Input-Centric Program Behavior Analysis & Optimizations

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What is the common, fundamental prerequisite for program optimizations?

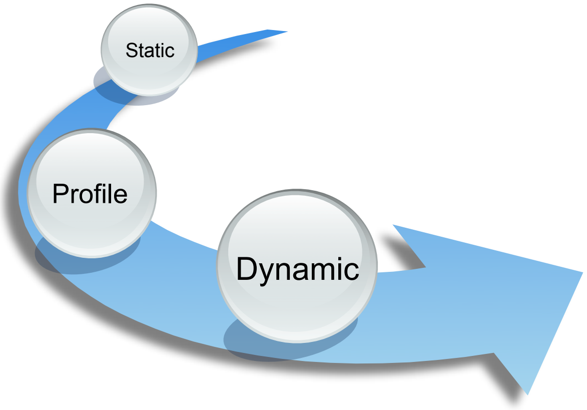
Prediction of how the program would behave.

Program Behaviors

(calling freq, locality, loop tripcount, ...)

Program Behavior Analysis

- Goal is to uncover patterns for prediction
- Current approaches



Our Goal

A new paradigm:

input-centric program behavior analysis.

Include program inputs into the focus.

Outline

- Why input-centric?
- How to exploit inputs for program optimizations?

What are inputs?

- All the data that are not generated but accessed by the program
  - command arguments
  - input files
  - ... ...

Why input-centric?

Strong and predictive correlations between inputs and behaviors.

Better behavior analysis.

Better prediction.

Better optimizations.

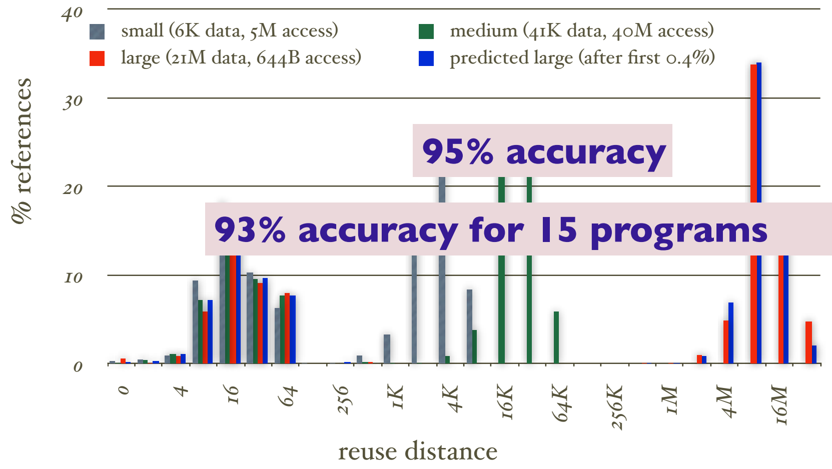
Qualitative View

Prog Beh = Code + Inputs + Running Environments

Input is the only deciding factor for a given program in a given environment.

Quantitative Evidence

- Reuse distance histograms of *lucas* [Zhong+:TOPLAS'09]



95% accuracy

93% accuracy for 15 programs

Quantitative Evidence (cont.)

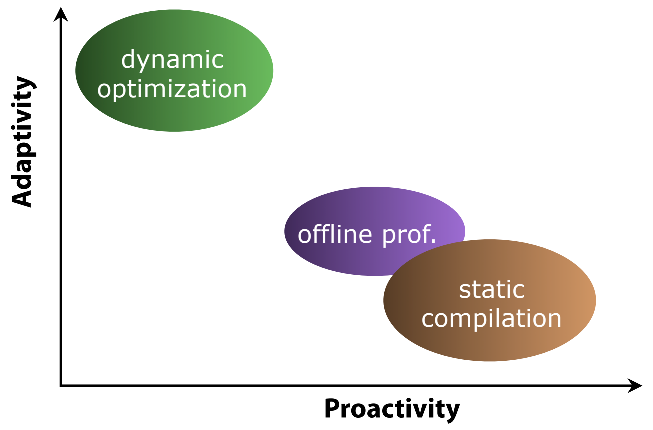
- JIT optimization levels [Mao+:CGO'09]
- Profitability of speculation [Jiang+:ICPADS'09]
- Minimum required heap size [Mao+:VEE'09]
- Optimization parameters for GPU [Liu+:IPDPS'09]
- Cache contention on CMP [Jiang+:EuroPar'08]

