Software Quality Engineering

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Testing, Quality Assurance, and Quantiable Improvement
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Chapter 11. Control Flow, Data Dependency, and Interaction Testing

- General Types of Interaction in Execution.
- Control Flow Testing (CFT)
- Data Dependency Analysis
- Data Flow Testing (DFT)

Extending FSM for Testing

- FSMs and extensions:
  - Difficulties with FSMs: state explosion

    => UBST with Markov-OPs/UMMs

  - FSM Limitation: node/link traversal

    => other testing for complex interactions

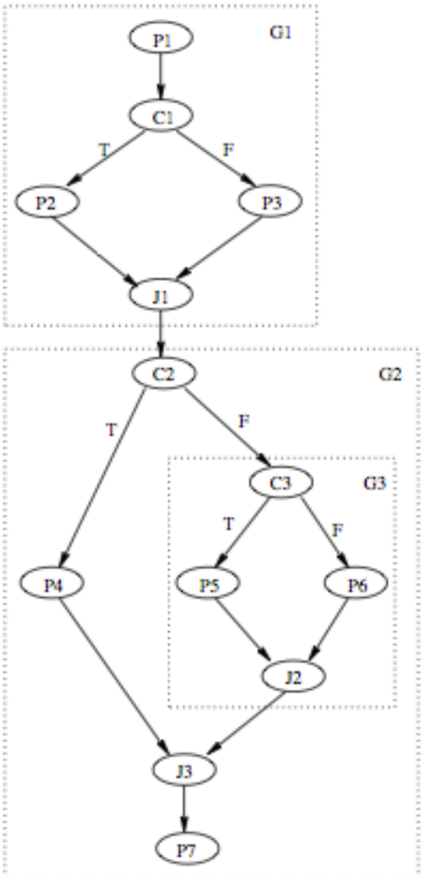
- Interactions in program execution
  - Interaction along the execution paths
    - path: involving multiple elements/stages
    - later execution affected by earlier stages
    - tested via control flow testing (CFT)
    - control flow graph (CFG) belongs to FSM
  - Computational results affected too
    - data dependency through execution
    - analysis: data dependency graph (DDG)
    - tested via data flow testing (DFT)

CFGs and FSMs

- CFG (control flow graph)

    - Basis for control flow testing (CFT)
    - CFG as specialized FSMs
        - type II: processing & I/O in nodes
        - links: "is-followed-by" relation, some annotated with conditions
- CFG elements as FSM elements
    - nodes = states = unit of processing
    - links = transitions = "is-followed-by"
    - link types: unconditional and conditional, latter marked by branching conditions

CFG Example



- Example: Fig 11.1 (p.177)

  for a proper structured program (seq. concat. + nesting, no GOTOs)

CFG: Nodes and Links

- Inlink and outlink defined w.r.t a node
- Entry/exit/processing nodes
    - Entry (source/initial) nodes
    - Exit (sink/final) nodes
    - Processing nodes
- Branching & junction nodes & links
    - Branching/decision/condition nodes
        - multiple outlinks
        - each marked by a specific condition
        - only 1 outlink taken in execution
    - Junction nodes
        - opposite to branching nodes
        - but no need to mark these inlinks
        - only 1 inlink taken in execution
    - 2-way and N-way branching/junction

CFG for CFT

- CFGs for our CFT
    - Separate processing/branching/junction nodes for clarity
    - Sequential nodes: mostly processing

      => collapsing into one node (larger unit)
    - No parallelism allow

      (single point of control in all executions)
    - Mostly single-entry/single-exit CFGs
    - Focus: structured programs, no GOTO
        - GOTOs => ad hoc testing
- Notational conventions
    - "Pi" for processing node "i"
    - "Ji" for junction node "i"
    - "Ci" for condition/branching node "i"

CFT Technique

- Test preparation
    - Build and verify the model (CFG)

  - Test cases: CFG) path to follow
  - Outcome checking: what to expect and how to check it
- Other steps: Standard (Chapter 7)
  - Test planning & procedure preparation
  - Execution: normal/failure case handling
  - Analysis and Followup
- Some specific attention in standard steps

