de (also aiSee)
- www.cs.uni-sb.de/~ martin/pag
- F. Martin Generating Program Analyzers. PhD Thesis. Universität Saarbrücken.
- Martin Trapp. Optimierung Objekt-Orientierter Programme. Springer Verlag, Heidelberg, January 2001.
- Ole Agesen, Jens Palsberg, and Michael I. Schwartzbach. Type inference of SELF. In Oscar Nierstrasz, editor, ECOOP'93-Object-Oriented Programming, 7th European Conference, volume 707 of Lecture Notes in Computer Science, pages 247-267, Kaiserslautern, Germany, 26-30 July 1993. Springer.

53.1 Different Approaches to Interprocedural Analysis

- Abstract interpreters can treat procedure calls in different ways, from ignoring and summarizing them, to expanding them or lazily exanding them.

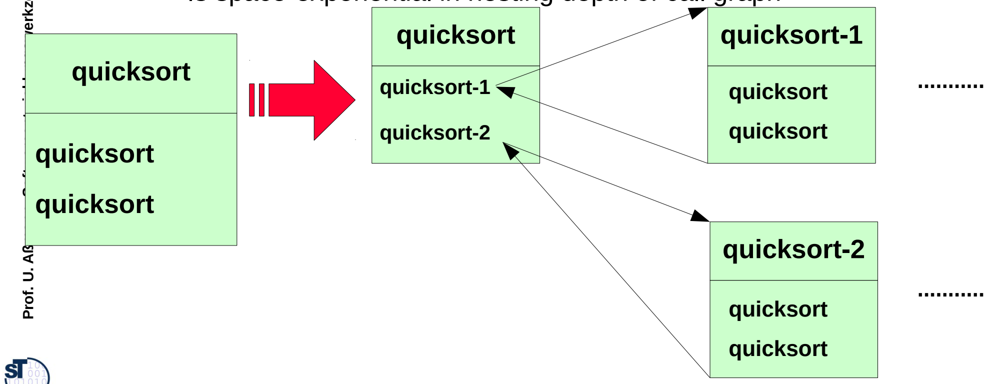
Invalidating Approach to Abstract Interpretation (Worst-Case Assumption)

- During the abstract interpretation, all information is invalidated by a call
  - After the call, worst case value is assumed (top of lattice)
  - Every procedure is analyzed in isolation
- Simple strategy: be conservative (and know nothing about calls)
  - too pessimistic, resulting in imprecise information
- Improvement:
  - Invalidate everything that might be written by the callee
  - However then alias analysis must run before



The Cloning/Inlining Approach to Abstract Interpretation

- **Inlining abstract interpretation (interprocedural analysis)** copies a procedure's body for every call and propagate information separately in body (builds up a interprocedural control flow graph, ICFG)
- Corresponds to *inlining* into every callee
- Leads to bloat of code and analysis information
  - Is space-exponential in nesting depth of call graph



The Functional Approach to Abstract Interpretation (Effect Approach)

- Also called *effect calculation approach*
- **Functional interprocedural analysis** calculates a function/effect E_f for every procedure f
  - Which is applied to the current input values at a caller to receive the output values after the call
  - Parametric execution with an "abstract" function E_f
- E_f is stored in an **function effect table**, mapping abstract input value to abstract output value (i.e., an associative array of abstract values)
- Whenever the analysis reaches the callee, the current abstract input value is looked up
  - If found, reuse output value
  - Otherwise reanalyze body

The k-Call Context Approach to Abstract Interpretation

- The **k-contextual interprocedural analysis** maintains the calling context with a limited stack of depth k
  - Also called *k-call string approach*
  - The call history of the called procedure is incorporated in the underlying lattice D (*call strings*)
- Different bodies at different call sites are distinguished by the call strings
  - In case of k=1 all call sites are distinguished
  - K=2 all call sites, with calling context of callers
  - K=3: all call sites, all calling contexts of the grandfathers
  - ...

