Parallel Test Generation and Execution with Korat

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Motivation

- Testing a program developed at Google
  - Input: based on acyclic directed graphs (DAGs)
  - Output: sets of nodes with specific link properties
- Manual generation of test inputs hard
  - Many “corner cases” for DAGs: empty DAG, list, tree, sharing (aliasing), multiple roots, disconnected components…

Automated generation with Korat

- Korat is a tool for automated generation of structurally complex test inputs
  - Well suited for DAGs
- User manually provides
  - Properties of inputs (graph is a DAG)
  - Bound for input size (number of nodes)
- Tool automatically generates all inputs within given bound (all DAGs of size S)
  - Bounded-exhaustive testing

Problem: Large testing time

- Korat can generate a lot of inputs
  - Example: DAGs with 7 nodes: 1,468,397
- How to reduce testing time?
  - Generation: Speed up test generation itself
  - Execution: Generate fewer inputs
- Solutions
  - Parallel Korat: Parallelized generation and execution of structurally complex test inputs
  - Reduction methodology: Developed to reduce the number of equivalent inputs

Outline

- Overview
- Background: Korat
- Parallel Korat
- Reduction Methodology
- Conclusions

Korat: input

- User writes:
  – Representation for test inputs

```
public class DAG {
  DAGNode[] nodes;
  int size;
}
```

```
public class DAGNode {
  DAGNode[] children;
}
```

  – Imperative predicate method to identify valid test inputs
  – Finitization defines search bounds

Imperative predicate: repOK

- Methods that check validity of test inputs

```
public class DAG {
  public boolean repOK() {
    Set<DAGNode> visited = new HashSet<DAGNode>();
    Stack(DAGNode> path = new Stack<DAGNode>();
    for (DAGNode node : nodes) {
      if (visited.add(node))
        if (!node.repOK(path, visited))
          return false;
    }
    return size == visited.size();
  }
}
public class DAGNode {
  public boolean repOK() { ... } // 11 lines
}
```

Finitization

- Bounds search space
- Example
  - Number of objects
    - 1 DAG object (D_0)
    - S DAGNode objects (N_0, N_1, … N_{S-1})
  - Values for fields
    - S exactly for `size` (could be 0..S)
    - 0..S-1 children for each node
    - Each child is one of S nodes

Korat: output

- Generates structurally complex data
  - Example: DAG
    - Set of nodes and set of directed edges
    - No cycles along those directed edges

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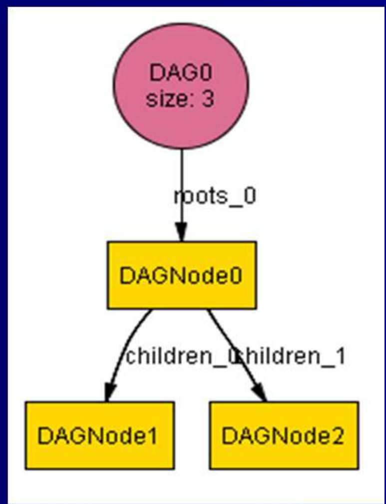

