Exploiting Statistical Correlations for Proactive Prediction of Program Behaviors

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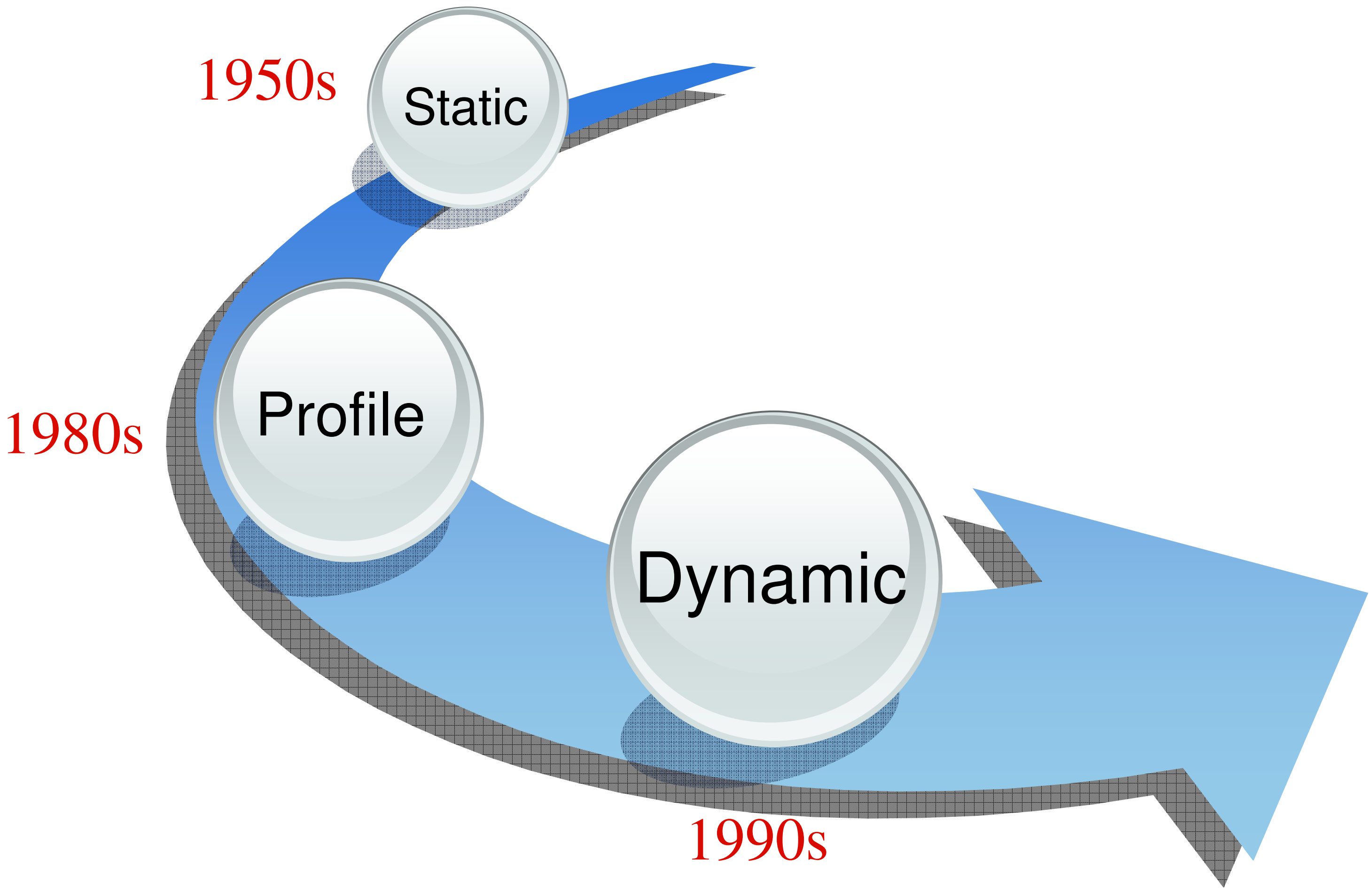
Program Optimizations



Prerequisite for Optimizations

Accurate prediction of <u>how programs would behave</u>.

Program Behaviors

↓

(procedure calling freq,
locality, loop trip counts...)

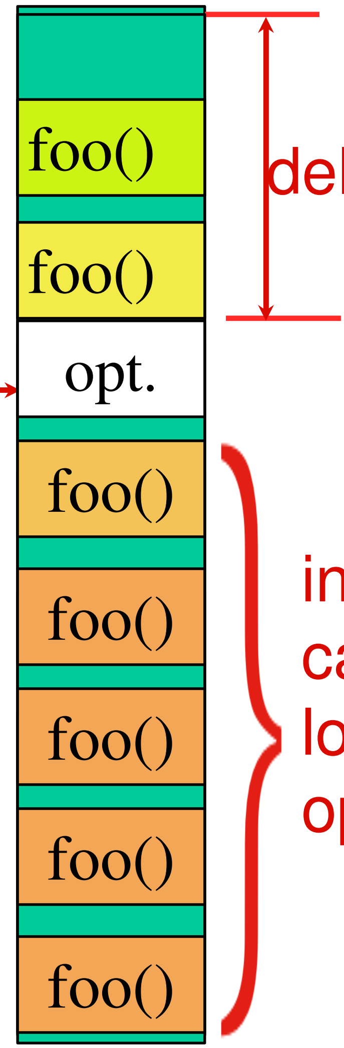
Program Behavior Predictions

Property / Opt	Accuracy	Scope	Timing (Proactivity)
Static Compilation	↗	↗	↗
Profile Feedback	↗	↗	↗
Runtime Adaptive Optimization	↗	↗	↗