Current Treatments to Inputs

- Static compilation: code only.
- Offline profiling: not adapt to input changes.
- Runtime sampling: no explicit treatment to inputs, hence loses proactivity in prediction and optimizations.

predicting behaviors before or early in a run.

Adaptivity-Proactivity Dilemma

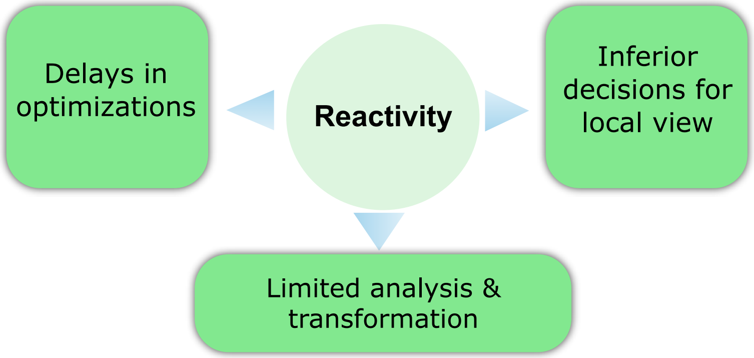


dynamic optimization

offline prof.

static compilation

Drawbacks of Reactivity


Delays in optimizations
Reactivity
Inferior decisions for local view
Limited analysis & transformation

Potential

21%

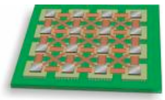
JVM [CGO'09]

50%

Parallelization [ICPADS'09]

12%

GC[VEE'09]


14%

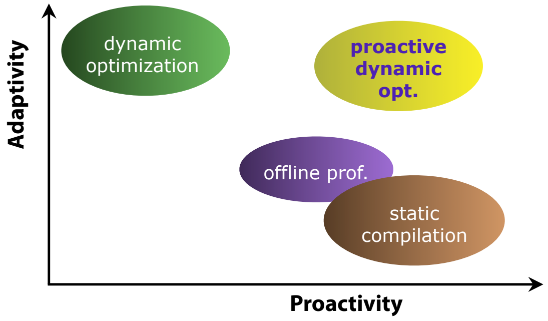
CMP Sched. [PACT'08]

2.8X

GPU [IPDPS'09]

Opportunities from Inputs

- Inputs come early
- Strong predictive input-behavior correlations lead to proactive prediction.
- The prediction is meanwhile cross-input adaptive.

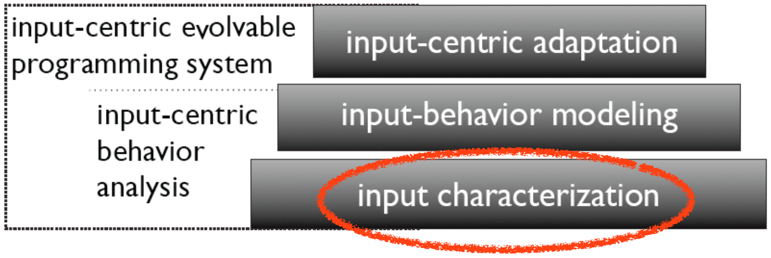


Outline

- Why inputs?

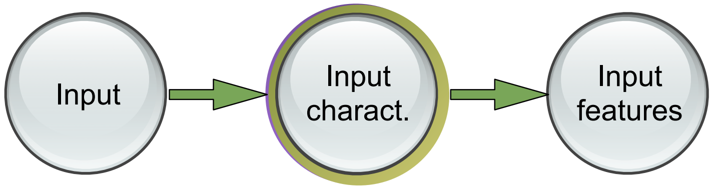
- How to exploit inputs for program optimizations?