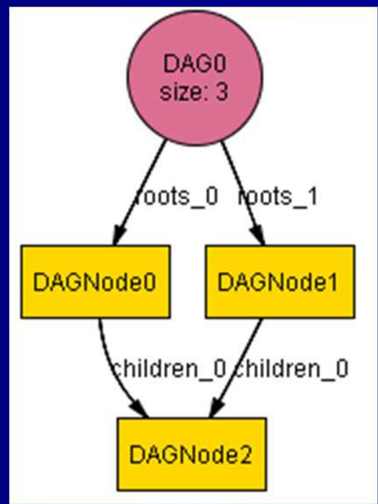

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Korat: input space

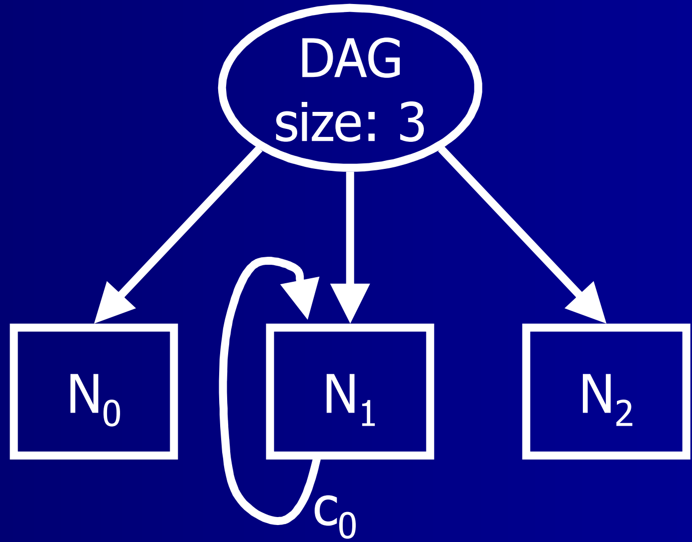
- Korat exhaustively explores a bounded input space
- Finitization describes all possible inputs
  - Example for S=3

D_0	N_0			N_1			N_2		
size	len	c_0	c_1	len	c_0	c_1	len	c_0	c_1
3	0	N_0	N_0	0	N_0	N_0	0	N_0	N_0
	1	N_1	N_1	1	N_1	N_1	1	N_1	N_1
	2	N_2	N_2	2	N_2	N_2	2	N_2	N_2

Candidate vector

- Sequence of indexes into possible values
- Encodes 1 object graph, valid or invalid
- Example (invalid DAG)

D_0	N_0			N_1			N_2		
size	len	c_0	c_1	len	c_0	c_1	len	c_0	c_1
0	0	-	-	1	1	-	0	-	-



Korat: search

- Starts from candidate vector with all 0’s
- Generates candidate vectors in a loop until the entire space is explored
  – For each vector, executes repOK to find
  (1) whether the candidate is valid or not
  (2) what next candidate vector to try out
  – Field-access stack
    - Korat monitors field accesses during execution of repOK
    - Backtracks on last accessed field on stack, pruning large portions of the search space

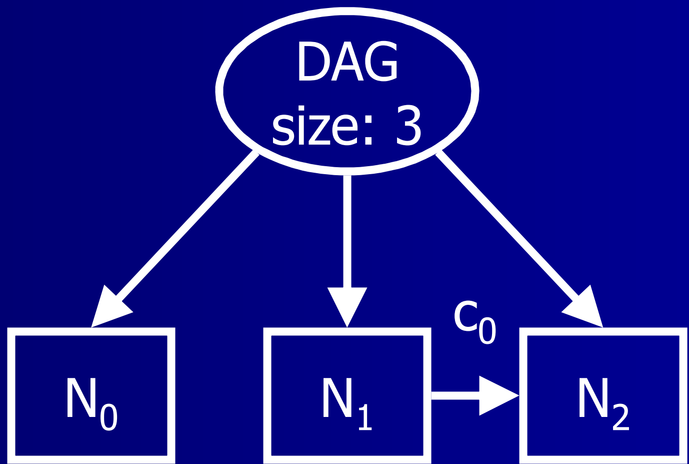
Korat: next candidate vector

- Backtracking on $N_1.c_0$

D_0	N_0			N_1			N_2		
size	len	c_0	c_1	len	c_0	c_1	len	c_0	c_1
0	0	-	-	1	1	-	0	-	-

- Produces next candidate (valid DAG)

0	0	-	-	1	**2**	-	0	-	-



Two key Korat concepts

- repOK
  - User provides predicates that check properties of valid inputs
- Candidate vector
  - Used in Korat search
  - Next vector computed from previous by executing repOK

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Parallel Korat: design goals

- Target clusters of commodity machines
  - Google infrastructure
- Minimize inter-machine communication
  - Improves overall performances by removing any expensive message passing
  - Makes code easily portable
- Challenge for load balancing: partition search space among various machines statically (before starting parallel search)
  - No overlap of work among machines

Korat: easy for parallelization

- Candidate vector compactly encodes the entire search state, both
  – Part that has been explored
  – Part that is yet to be explored
- Easy to parallelize search by using candidate vectors as the bounds for the ranges that split state space