Importance of Proactivity

```
while (...){
   foo ();
}
```

overhead



delay

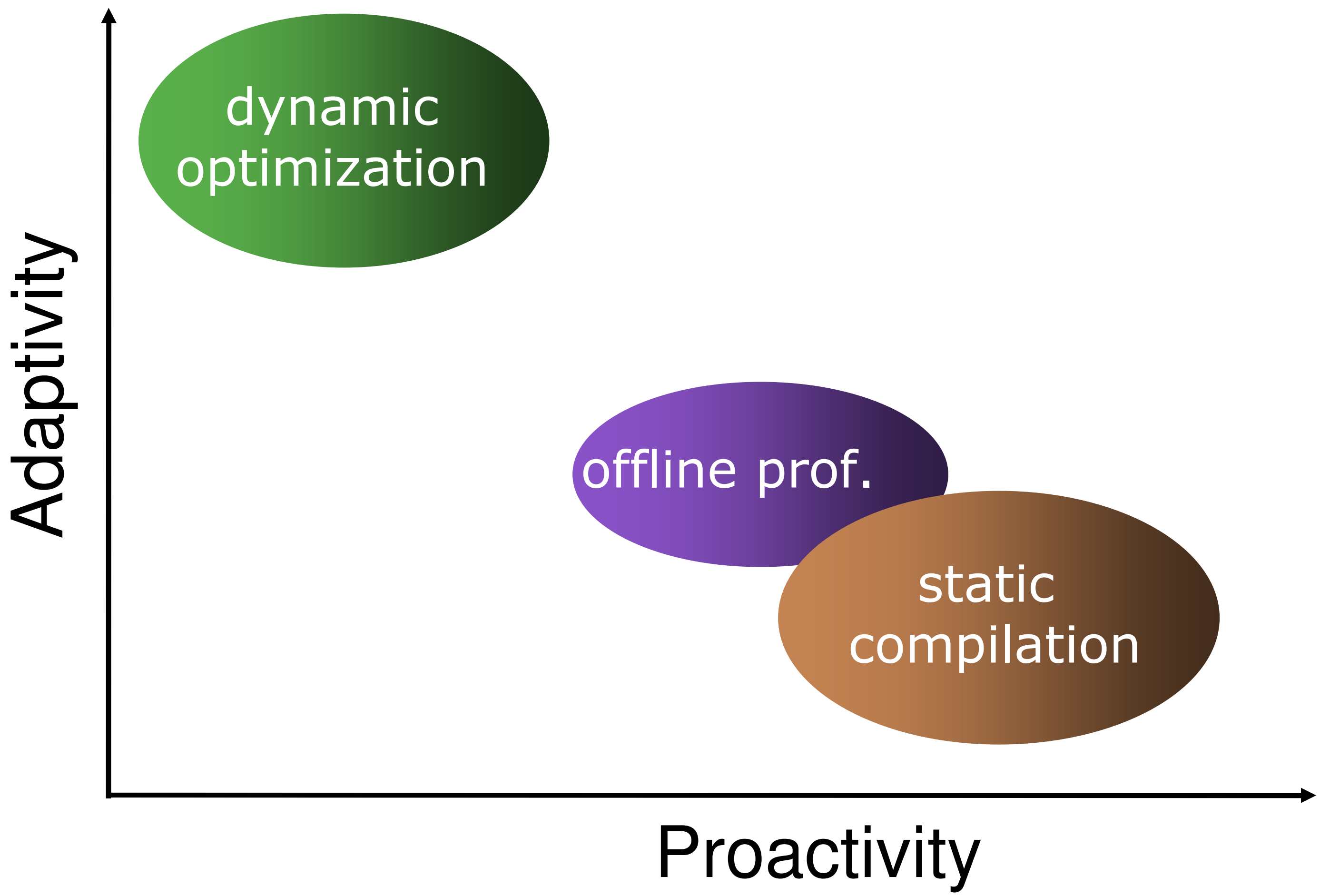
Reactive approach

inferior performance caused by local view-based optimizations

47% on J9 [Arnold+' 05]