Expanded Supergraphs

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- The analysis information (the abstract values) is replicated for every caller
- Procedures are not inlined, but parameter information is replicated
- Call and Return connectors connect the right incarnation of the value to a caller site

- Efficient representation of interprocedural analysis information

The Lazy Cloning Approach to Abstract Interpretation

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- [Agesen: Type inference for SELF]
- Idea: do a *lazy cloning (on-demand replication)* of the parameter values
- During propagation, store all input values of functions analyzed so far
- If an input value for a function differs from an already memoized one, clone the parameter (i.e., distinguish it)
- Cloning parameters only
- Cloning them on demand
- Cloning can be restricted
  - Analysis works less precise but costs less memory

The Interprocedural Phi-Approach to Abstract Interpretation

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- M. Trapp (Optimization of object oriented programs) introduces interprocedural phi functions (i-phi)
- i-phis are "small-ifs" or "ifs for one value"
- Every formal parameter of a procedure gets as input an i-phi
- The i-phi depends on the control flow condition

53.2 Interprocedural Analysis with PAG

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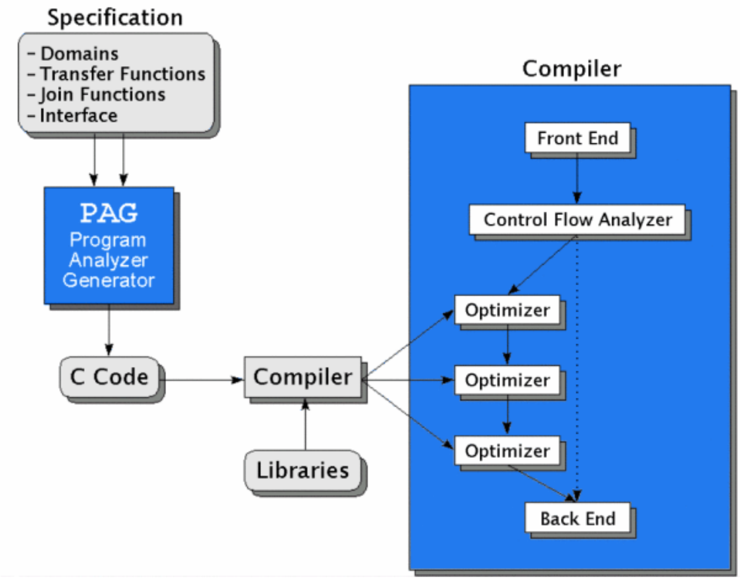
PAG

- Intra- and interprocedural analysis
- Extended super graph for interprocedural case (cloning of parameter information for call sites)
- Special Languages for:
  - DDL for the specification of the intermediate program representation
  - DDL for the Lattice (abstract domains)
  - Functional language for the abstract interpreter (abstract/flow/transfer functions)

Generated Analyzer in Compiler



Node Orderings for Visits during Abstract Interpretation

- During the interprocedural abstract interpretation, instruction nodes are ordered in the worklist.
- Different orderings are possible, for which PAG can generate implementations:
- DFS: depth-first
- BFS: breadth-first
- SCC-D: strongly connected components in visit order depth first.
- SCC-B: same in breadth first
- WTO-D: SCCs, but ordered in weak topological ordering of Bourdoncle. Depth-first.
- WTO-B: same, but breadth-first

PAG-DDL: Data Type Specifications

- Basic sets
  - Snum (signed numbers), unum, real, chr, string
- Basic Lattices
  - Lsnum (lattice of signed numbers), lunum, bool, a..b, enum
- Type constructors for lattices
  - Disjoint sum
  - Tuple construction *
  - Powerset operator
  - List operator
  - Function on S1 -> S2

PAG-DDL: Lattice Specifications

- Lattice operators
  - flat: Set S → Lattice
  - lift(Lattice L)
  - powerset: Set → Lattice
  - dual(Lattice L)
  - reduce(Lattice E, reduction function f)
- Tuple space
- Function space (function lattice) S->L, pointwise ordering

Example: PAG-DDL for Live Variables Analysis


```
// a simple powerset lattice for signed numbers
GLOBAL
  maxvar: snum
SET
   vars = [0..maxvar]
LATTICE
   varset = set(vars)
   var = lift(varset)
```


Example: PAG-DDL for Caches


```
GLOBAL
   storeMin: unum
   storeMax: unum
   cacheSize: unum
   aWays: unum<24
SET
  storeLine = [storeMin..storeMax]
  direct= [0..cacheSize]
LATTICE
  cacheLine=[0..aWays]
  age = lift(cacheLine)
  assoc = storeLine -> age
  cache = direct -> assoc
  dfi = cache * cache
```


Example PAG-DDL for Intervals as Abstract Domain


```
LATTICE
  upperBound = lsnum
  lowerBound = dual(lsnum)
  interv = lowerBound *upperBound
  env = snum -> interv     // variables to intervals
  dom = lift(env)
```

Example PAG-DDL for Heap Analysis


```
LATTICE
  node = set(snum)                    // nodes abstract vars
  edge = node * snum * node
  edges = set(edge)
  sedge = snum * node
  sedges = set(sedge)
  shared = set(node)                  // predicate
  graph = sedges * edges * shared
  dfi = lift(graph)
```