Overview


input-centric evolvable programming system
input-centric behavior analysis
input-centric adaptation
input-behavior modeling
input characterization

Input Characterization

To extract important features from raw inputs



Challenges

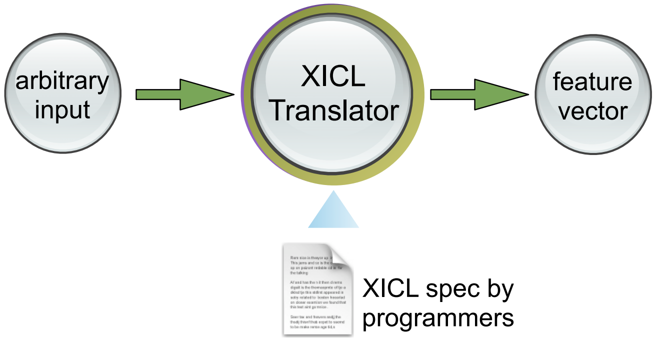
- Input attributes rather than values matter
  - e.g., data distribution
- Complex input syntax & semantics
  - e.g., a graph or a tree or a signal
- Interplay among input components
  - overshadow, equivalence, default values, etc.

Domain knowledge needed;
automatic solutions are difficult.

Specification-Based Solution

[CGO'09]

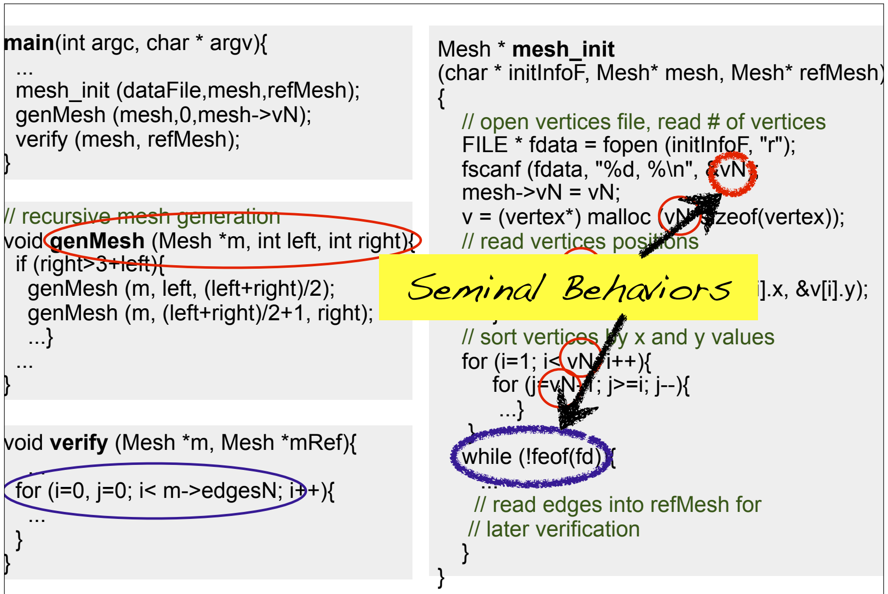
- e**X**tensible **I**nput **C**haracterization **L**anguage