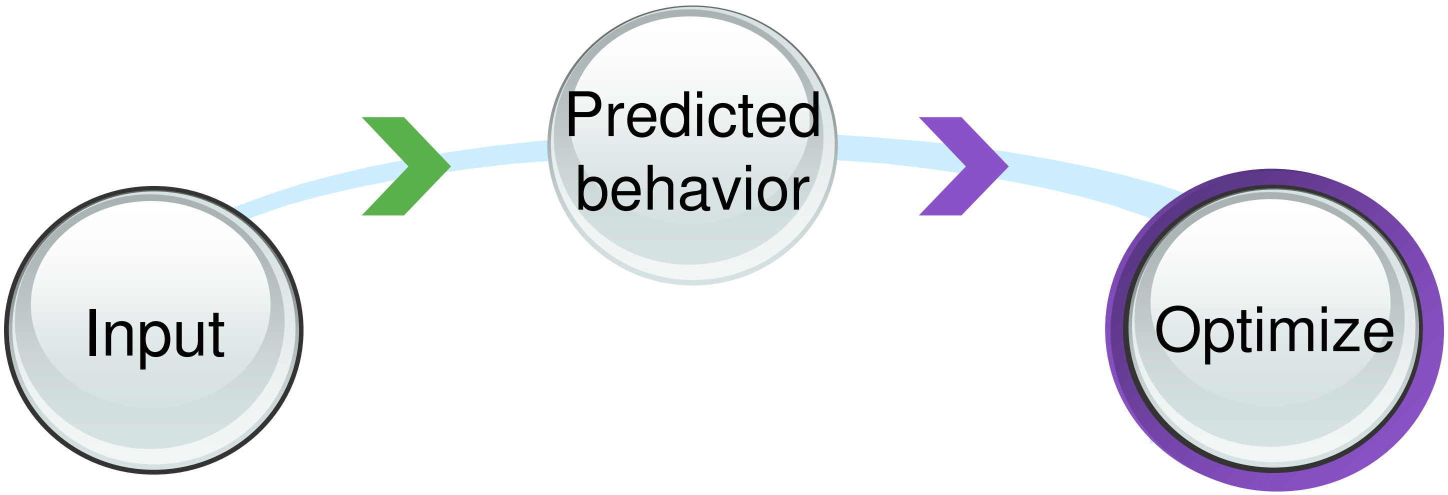
21% on JikesRVM [Mao+' 09]

Adaptivity-Proactivity Dilemma



Prior Solution: Input-Based Prediction

[Mao+:CGO'09]



Idea: Predicting behavior from inputs as program starts

Problem: Requiring manual characterization of inputs

Our Solution

Exploit correlations among program components for proactive runtime prediction and optimization

```
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
                                    [i].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
    }
}
```

Seminal Behaviors

Questions to Answer

- Do such correlations exist commonly?
- How can they be automatically identified?
- Are they useful for program optimizations?

Outline

- A systematic measurement of correlations
- A framework for identification and modeling
- A demonstration of uses for optimizations
- Related work and conclusion

Behaviors under Study

- Loop trip-counts (by a modified GCC)
- Procedure calling frequencies (by GNU gpof v2.19)
- Block access freq. (data profiles) (by IBM XL C 10.1)
- Edge profiles and node profiles (by IBM XL C 10.1)

Correlations to Measure

- Among same types of behaviors of different components
  - E.g. trip-counts of two loops
- Among different types of behaviors of different components
  - E.g. trip-counts *vs* procedure calling freq.

Benchmarks [spec 2000 & 2006]

Program				Factor of changes
name	lines	inputs	loops	caused by inputs
ammp	13263	20	425	9.9×10^1
art	1270	108	101	4.0×10^4
crafty	19478	14	425	4.6×10^8
equake	1513	100	106	1.0×10^2
gap	59482	12	1887	1.1×10^8
gcc	484930	72	7615	1.1×10^6
gzip	7760	100	223	4.3×10^7
h264ref	46152	20	2074	2.1×10^9
lbm	875	120	27	6.0×10^6
mcf	1909	64	76	1.4×10^5
mesa	50230	20	995	2.0×10^1
milc	12837	10	473	2.1×10^9
parser	10924	20	1350	2.1×10^6
vpr	16976	20	435	3.9×10^6

[Thanks to Amaral's group for extra inputs]