Korat: hard for parallelization

- Korat pruning
  - Makes search more efficient ☺
  - Makes search mostly sequential ☹
    - Next candidate vector depends on the execution of `repOK` on current candidate vector
- Implication: given an arbitrary candidate vector, cannot statically know if the search would explore that vector or not
- Cannot purely randomly choose candidate vectors for partitioning

Parallel Korat: four algorithms

- Test generation can be
  - SEQuential: use one machine
  - PARallel: use multiple machines
- Test execution always parallel, can be
  - OFF-line: generation and execution decoupled (all inputs stored on disk)
  - ON-line: execution follows generation (inputs not stored on disk)
- Four algorithms
  - SEQ-OFF, SEQ-ON, PAR-OFF, PAR-ON

SEQ-OFF algorithm

- Runs test generation sequentially (SEQ) and stores to disk all test inputs
- Distributes test inputs evenly across several worker machines to execute code under test in parallel (OFF)
- Use case
  - Generation requires a lot of search and produces only few inputs (so it is preferred to store them for future execution)

SEQ-ON algorithm

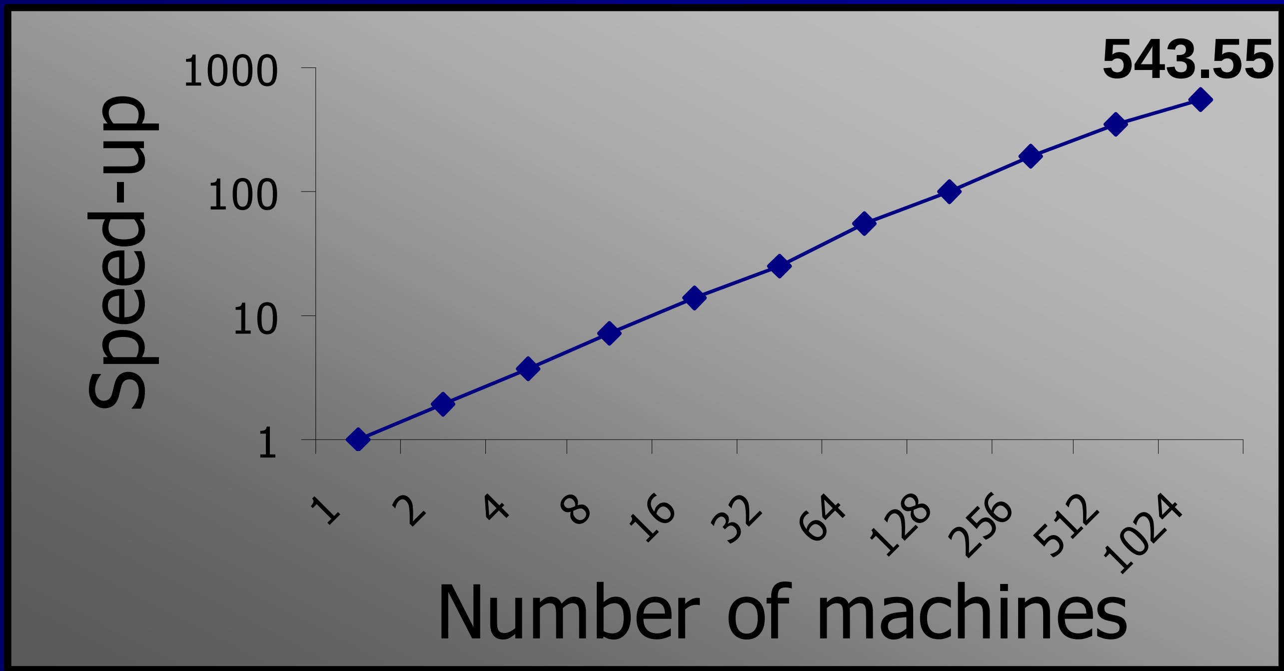
- Use case: do not store inputs on disk
- Goal: Run sequentially once (SEQ) but prepares to make future runs parallel
- Sequential test generation stores to disk *m* equidistant candidate vectors: $v_1 \ldots v_m$
  - Union of ranges $[v_i, v_{i+1})$ covers entire space
  - Each range explores same # of candidates
- All future generations/executions done in parallel on $w <= m$ worker machines (ON)