Automatic Solution

Seminal-Behavior Analysis

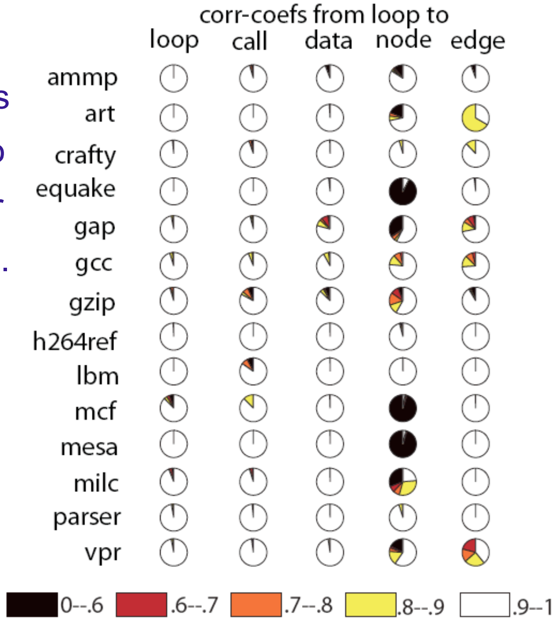
- Key observation: correlations in a program.



```
main(int argc, char * argv){
  ...
  mesh_init (dataFile,mesh,refMesh);
  genMesh (mesh,0,mesh->vN);
  verify (mesh, refMesh);
}

// recursive mesh generation
void genMesh (Mesh *m, int left, int right){
  if (right>3+left){
    genMesh (m, left, (left+right)/2);
    genMesh (m, (left+right)/2+1, right);
    ...}
  ...
}

void verify (Mesh *m, Mesh *mRef){
  ...
  for (i=0, j=0; i< m->edgesN; i++){
    ...
  }
}
```

```
Mesh * mesh_init
(char * initInfoF, Mesh* mesh, Mesh* refMesh)
{
   // open vertices file, read # of vertices
   FILE * fdata = fopen (initInfoF, "r");
   fscanf (fdata, "%d, %\n", &vN);
   mesh->vN = vN;
   v = (vertex*) malloc (vN*sizeof(vertex));
   // read vertices positions
                              ].x, &v[i].y);

   // sort vertices by x and y values
   for (i=1; i< vN; i++){
       for (j=vN-1; j>=i; j--){
         ...}
   }
  while (!feof(fd)){
     ...
    // read edges into refMesh for
   // later verification
  }
}
```

Strong correlations exist from loops to loops and to other types of behaviors.



Intuition

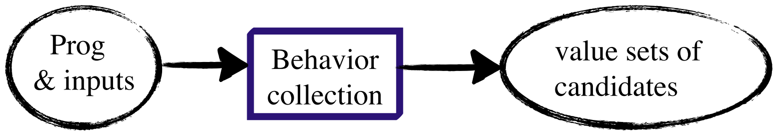
Prog Beh = Code + Inputs + Running Environments

Input is the only deciding factor for a given program in a given environment.

Seminal Behaviors

- Definition (informal)
  - Behaviors that can lead to accurate prediction of all behaviors of interest, and appear early in a run.
- Reflection of critical program input features.
- Implication
  - Enable proactive & adaptive optimizations.
  - Remove the needs for explicit input characterizations.

Recognition of Sem Beh


Prog & inputs

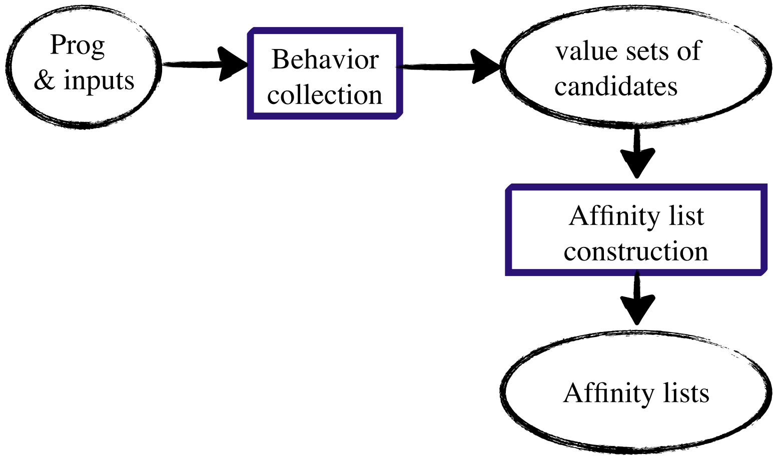
Behavior collection

value sets of candidates

Candidate Seminal Behaviors

- Loop trip-counts
- Interface behaviors
  - values directly obtained from program inputs.
  - ignore massive file content
    - include corresponding loop trip-counts

Recognition of Sem Beh


Prog & inputs

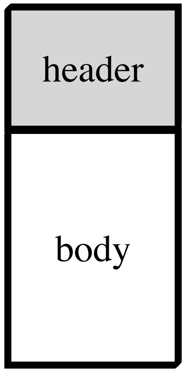
Behavior collection

value sets of candidates

Affinity list construction

Affinity lists

Behavior Affinity List



Header can predict body accurately.

Affinity List of *mcf*

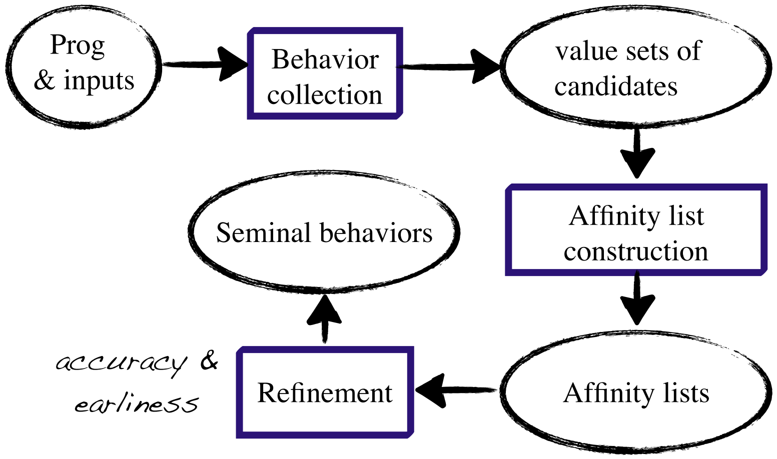
list 0	list 1	list 2	list 3		list 9	list 10
Interface: filesize net.m flow_cost new_arcs net.n_trips net.iterations i	LoopID8	LoopID17	LoopID66	. . .	LoopID14	LoopID9
LoopID1 LoopID3 LoopID20 LoopID11 .... LoopID13 LoopID38 LoopID16	LoopID2 LoopID5 LoopID12 .... LoopID23 LoopID37 LoopID15	LoopID62 .... LoopID43 LoopID31 LoopID25	LoopID32 .... LoopID63			

- Incremental construction
  - start with interface behaviors
  - iteratively find headers from the rest based on their predictive capability.

Predictive Capability

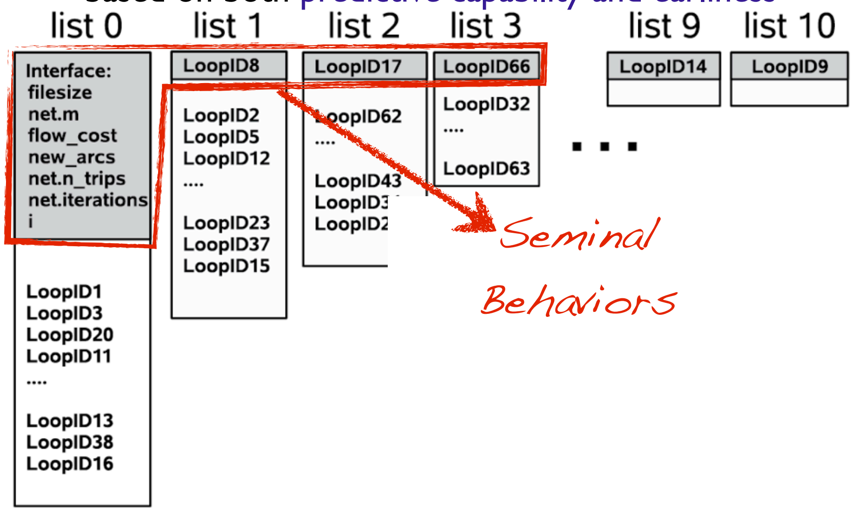
- Regression models
  - LMS (Least Mean Square)
  - Regression Trees
- 10-fold cross-validation