Calculation of Correlations

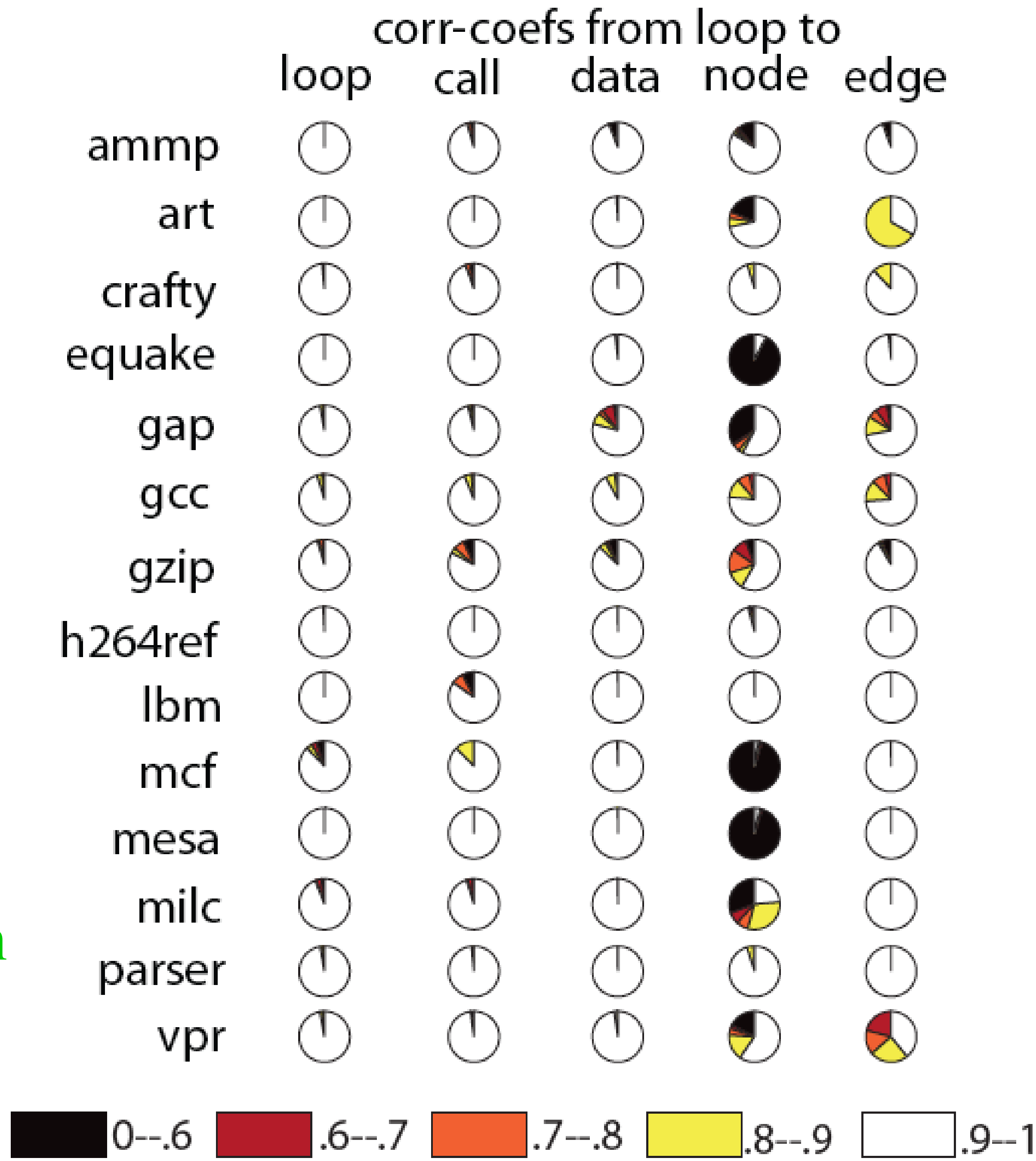
$$r_{XY} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_X s_Y}$$

Sample standard deviation

The higher r is, the easier to predict one from the other.

Strong correlations from loops to loops and to other behaviors

Uses for runtime behavior prediction



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Two Goals

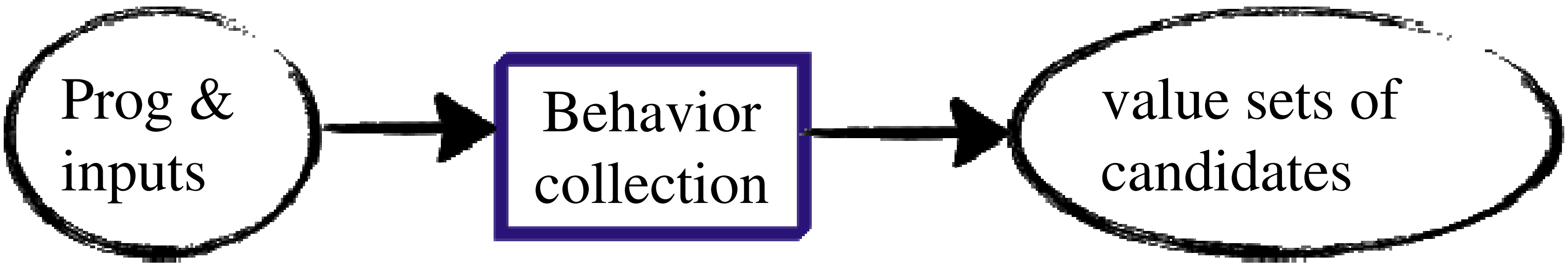
- Identify Seminal Behaviors
- Build predictive models

Target behavior value = f (values of seminal behaviors)

Seminal Behaviors

- A small set of program behaviors
  - Predictive capability
    - Strongly correlate with target behaviors
  - Earliness
    - Values become known early in an execution