Equidistancing algorithm

- Challenge: Choose *m* equidistant vectors not knowing total number before search
  - If we knew total *T*, we would store *T/m*-th
- Solution uses an array of size *2m* to remember specific candidate vectors
  - Example for *m*=3
  - Fill out the array: 1,2,3,4,5,6
  - Halve the array: 2,4,6
  - Double distance: 2,4,6,8,10,12
  - Repeat these 3 steps: 4,8,12… 16,18,20…

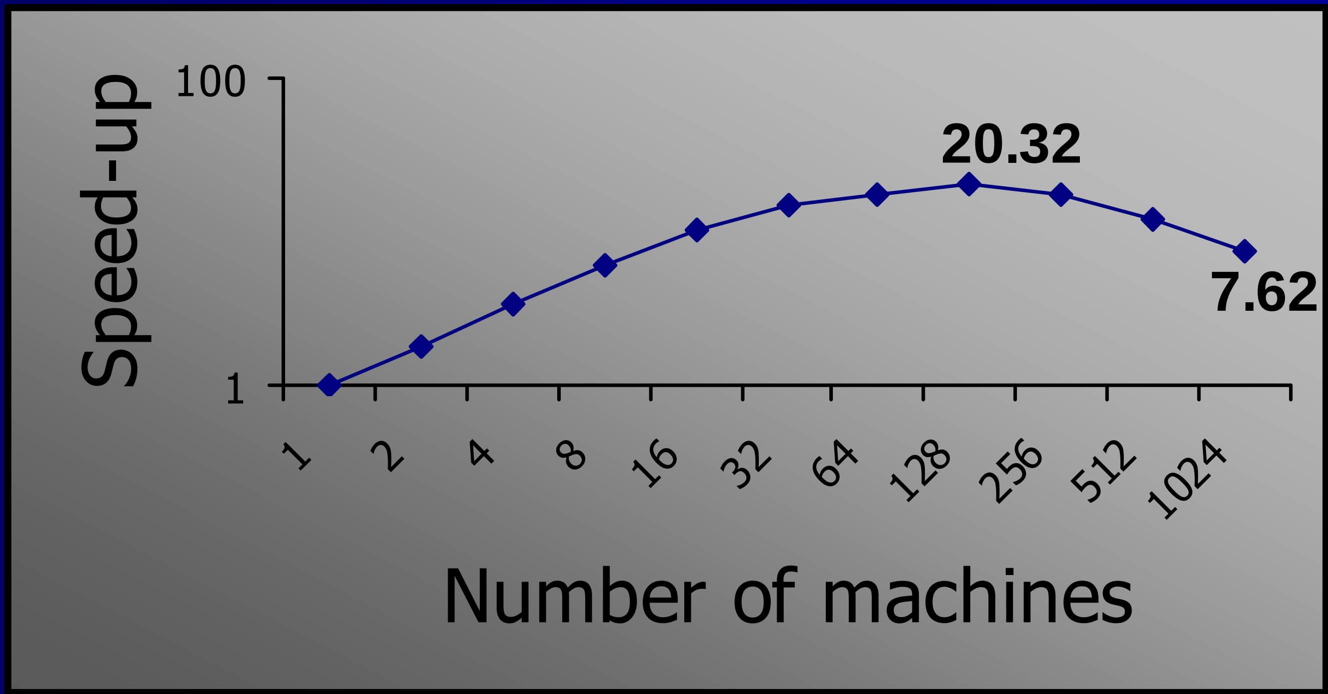
Evaluation: SEQ-ON, DAGs of size 8

- Experiments on Google infrastructure
  - Up to 1024 machines, Google File System
  - Testing time: from 35.9 hours (1 machine) to 4 mins (1024 machines)



Evaluation: SEQ-ON, DAGs of size 7

- Experiments on Google infrastructure
  - Peek on 128 machines
    - Testing time: from 10 mins to 1/2 min
  - A lot of time goes on file distribution