PAG-DDL: Specification of Program Representation (Metamodel of the Language)

- Types of the nodes of the CFG can be specified.
  - Constructor based
  - With alternatives
- In general, other DDLs can be employed (e.g., UML)

```
SYNTAX
  START: Unlabstat
Unlabstat: M_Assign(var:Var, exp:Exp)
              | M_While(exp:Exp, body:Stat*)
              ...
```


Specification of Abstract Interpretation Functions

- Similar to function specification in ML
- Pattern matching on IR nodes
- Functions are annotated to control flow graph nodes
  - Implicit paramater @ for data flow value
  - Return a value
- Dynamic Functions (updatable)
  - Application f({!x!})
  - Updating of values f\[n->v]
  - Constant function [->v]

Specification of Abstract Interpretation Functions

- Lattices provide combine functions (merge, joins) for abstract values, when control flow joins
  - least-upper bound lub
  - greatest-lower bound glb
  - comparison relation <, >
- Operations for latted and lifted lattices
  - drop, lift
- ZF Zermelo-Fränkel Set Expressions:
- [x !! x<-- set, if x >= 0]

Example: Analysis of a While Loop

```
// Source code expression:
// while(id <=exp)
// 1) pattern matching of the expression
M_While(M_Binop(M_op_leq(),
                M_Var_exp(M_simpl_var(id)),
                exp),_)
        ,true_edge):
// 2) the abstract interpretation function
let f <= @; // assignment of f to implicit data flow
 value
   id = val-Identifier(id);
in
  let erg = f{!id!} glb (top,(eval(exp,f))!2);
  in if is_ok(erg) then lift(f\[id->erg])=
      else bot;
      endif;
```


Other Parts of the Specification

- Direction specification: forward/backward
- Carrier graph: control-flow graph
- Init value: default initialization of values
- Init_start: init value of start node
- Equal: equality test for fixpoint detection
- Widening function
- Narrowing function

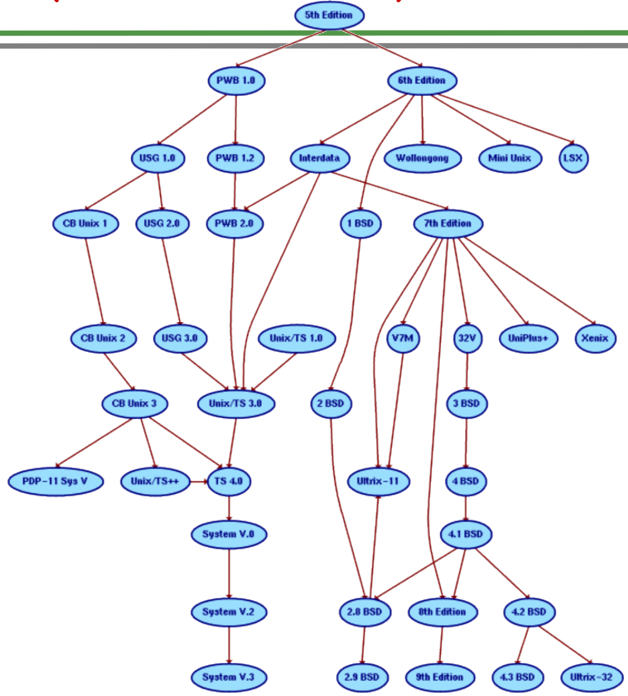
Example

```
PROBLEM interval
  direction: forward
  carrier: dom
  init_start: lift([->(dual(0),0)])
  widining: wide
  narrowing: narrow
```


Debugging Specifications

- Export to VCG file format (or aiSee)
- Many visualizations possible
- Specific ones for flow graphs
  - Lattice values annotated without edges to the nodes or edges of the flow graph
  - Zoom in/out
  - Hiding relations
  - Blocks of nodes as regions with different color

AiSee (Successor to VCG)



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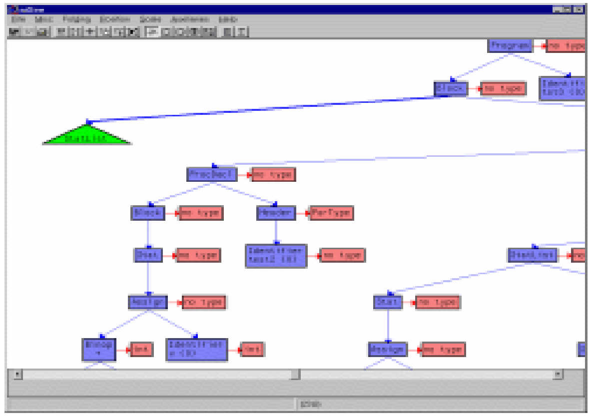