Identification of Sem Beh

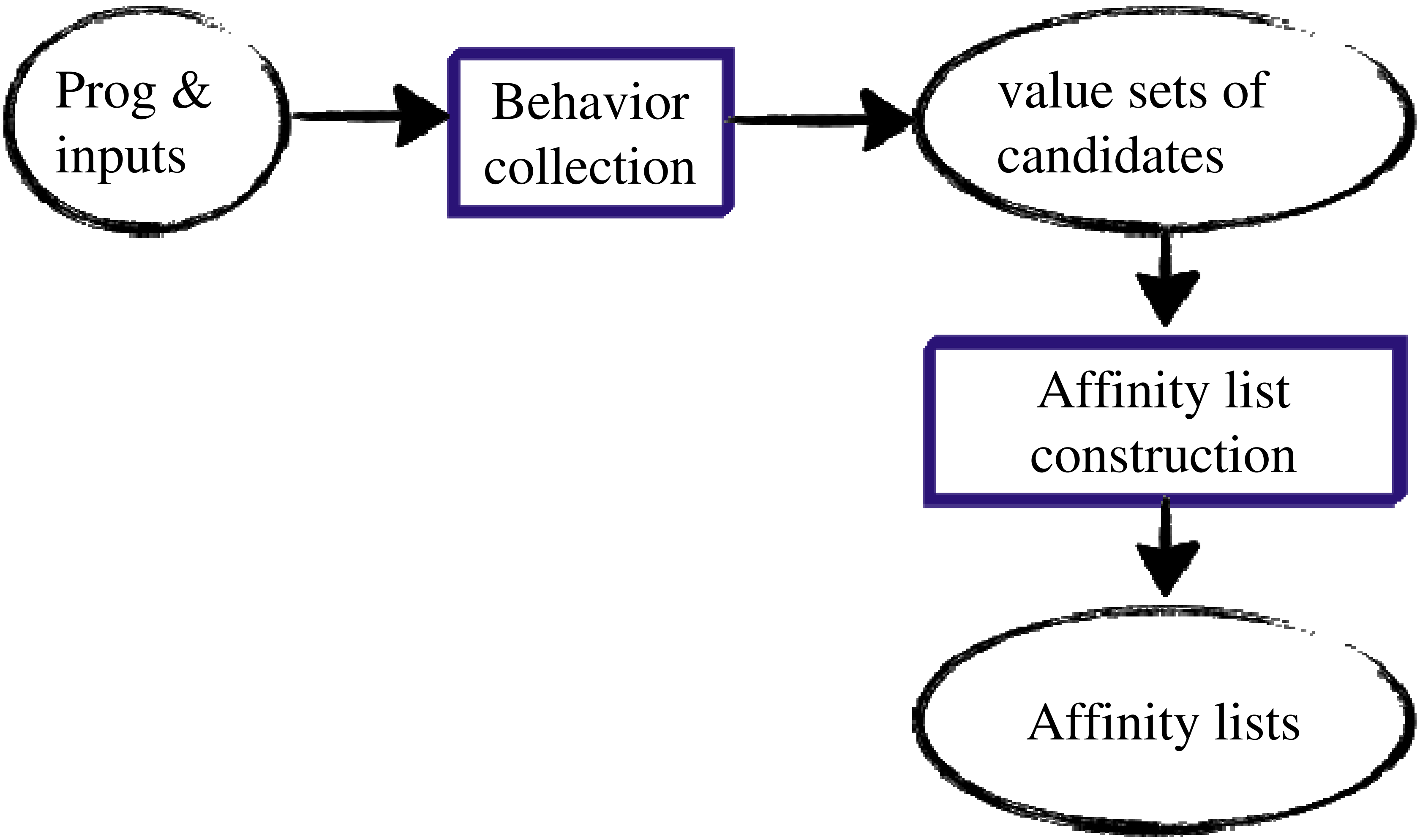


Candidate Seminal Behaviors

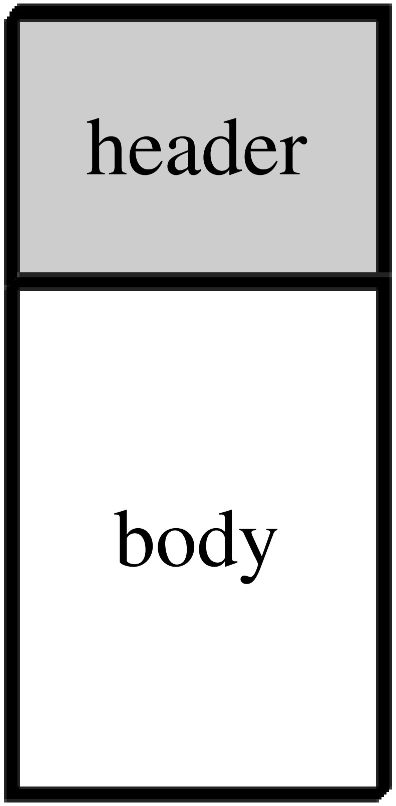
- Interface behaviors
  - Values directly obtained from program inputs
  - Ignore massive file content
    - Include corresponding loop trip-counts

- Loop trip-counts
  - Importance in programs and strong correlations with other behaviors