PAR-OFF algorithm

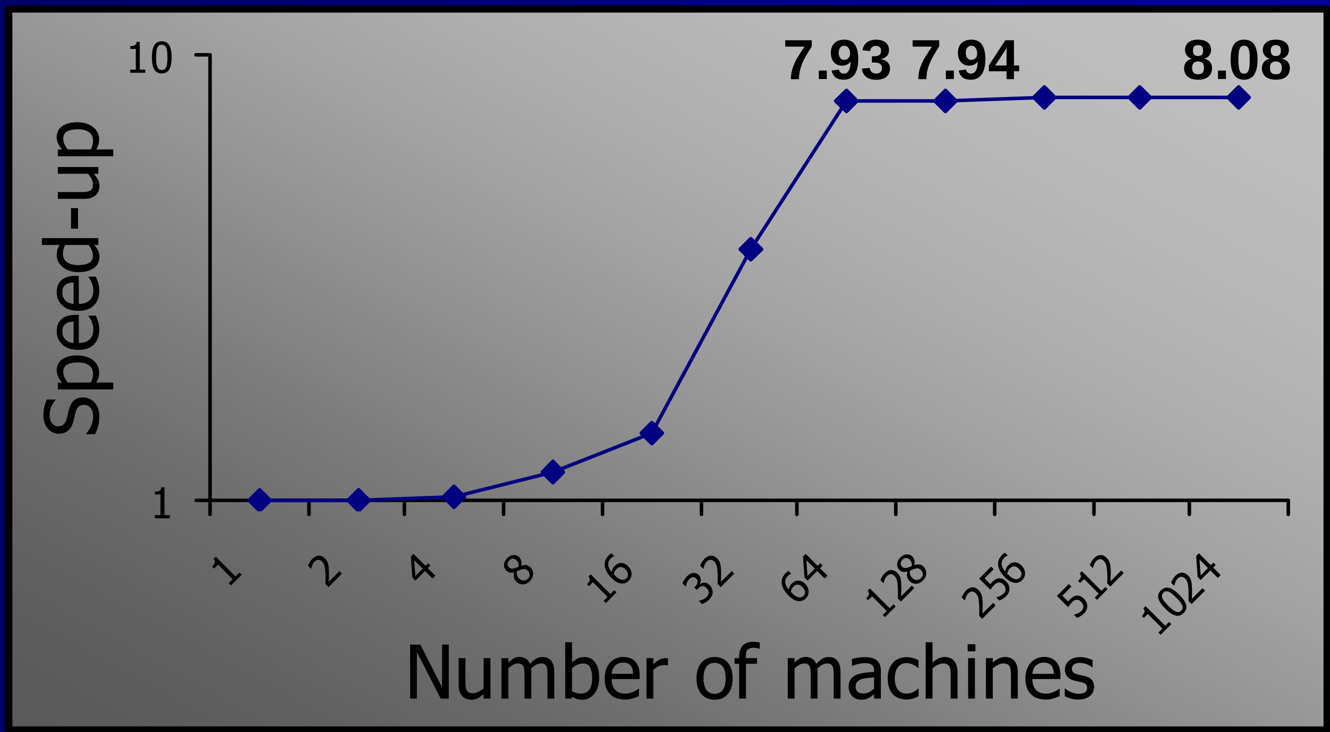
- Parallelizes the initial run (PAR)
  - Challenges:
    - How to partition input space into several ranges without generating all inputs as in SEQ-ON
    - Hard to estimate the number of vectors explored between two given vectors (Korat's dynamic pruning)
  - Solution: use randomization
    - Randomly fast-forward search on one machine to generate vectors that cover the entire search space
- Parallelize search for generated vectors and write all generated test inputs to disk
- Performs test execution separately (OFF)

Fast-forwarding algorithm

- Randomly chooses *m* candidate vectors
  - Starts from candidate with all 0’s (as Korat)
  - Repeatedly
    - Chooses randomly a number of usual Korat steps to apply
    - Chooses randomly a “jump” in search (discarding some fields from access stack)
    - Stores current candidate
  - If search space explored before storing *m* candidates, repeat the process from 0’s
  - Sort the candidates by their indexes