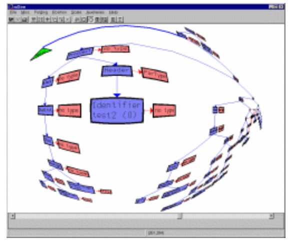

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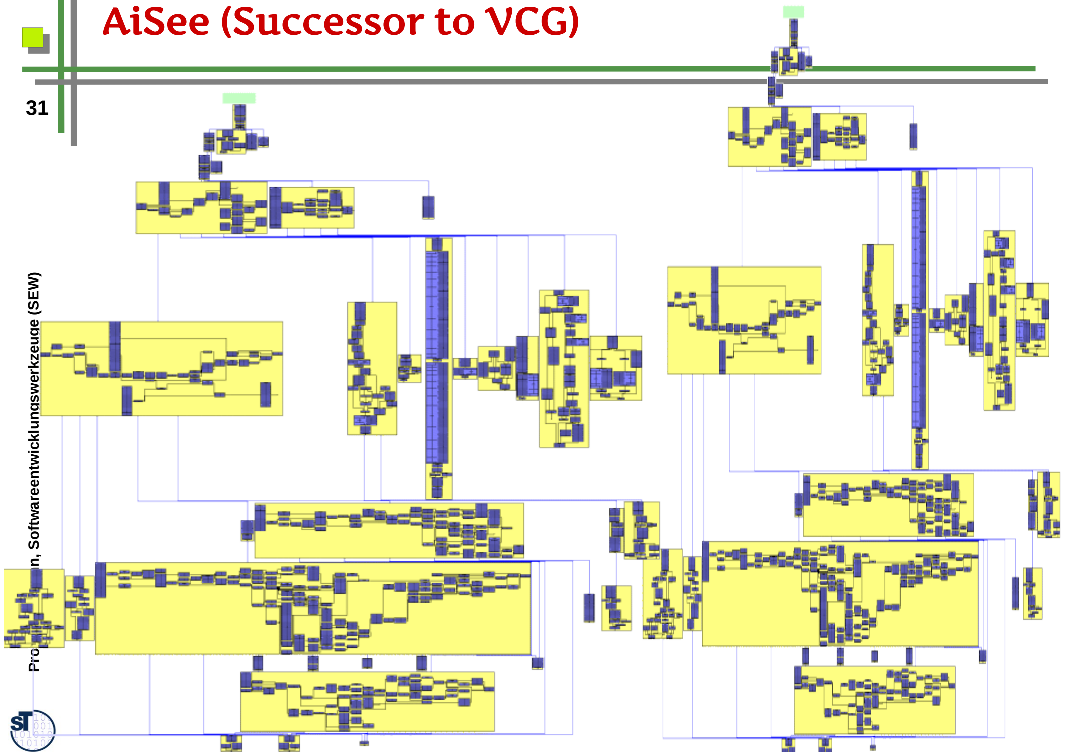

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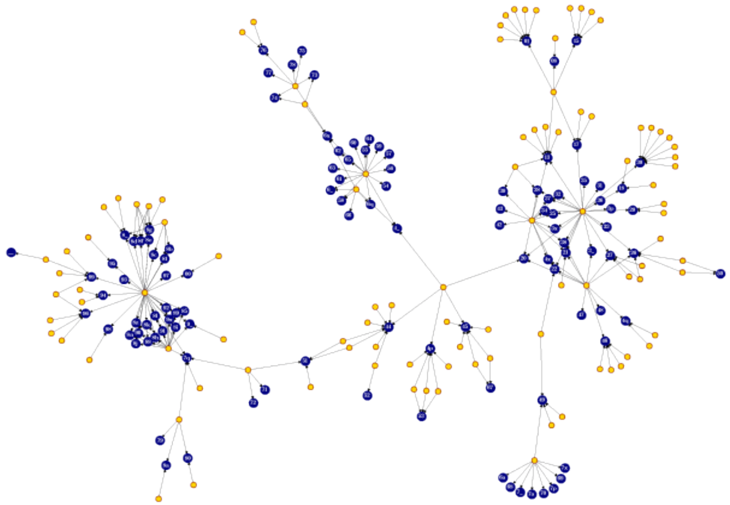

What have we learned?

- Interprocedural analysis can be done in several ways, spending different amount of resources, trading precision
- PAG is a tool to generate interprocedural analyzers
  - offering a specification language for lattices of abstract values
  - industrial strength
  - useful to specify many analyses, such as
    - classical data-flow analysis
    - cache analysis
    - heap analysis
    - alias analysis

The End