Recognition of Sem Beh

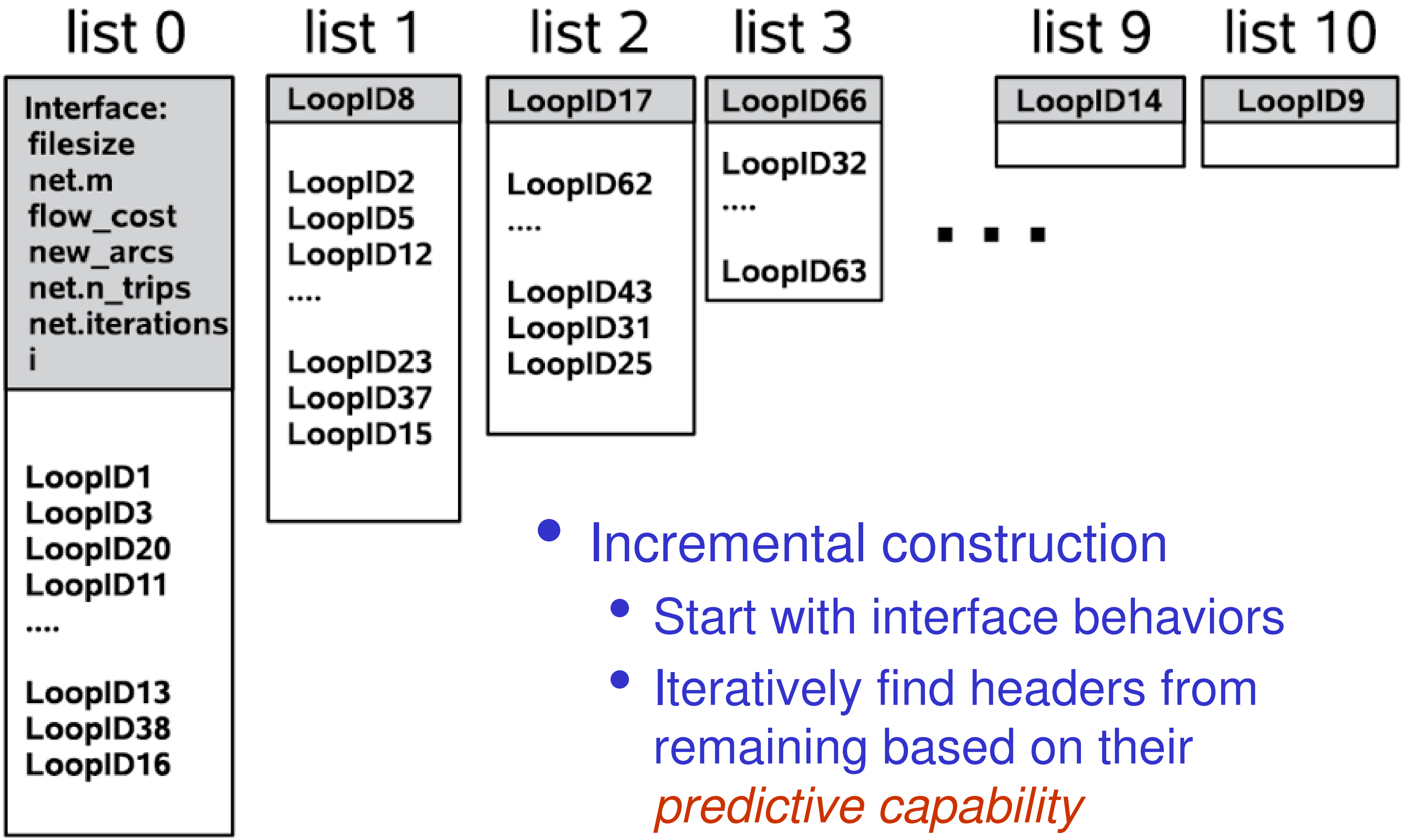


Behavior Affinity List



Header can predict body accurately.