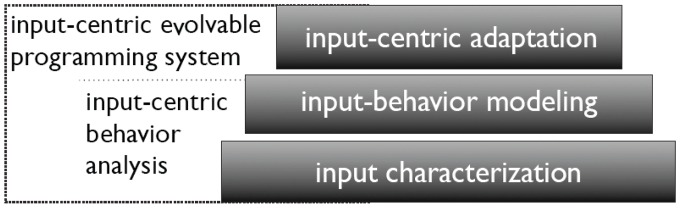
Recognition of Sem Beh



Refinement

based on both predictive capability and earliness

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Modeling and Adaptation

- Modeling --- construct predictive models

  Target Behaviors = f (Seminal Behaviors)

  - Machine learning problem
  - Classification (e.g., for optimization levels)
  - Regression (e.g., for calling frequencies)
- Adaptation
  - Runtime version selection
  - JIT
  - Dynamic speculation
  - ... ...

Evaluation

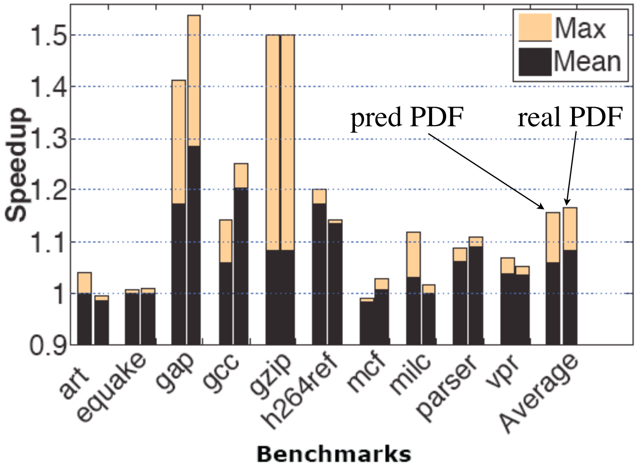
- Predictive capability of seminal behaviors
- Potential for program optimizations

Prog	interface values						earliness ≥ 90%					
	num	accuracy					num	accuracy				
		loop	call	edge	node	data		loop	call	edge	node	data
ammp	1	99.5	96.7	100	91.1	99.7	1	99.5	96.7	100	91.1	99.7
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
gap	2	97.5	44.9	11.9	44.2	76.6	7	99.5	78.7	56.3	69.7	88.5
gcc	4	82.9	38.9	56.2	61.0	78.5	54	97.0	86.1	93.6	95.4	95.6
gzip	3	92.2	87.0	84.1	67.5	94.5	6	91.6	87.6	83.5	69.0	94.5
h264ref	3	99.8	99.8	98.7	98.8	99.8	4	99.8	99.7	97.0	97.8	99.7
lbm	3	99.8	90.1	100	100	100	3	99.8	90.1	100	100	100
mcf	5	87.3	87.7	100	92.2	97.8	10	92.2	91.0	100	89.5	97.5
mesa	1	100	100	99.5	12.2	100	1	100	100	99.5	12.2	100
milc	2	79.2	72.1	37.1	27.4	93.9	18	83.0	72.8	100	52.0	99.7
parser	1	90.2	85.4	73.8	75.9	87.6	2	91.8	88.0	79.2	78.0	90.8
vpr	3	93.3	95.1	60.4	81.9	94.6	9	95.2	95.5	64.0	82.2	95.8
Average	2.4	92.9	82.4	79.3	69.0	92.5	8.7	95.0	89.0	90.3	75.5	95.5

100+ options, 130 files, 484930 lines of code, 7615 loops

Speedup by PDF Compilation on Pred & Real Profiles

(IBM Power5 with XL v11.1)



Conclusions

- Inputs strongly correlate with program behaviors and are beneficial to exploit.
- Input-centric behavior analysis is a promising solution.

Acknowledgment

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  - Yunlian Jiang, Eddy Z Zhang, Kai Tian, Yixun Liu, Feng Mao, Malcom Geathers
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Thanks!
Questions?