Results for PAR-OFF

- Ran PAR-OFF to select *m* candidates $v_1 \ldots v_m$
  - Divided # of candidates over largest range $[v_i, v_{i+1})$
- Repeated for 50 random seeds, averages:



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Reduction methodology

- Independent of parallel algorithms
- Goal to generate fewer equivalent inputs
  - Equivalent: either all or none show bugs
  - Korat prunes out some equivalent inputs
  - User may want to prune out even more
- Methodology: Manually change repOK
  - Add more checks to repOK to prune some valid (but equivalent) inputs
  - User encodes an ordering on candidates such that "larger" can be pruned

Equivalence of DAGs

- Three versions of repOK
  - Basic: no ordering
  - Children: number of immediate children
  - Descendants: total number of descendants
- DAGs of size 6: non-equivalent 5,984

	repOK size	Inputs	Time [s]
Basic	22	1,336,729	213.36
Children	26	185,569	75.07
Descendants	34	21,430	30.48

Speedup: 60x exec. 7x gen.

Conclusions

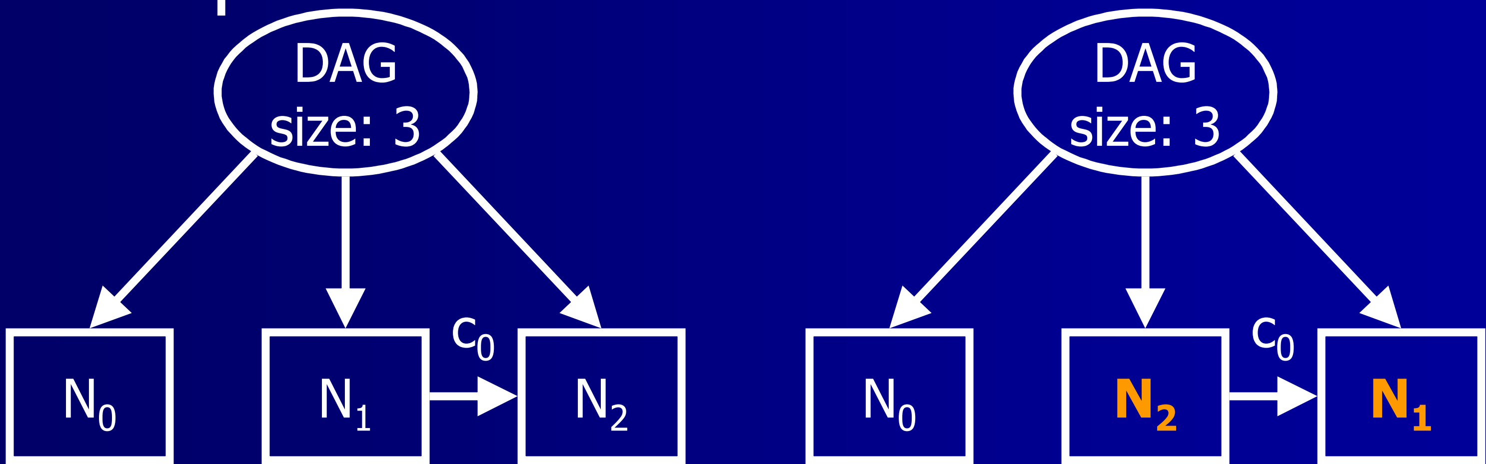
- Developed parallel Korat
  - Example speedups evaluated at Google
    - Over 500x on 1024 machines for DAGs of size 8
    - Slowdown after 128 machines for DAGs of size 7
- Developed reduction methodology
  - Example improvements for DAGs of size 6
    - Over 7x reduction in generation time
    - Over 60x fewer test inputs (execution time)

http://korat.sourceforge.net

Thanks!

Isomorphic inputs

- Korat generates all valid non-isomorphic test inputs within given bounds
- Isomorphic object graphs have:
  - Same shape and primitive values
  - Potentially different node identities
- Example



Equivalent inputs

- Isomorphism != equivalence
  - Example: Two DAGs are equivalent if they are isomorphic as graphs not object graphs
- Problem: Korat can generate object graphs non-isomorphic at concrete level but equivalent at abstract level, e.g.: