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# Software Reliability Estimation Based on Static Error Detection

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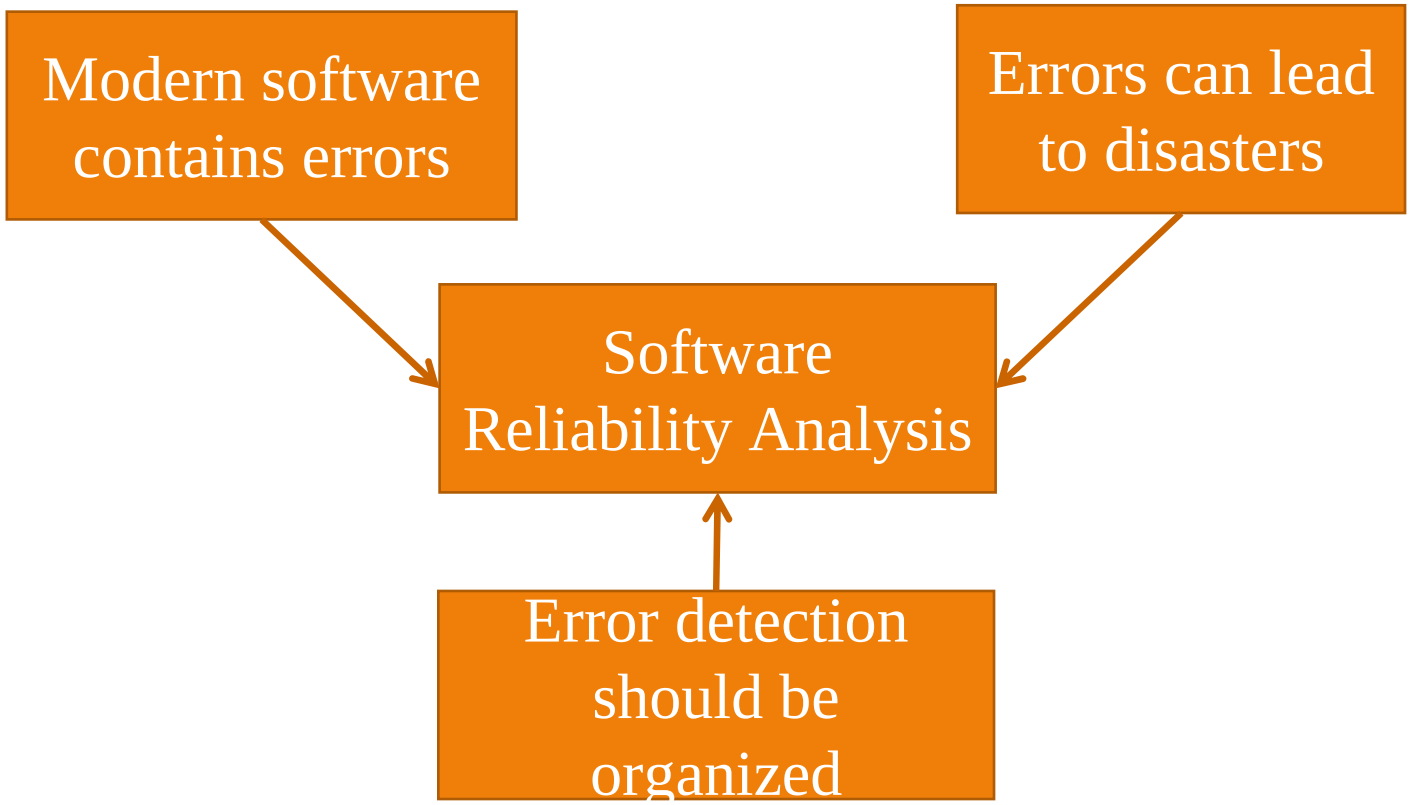
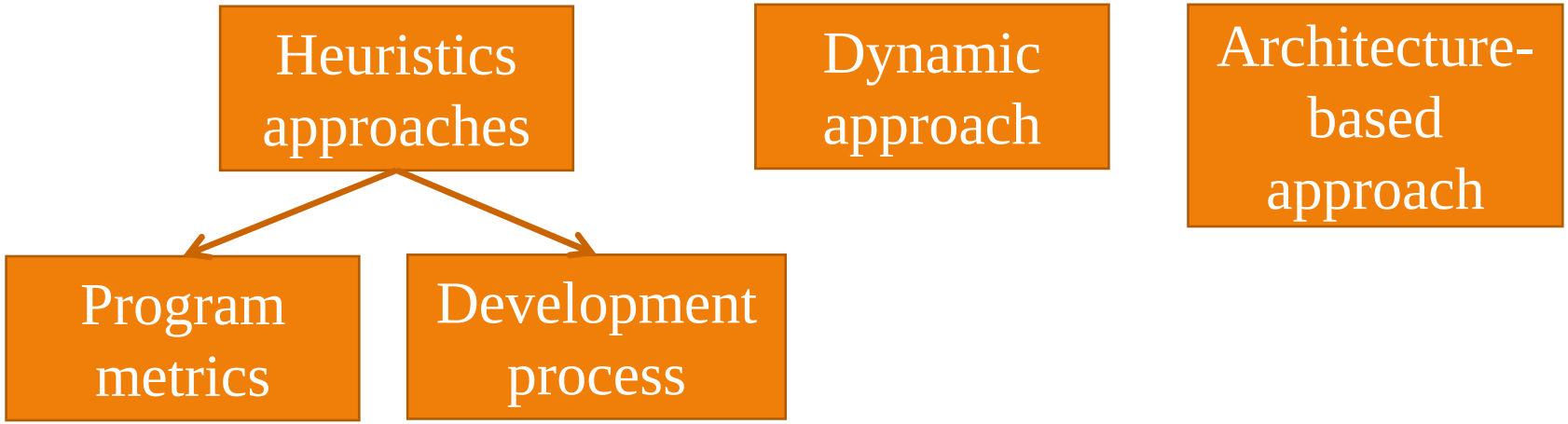
# Importance of Software Reliability Analysis



# Known Approaches



# Known Approaches – Program Metrics

- Based on simple code properties, such as
  - number of statements
  - number of conditions
  - number of loops
  - number of functions
  - ...

# Known Approaches – Development Process Metrics

- Based on development process properties, such as
  - duration of development
  - number & qualification of developers
  - number & qualification of testers
  - methodology used
  - automation tools used

# Known Approaches – Others

- Runtime
  - Based on failures observed at run-time
- Architecture-based
  - Based on known reliability of program components

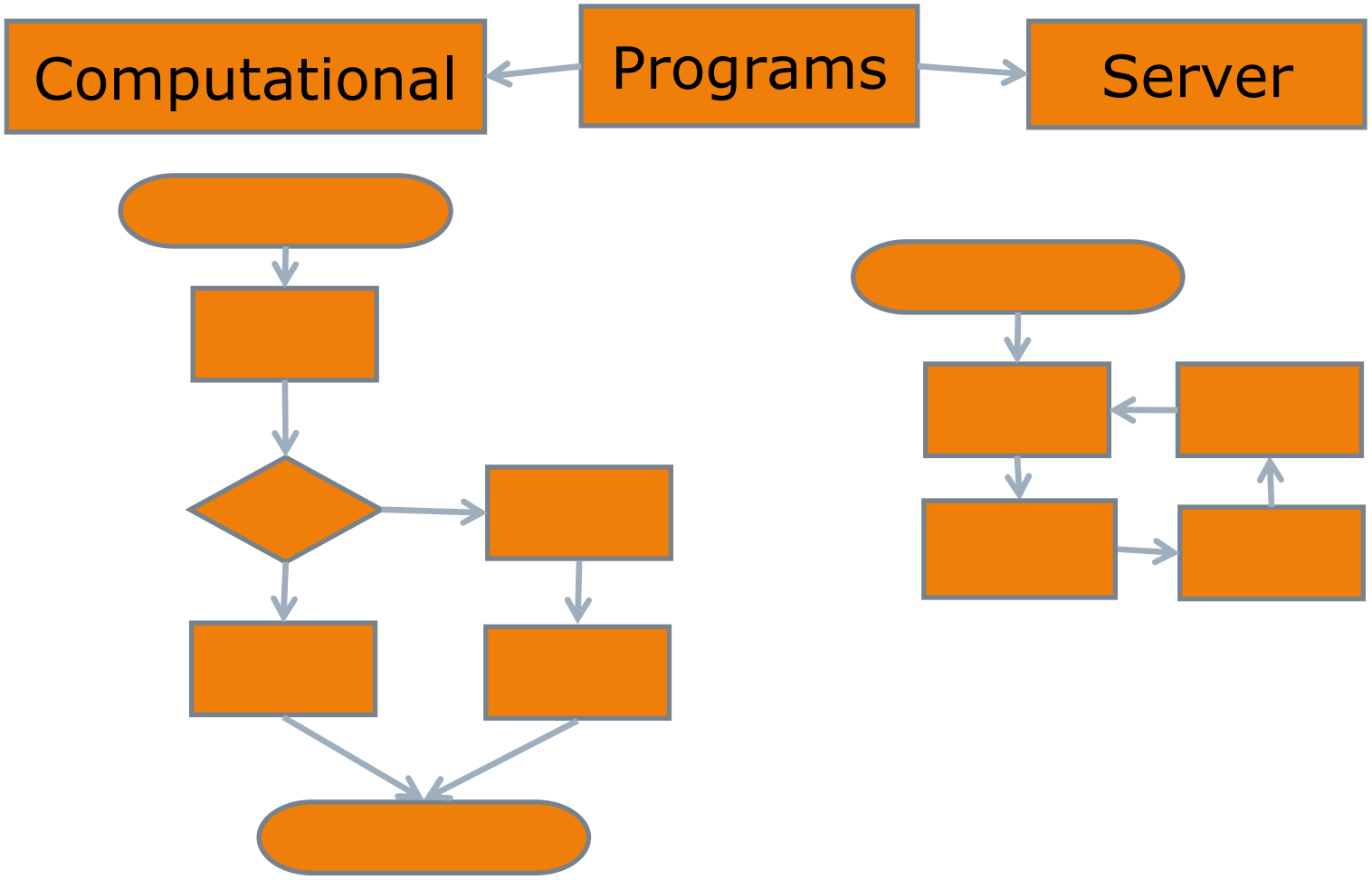
# Our Approach

- Based on source code static analysis
- Delivers
  - Ranking of errors (based on failure probability)
  - Reliability characteristics
- Limitations
  - Single-threaded C programs
- Error types
  - uninitialized variable use
  - incorrect pointer dereference
  - pointer out of bounds

# Features of Our Approach

- Analysis of a program model
- Analysis of all possible execution paths
- Advantages
  - Reliability estimations is based on real errors
  - Results are applicable for any exploitation conditions
  - Makes debugging more effective
- Drawbacks
  - Does not consider quantitative time
  - Does not consider normal program exploitation
  - Execution path probability estimation
  - False positives problem

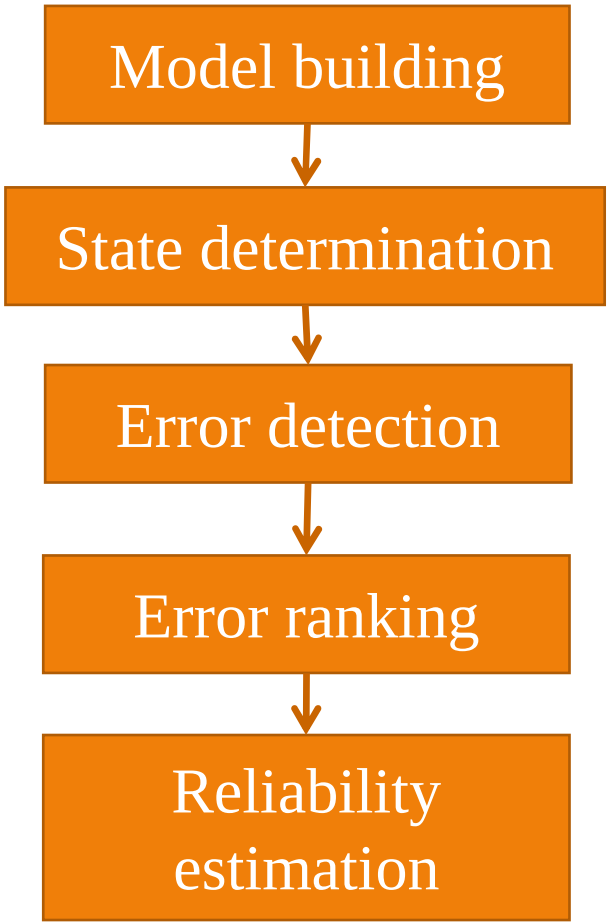
# Program Classes



# Reliability characteristics used

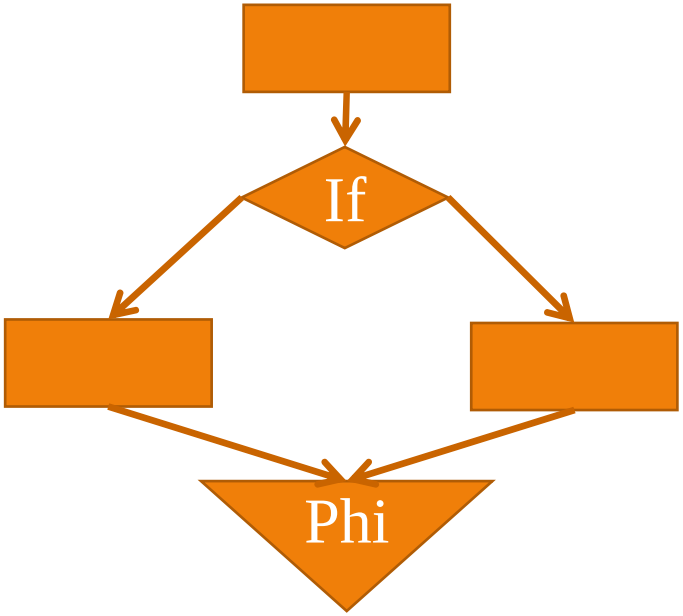
- Computational programs
  - Probability of whole program successful execution $P(\infty)$
- Server programs
  - Probability of *n* statements successful execution $P(n)$
  - Mean executed statement number before failure $\bar{n}$

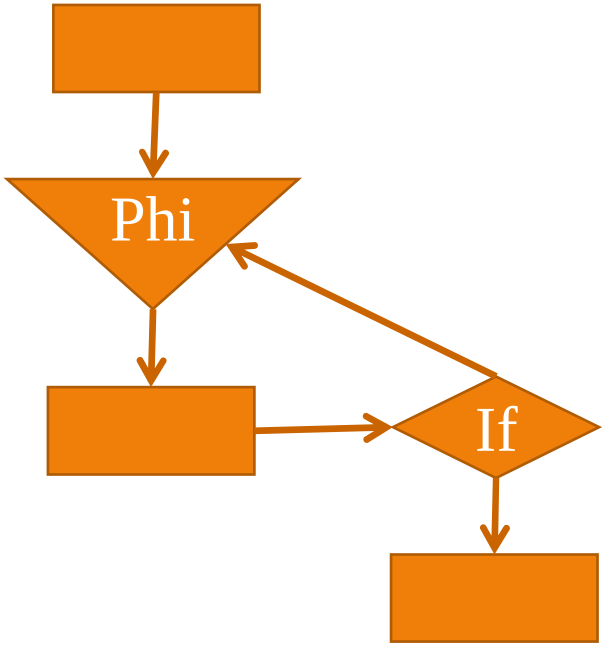
# Algorithms


Model building
State determination
Error detection
Error ranking
Reliability estimation

# Program Model Features

- Control flow graph
- Three-operand assignment form A = B op C
- If and Phi statements



# State Determination Algorithms

- State representation
- Control flow analysis
  - Statement analysis
    - Sequential
    - If statement analysis
    - Phi statement analysis
  - Loop analysis
  - Interprocedural analysis

# Program State Representation

- Based on objects, values, and probabilities
  - set of triples $Q = \{(o_j, v_k, p_{jk})\}$
  - state probability $P(Q)$
- Object values
  - intervals
  - pointers
  - resource descriptors

# Probability normalization

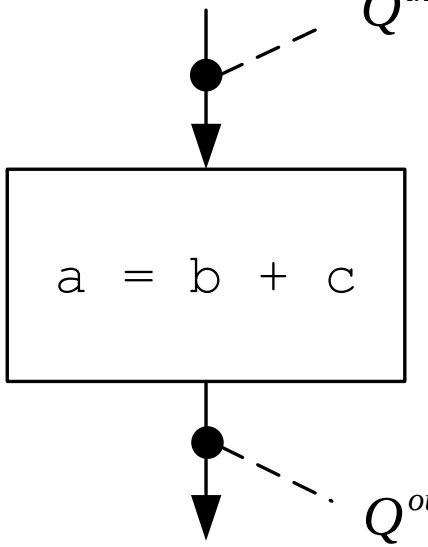
- Control flow normalization

$$\sum_{\forall Q_j^{in} \in Input(s)} P\left(Q_j^{in}\right) = \sum_{Q_j^{out} \in Output(s)} P\left(Q_j^{out}\right)$$

- State normalization

$$\forall o_j : \exists \left(o_j, v_k, p_{jk}\right) \in Q \Rightarrow \sum_{\forall \left(o_j, v_k, p_{jk}\right) \in Q} p_{jk} = P(Q)$$

# Sequential Statement Analysis




$$Q^{in} = \left\{ \begin{matrix} (b,(1..2),1), \\ (c,(3..6),1),... \end{matrix} \right\} = \left\{ \begin{matrix} \left(b,1,\frac{1}{2}\right),\left(b,2,\frac{1}{2}\right) \\ \left(c,3,\frac{1}{4}\right),\left(c,4,\frac{1}{4}\right), \\ \left(c,5,\frac{1}{4}\right),\left(c,6,\frac{1}{4}\right),... \end{matrix} \right\}$$

$$Q^{out} = \{(a,(4..8),1),...\} = \left\{ \begin{matrix} \left(a,4,\frac{1}{8}\right),\left(a,5,\frac{1}{4}\right), \\ \left(a,6,\frac{1}{4}\right),\left(a,7,\frac{1}{4}\right), \\ \left(a,8,\frac{1}{8}\right),... \end{matrix} \right\}$$

# If Statement Analysis

- True and false combination consideration

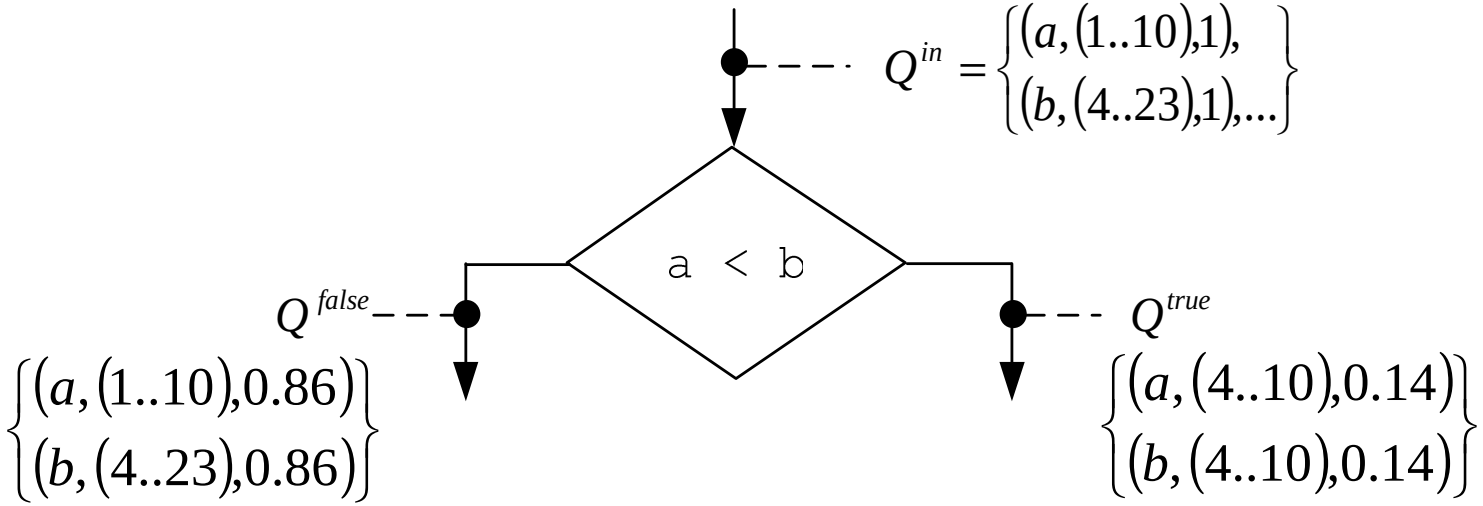
$$P\left(Q^{true}\right)=\sum_{c\in C^{true}}\prod_{\left(o_j,v_k,p_{jk}\right)\in c}p_{jk},$$

$$P\left(Q^{false}\right)=\sum_{c\in C^{false}}\prod_{\left(o_j,v_k,p_{jk}\right)\in c}p_{jk}.$$

- Normalization of state probabilities
- Normalization of non-affected triples probabilities

# If Statement Analysis Example

- 172 combinations where a < b
- 28 combinations where a >= b




- Normalization: 0.86 for true, 0.14 for false

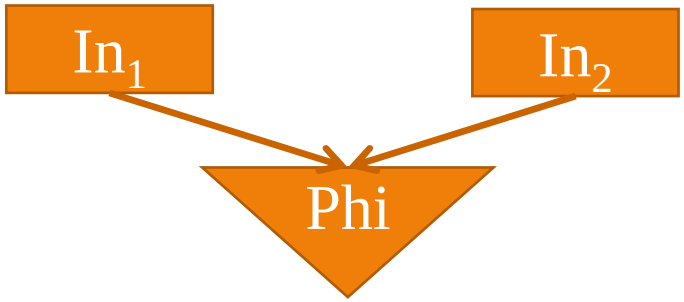
# Phi Statement Analysis

- Identical triples are added together

$$\forall o_j, v_k : (o_j, v_k, p_{jk}) \in Q_1^{in}, (o_j, v_k, r_{jk}) \in Q_2^{in} \Rightarrow$$

$$(o_j, v_k, p_{jk} + r_{jk}) \in Q^{out}$$

- Control flow normalization $P(Q^{out}) = P(Q_1^{in}) + P(Q_2^{in})$

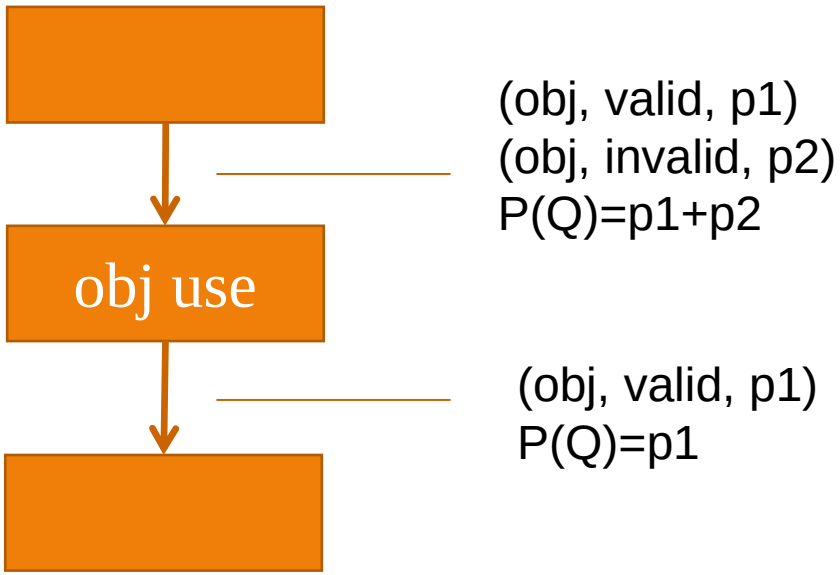


# Error Detection

- Based on incorrect values in state
  - uninitialized variable use $(o_j, v_{noninit}, p_k)$
  - pointer dereference $(o_j, v_{noninit}, p_k)$

    $(o_j, v_{null}, p_k)$ $(o_j, v_{invalid}, p_k)$
  - out of bounds $(o_i, (o_j, offset_j), p_k)$
    - correct if $0 \leq offset_j < sizeof(o_j)$
    - otherwise error is detected

# Error Inhibition



# Error Ranking

- Errors are sorted according to probability of occurrence
  - Most dangerous errors can be corrected first
- Probabilities are summarized for same errors in the same statement

# Overall reliability estimation

- probability of successful execution

$$P(n) = \sum_{end\ statements} P(Q)$$

- probability of n statements successful execution

$$P(n) = \sum_{n\ statements\ executed} P(Q)$$

- mean executed statements number before failure

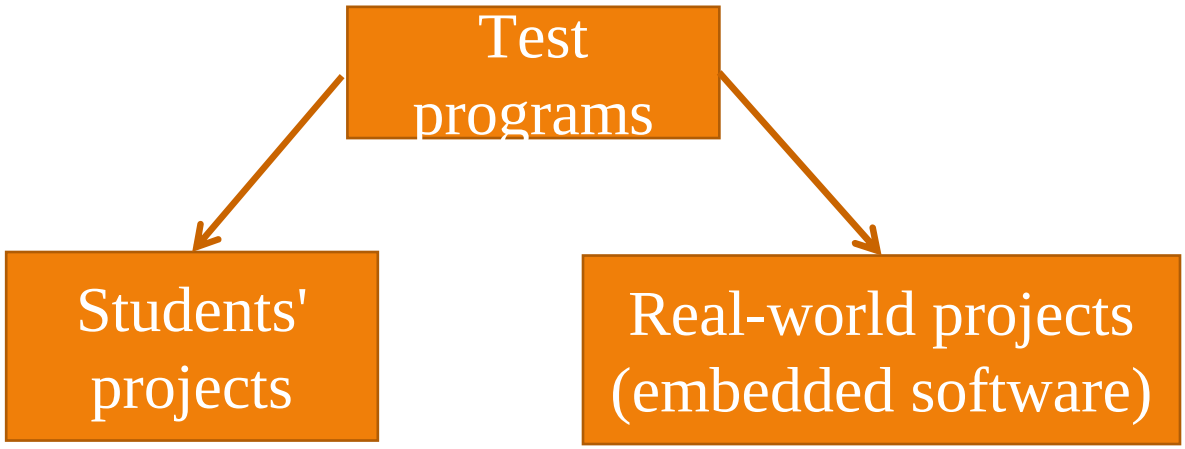
$$\overline{n} = \sum_{n=0}^{n_{\max}} \left(P(n) - P(n+1)\right) \cdot n$$

# Implementation

- AEGIS static analyzer
  - analysis of C/C++ source code
  - interval, points to, resource analysis
  - loop & interprocedural analysis
  - spread range of program errors detected
- Results
  - error ranking table
  - P(n) table
  - P(∞)
  - mean executed statements number before failure

# Experiments made

- Purpose
  - Testing of our approach
  - Debugging example



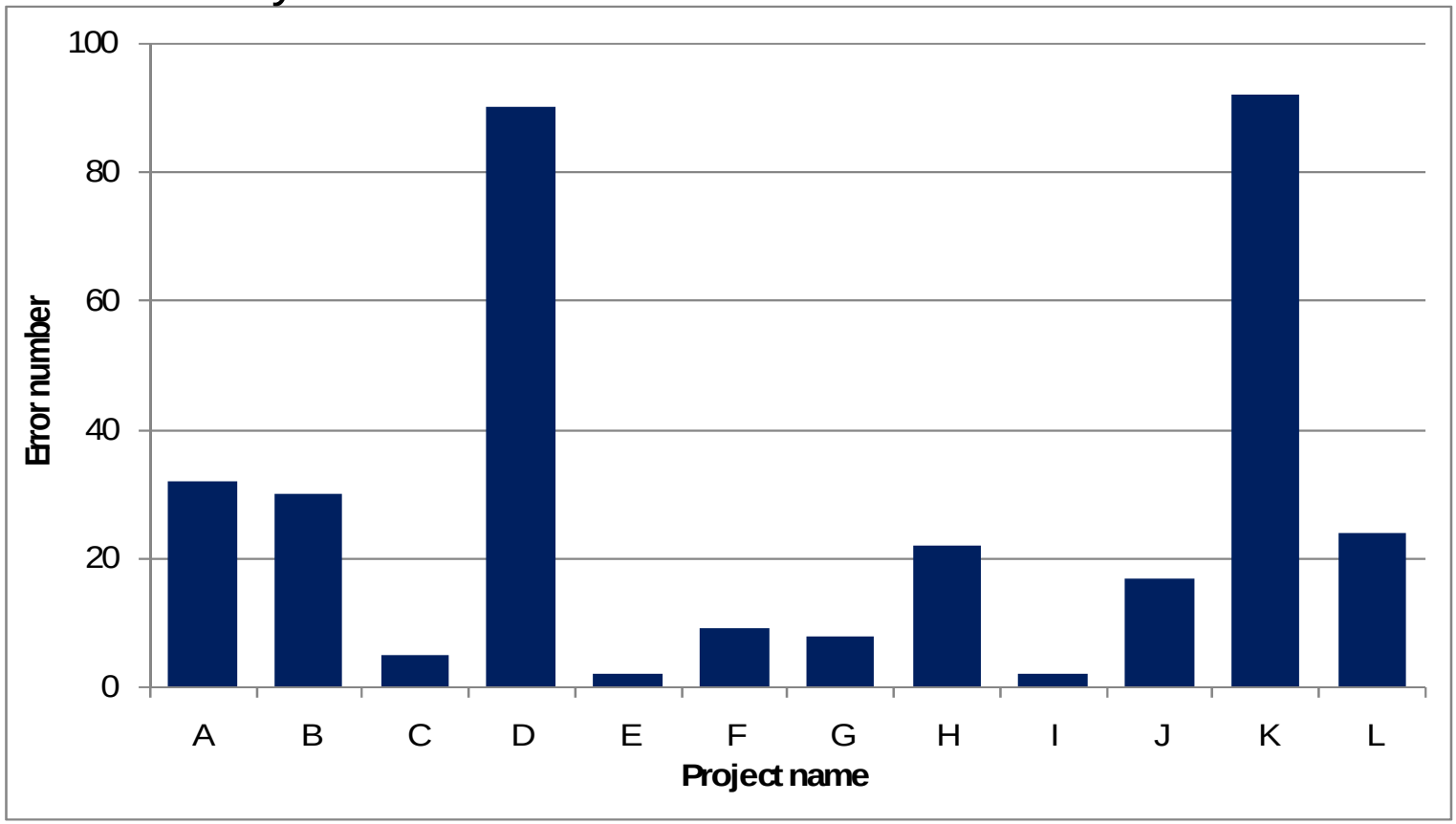
# Sample of reliability analysis

```
while (!(feof(f))) // 0.5
{
    i = t = 0;
    // Failure in one of three cases
    prov(&t, strlen(st), st);
}
```

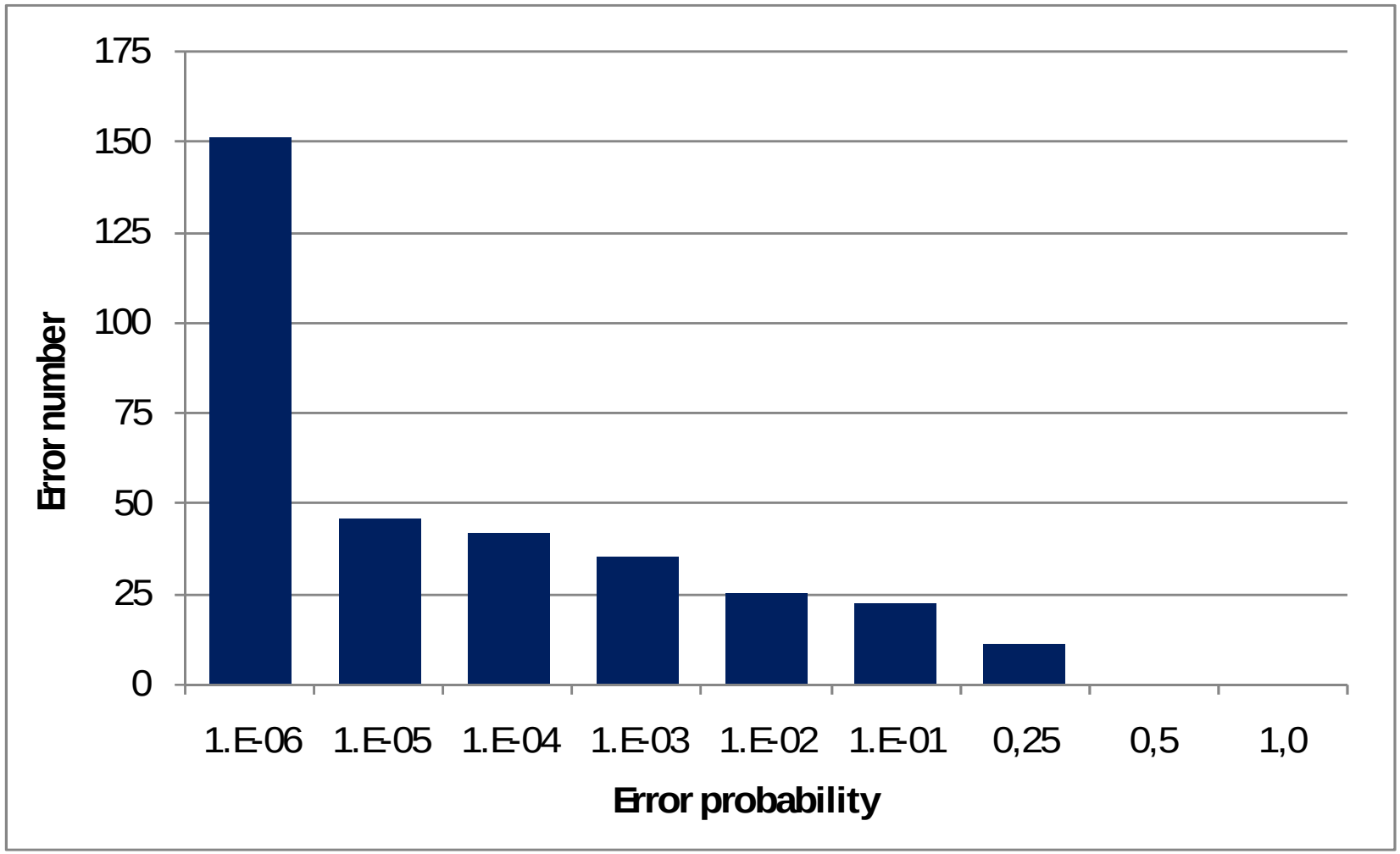
- Probability of successful execution is
  $0.75 = 0.5 + 0.5 * 0.33 + 0.5 * 0.33^2 + ...$

# Amount of errors in real-world projects

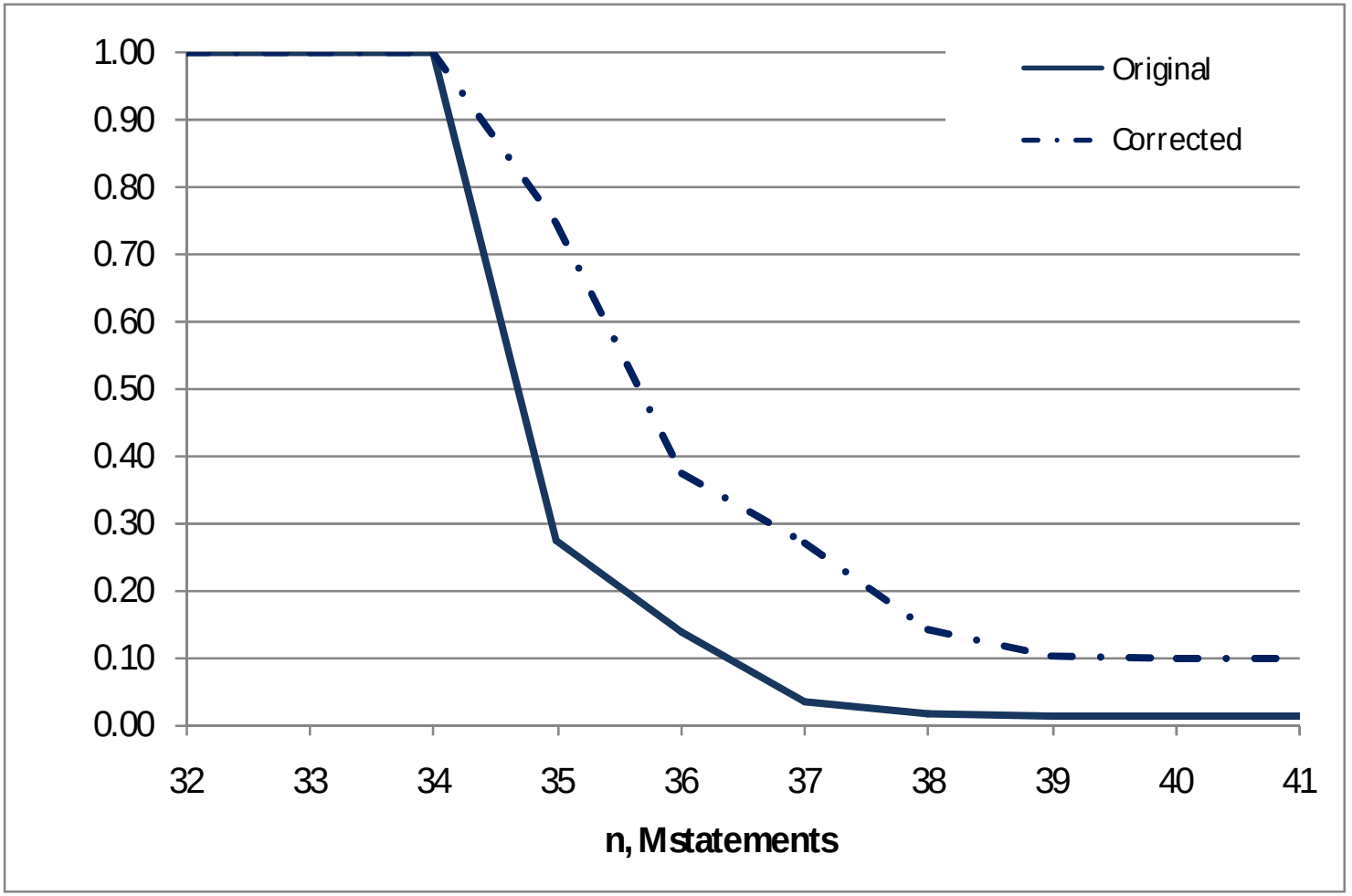
- More than 500 errors, 2/3 of considered types
- Density about 0.8/1KLOC



# Distribution of error number



# Debugging results



# Directions for Future Work

- Reliability estimation
  - Annotations for path probability estimations
  - Run-time analysis for path probability estimation
  - Execution time estimation
- Static analysis itself
  - Soundness & precision
  - Parallel program analysis
  - Annotations for functional error detection

# Conclusion

- Approach for software reliability estimation
  - based on error detection using static analysis
- Implementation in AEGIS tool (prototype)
  - ranking of errors by the probability of occurrence
  - probability of successful execution
  - probability of N statement successful execution
  - mean number of executed statements before failure

# Contacts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