Affinity List of *mcf*

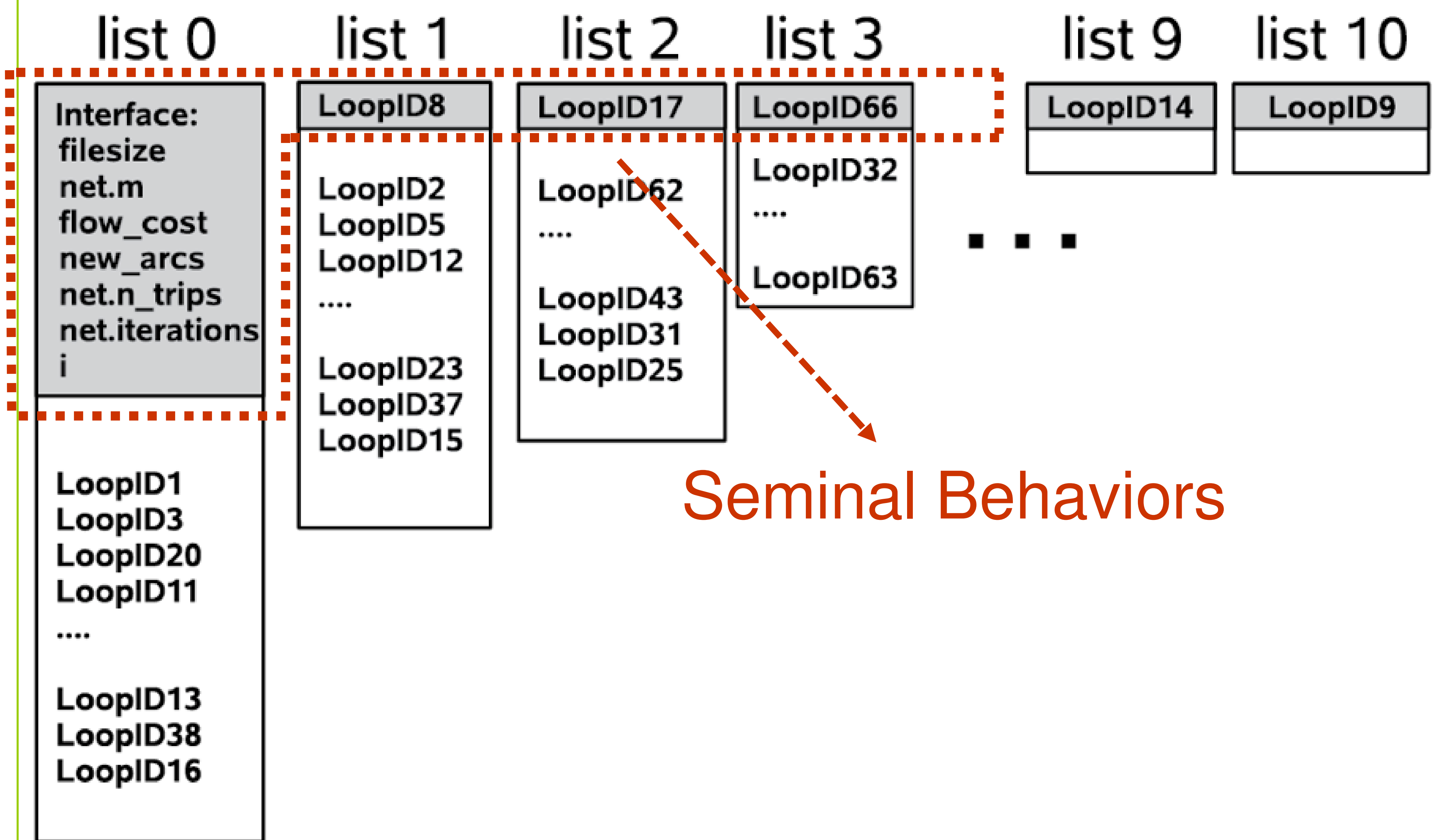


- Incremental construction
  - Start with interface behaviors
  - Iteratively find headers from remaining based on their *predictive capability*

Predictive Capability

- Predictive models
  - LMS (Least Mean Square)
  - Regression Trees
- Compute predictive capability
  - 10-fold cross-validation

Refine by *predictive capability* & *earliness*



Seminal Behavior Based Predict

Num of seminal behaviors and prediction accuracy

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
art	4	91.0	96.8	100	82.0	96.8	4	91.1	96.8	100	80.0	96.1
crafty	1	89.9	58.9	88.2	35.5	76.0	2	91.1	63.0	90.8	44.5	79.3
equake	1	98.0	100	100	96.3	99.3	1	98.0	100	100	96.3	99.3
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

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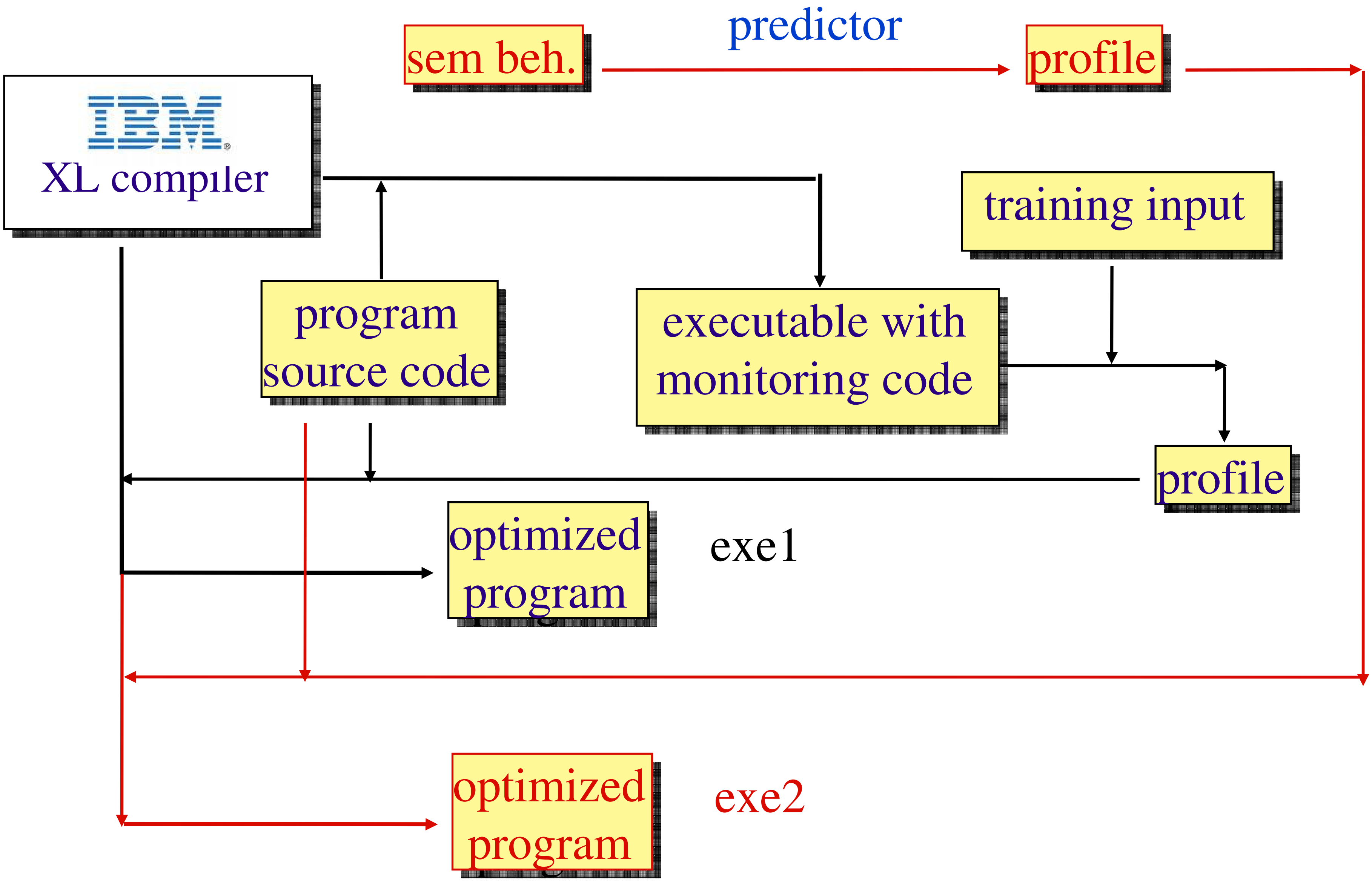
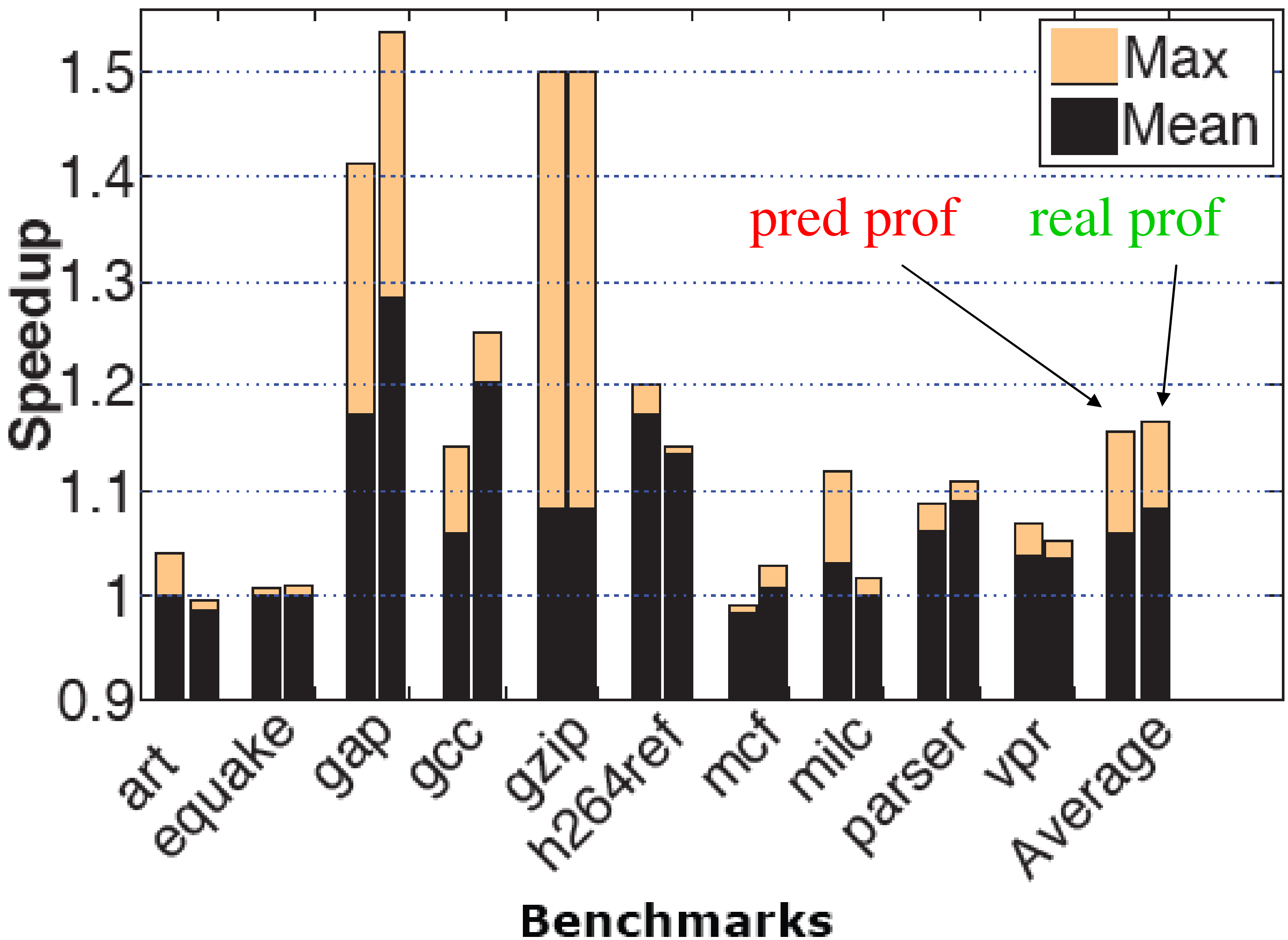


predictor
sem beh.
profile
IBM
XL compiler
training input
program source code
executable with monitoring code
profile
optimized program
exe1
optimized program
exe2

Performance Improvement

(Baseline: highest static opt)



IBM Power5

XL 11.1

More Potential Uses

- Help JIT compilers make better decisions in managed environment
  - i.e. JVMs
- Boost performance through dynamic code version selection
  - for imperative languages such as C

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Related Work

- Correlations between control flow signatures and hardware performance
  - [Sherwood+:ASPLOS'02, Annavaram+:Micro 04, etc.]
- Adaptive dynamic optimization
  - [Arnold+:OOPSLA'00, Chen+:PLDI'06,Lau+:PLDI'06, etc.]
- Exploiting inputs for optimization
  - [Wang+:PLDI'04, Mao+:CGO'09, Chen+:PLDI'10]

Conclusion

- Strong correlations exist among behaviors.
- Seminal behavior-based technique is promising.
- Significant potential for program optimizations.

Thanks!

Questions?

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