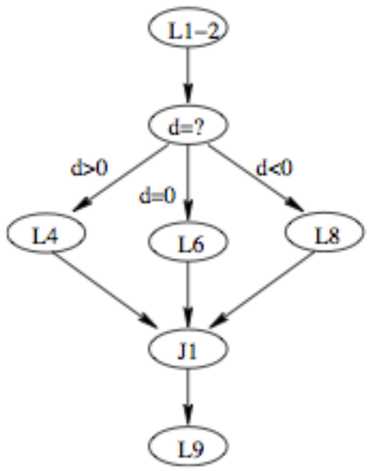
  Confirmation of outcome and route in analysis and followup

CFT: Constructing CFG

- Sources for CFG
  - White box: design/code
    - traditional white-box technique
  - Black box: specification
    - structure and relations in specs
- Program-derived (white-box) CFGs
  - Processing: assignment and calls
  - Branch statements
    - binary: if-then-else, if-then
    - multi-way: switch-case, cascading if's
  - Loop statements (later)
  - composition: concatenating/nesting
  - structured programming: no GOTOs
    - hierarchical decomposition possible
  - explicit/implicit entry/exit

CFT: Constructing WB/CFG

```
L1:     input(a, b, c);
L2:     d ← b * b - 4 * a * c;
L3:     if ( d > 0 ) then
L4:         r ← 2
L5:     else_if ( d = 0 ) then
L6:         r ← 1
L7:     else_if ( d < 0 ) then
L8:         r ← 0;
L9:     output(r);
```



- Example: Fig 11.2 (p.179)
    - analyze program code on left
    - derive CFG on right
    - focus on decision and branches

CFT: Constructing CFG

- Specification-derived (black-box) CFGs
    - Node: "do" (enter, calculate, etc.)
    - Branch: "goto/if/when/while/..."
    - Loop: "repeat" (for all, until, etc.)
    - Entry: usually implicit
    - Exit: explicit and implicit
    - External reference as process unit
    - General sequence: "do"...(then)..."do"
    - Example: CFG in Fig 11.2 from external specifications
- Comparison to white-box CFGs
    - Implementation independent
    - Generally assume structured programs
    - Other info sources: user-related items
        - usage-scenarios/traces/user-manuals
        - high-level req. and market analyses

CFT: Path Definition

- Test cases: CFG) path to follow

    - Connecting CFG elements together in paths
    - Define and select paths to cover
    - Sensitize (decide input for) the paths
- Path related concepts/definitions:
    - Path: entry to exit via n intermediate links and nodes
    - Path segment or sub-path

      proper subset of a path

    - Loop: path or sub-path with 1+ nodes visited 1+ times

    - Testing based on sub-path combinations
    - Loop testing: specialized techniques

CFT: Path Selection

- Path selection (divide & conquer)
    - Path segment definition
    - Sequential concatenation
    - Nesting of segments
    - Unstructured construction: difficult
    - Eliminate unachievable/dead paths

      (contradictions and correlations)

- "Divide": hierarchical decomposition for structured programs
- "Conquer": Bottom-up path definition one segment at a time via basic cases for nesting and sequential concatenation

CFT: Path Selection

- Graph G made up of G1 and G2 subgraphs, with M and N branches respectively
    - Subgraph: 1 entry + 1 exit
    - Key decisions at entry points
- Path segment composition
    - Sequential concatenation: G = G1 o G2
        - M x N combined paths
    - Nesting: G = G1 (G2)
        - M + N - 1 combined paths
- Example paths for Fig 11.1 (p.177)

  TT-, TFT, TFF, FT-, FFT, FFF

CFT: Sensitization

- Path sensitization/realization
    - Logic: constant predicates
    - Algebraic: variable predicates
    - Use simple, obvious test cases
    - Rely on good application knowledge
        - run through first
        - add other cases later
    - Obtain input values (test point)
        - select for non-unique solutions
    - Alternative solutions via DFT later
- Trouble sensitize => check others first
    - Unachievable?
    - Model/specification bugs?
    - Nothing above => failure

CFT: Logic Sensitization

- Segment and combination
    - Divide into segments (entry-exit)
    - Examine predicate relations
    - Uncorrelated: direct combination
    - Correlated
        - analysis => path elimination
        - combination
- Path elimination
    - Highly correlated
        - identical: direct merge
        - contradictory
        - logic implications
    - Repeat above steps

CFT: Algebraic Sensitization

- Complexity due to dynamic values
    - Symbolic execution
    - Replace conditions in predicates

    (sensitive to prior path segments?)
  - Then similar to logic sensitization
  - More complex than logical sensitization
- Segment and combination
  - Divide into segments (same)
  - Examine variable relation in predicates
  - Uncorrelated: combination (same)
  - Correlated: path elimination then combination using replaced values via symbolic execution

CFT: Other Steps

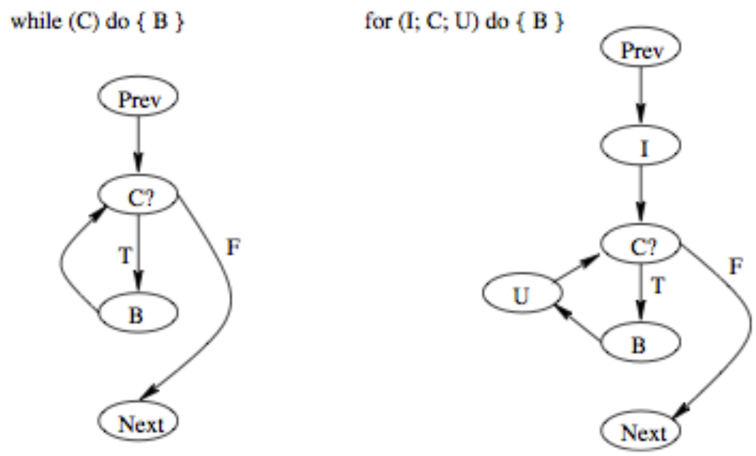
- Similar to Chapter 7
- Execution and followup
  - Path/statement-oriented execution
    - debugger and other tools helpful
  - Followup: coverage and analysis
- Outcome prediction and confirmation
  - Test oracle or outcome prediction
    - may use path-specific properties
  - Path confirmation/verification
  - Guard against coincidental correctness
  - Instrumentation may be necessary
  - Automation: dynamic execution path and related tracing

Loops: What and Why

- Loop: What is it?
  - Repetitive or iterative process
  - Graph: a path with one or more nodes visited more than once
  - Appear in many testing models
  - Recursion
- Why is it important?
  - Intrinsic complexity
    - coverage: how much?
    - effectiveness concerns (above)
  - Practical evidence: loop defects

- Usage in other testing

Loop Examples



- Common loop examples: Fig 11.3 (p.183)
  - left: "while" loops
  - right: "for" loops
  - other (structured) loops can be converted to these loops

Loop Specification

- Deterministic vs. nondeterministic
  - determining #iterations ahead of time?
- Individual loops
  - Loop control: node, predicate, and control variable
  - Loop entry/exit
  - Processing and looping: pre-test, post-test, mixed-test
- Combining loops: structured (nesting & concat.) vs. non-structured (goto)

Loop Testing

- Path coverage:
  - All: infeasible for nested loops:

$$\sum_{i=0}^{M-1} N^i = \frac{N^M - 1}{N - 1},$$

    - Works for i iterations

      => i + 1 iterations most likely fine too

    - Important: how to select?

        - heuristics and concrete measures
        - boundary related problems more likely
- Hierarchical modeling/testing

    - Test loop in isolation first
    - Collapse loop as a single node in higher level models

      ~ Other hierarchical testing techniques

Critical Values for Loop Testing

- General boundary problems

    - Under/over defined problems and closure problems
    - Boundary shift, +/- problem
    - Similar to boundary testing (Chapter 9)
- Lower bound problems

    - Initialization problem
    - Loop execution problem
    - Other boundary problems
- Lower bound test values

    - Bypass, once, twice
    - Min, min + 1, min - 1

Critical Values for Loop Testing

- Upper bound problems

    - Primarily +/-1 problem
    - Capacity problem
    - Other boundary problems
- Upper bound test values

    - Max, max + 1, max - 1
    - Practicality: avoid max combinations
    - Testability: adjustable max
    - Related: capacity/stress testing

Critical Values for Loop Testing

- Other critical values
    - Typical number ((cid:25) usage-based testing)
    - Implicit looping assumptions in hierarchical models
- Generic test cases:
    - Lower bound: alway exists

      => related critical values

    - Upper bound: not always exists
        - if so => related critical values
        - if not => related capacity testing
    - Other critical values

    - Level of details to cover in hierarchical modeling/testing

CFT Usage

- As white box testing (more often)
    - Small programs during unit testing
    - Coarse-grain system level model
- As black box testing (less often)
    - Model built on specification
        - higher level constraints as specs
    - Overall coverage of functionality

    - Can be used for UBST
- Application environment
    - Control flow errors (& decision errors)
    - In combination with other techniques

CFT: Other Issues

- Limit control flow complexity
    - Proper granularity
    - Hierarchical modeling ideas
        - external units/internal blocks
    - Combination with other strategies
        - CFT for frequently-used/critical parts
    - Language/programming methodology

    - Complexity measurement as guidelines

- Need automated support
  - Models from specifications/programs
  - Sensitization support | debugging
  - Path verification | tracing

Dependency vs. Sequencing

- Sequencing
  - Represented in CFT "is-followed-by"
  - Implicit: sequential statements
  - Explicit: control statements & calls
  - Apparent dependency
    - order of execution (sequential machine)
    - but must follow that order?
- Dependency relations
  - Correct computational result?
  - Correct sequence: dependencies
  - Synchronization
  - Must obey: essential
    - captured by data flow/dependency
  - PL/system imposed: accidental
    - CFT, including loop testing

Dependency Relations

- Convenient but not essential
  - stmts not involving common variables
  - some data relations (later in DFT)
  - intermediate variables
- Nonessential iteration/loops
  - most deterministic loops
  - due to language/system limitations
  - example: sum over an array
- Essential dependency
  - data in computation must be defined
  - essential loops: most nondeterministic
  - result depends on latest values

Need for DFT

- Need other alternatives to CFT
    - CFT tests sequencing
        - either implemented or perceived
    - Dependency <> sequencing
    - Other technique to test dependency
- Data flow testing (DFT)
    - Data dependencies in computation
    - Different models/representations

      (traditionally/often as augmented CFT)
    - DFT is not untouched data items within a program/module/etc
    - "data flow" may referred to information passed along from one component to another, which is different from DFT
    - Key: dependency (not flow)?

DFT: Data Operations

- Types of data operation/references
    - Definition (write) and use (read)
    - Define: create, initialize, assign

      (may also include side effect)
    - Use: computational and predicate

      (referred to as C-use or P-use)
- Characteristics of data operations
    - U: nothing change to original, but
        - P-use affects execution path
        - C-use affects computational result
    - D: new (lasting) value
    - Focus on D and related U

Data Flow or Data Dependencies

- Pairwise relations between data operations
    - U-U: no effect or dependency
        - therefore ignore
    - D-U: normal usage case

        - normal DFT
    - D-D: overloading/masking
        - no U in between => problems/defects?

          (racing conditions, inefficiency, etc.)

        - implicit U: D-U, U-D

          expand for conditionals/loops

    - U-D: anti-usage
        - substitute/ignore if sequential
        - convert to other cases in loops
- Data dependency analysis may detect some problems above immediately
- DFT focuses on testing D-U relations

DDG and DFT

- Data dependency graphs (DDGs)

  Computation result(s) expressed in terms of input variables and constants via intermediate nodes and links

- DFT central steps (test preparation)
    - Build and verify DDGs
    - Define and select data slices to cover

      (Slice: all used to define a data item)

    - Sensitize data slices
    - Plan for result checking
- Other steps in DFT can follow standard testing steps for planning and preparation, execution, analysis and followup

DDG Elements

- Nodes in DDG: data definitions (D)
    - Represent definitions of data items
        - typically variables and constants
        - also functional/structural components

          e.g., file/record/grouped-data/etc.

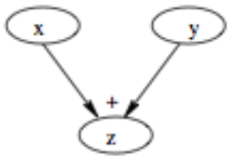
    - Input/output/storage/processing nodes
- Links: relating different D-nodes

  - relation: is-used-by (D-U relation)
  - an earlier D is used by a later D
- Conditional vs unconditional D’s
  - unconditional: directly link nodes
  - conditional: use data selectors (later)

Example DDG Elements

- Unconditional definition example

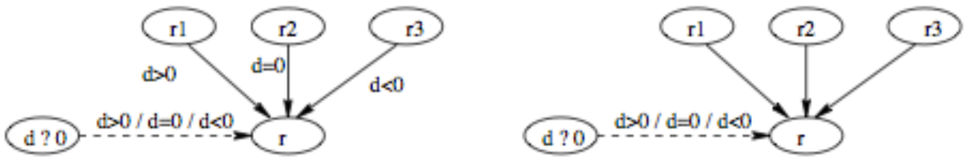
  Fig 11.4 (p.188) for z x + y



- Conditional definition example

  Fig 11.5 (p.190) with a data selector node

  - parallel conditional assignment
  - multi-valued data selector predicate
  - match control and data inlink values



DDG Characteristics and Construction

- Characteristics of DDG
  - Multiple inlinks at most non-terminal nodes
  - Focus: output variable(s)
    - usually one or just a few
  - More input variables and constants
  - "Fan" shape common
  - Usually more complex than CFG

        - usually contains more information

          (omit non-essential sequencing info.)

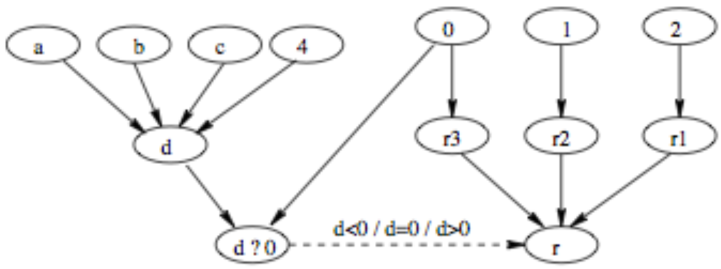
- Source of modeling
    - White box: design/code (traditionally)
    - Black box: specification (new usage)
    - Backward data resolution

      (often used as construction procedure)

Building DDG

- Overall strategy
    - Backward chaining/resolution
    - Computation flow
        - result backward
        - implementation forward
    - For DDGs based on specifications
- Basic steps
    - Identify output variable(s) (OV)
    - Backward chaining to resolve OV
        - variables used in its computation
        - identify D-U relations
        - repeat above steps for other variables
        - until all resolved as input/constants
    - Handling conditional definitions in above

Building DDG: An Example



- Example: Fig 11.6 (p.192)
    - data selector in Fig 11.5 as start

      (we did output r and its data selector already in Fig 11.5)

    - identify non-terminal nodes
    - resolve them, until only input/constants left (at top part)

Building DDG via Code or CFG

- Alternative DDG construction strategy
    - Difficulty with previous strategy

      => build CFG first and then DDG
    - DDG construction based on code

      (no need to build CFG first)
- Sequential D: y <- rhs
    - y defined by the expression rhs
    - no in a branching statement
    - identify all variables xi’s and constants ci’s in rhs
    - link xi’s and ci’s to y
    - if xi is not an input variable, it will be resolved recursively

Building DDG via Code or CFG

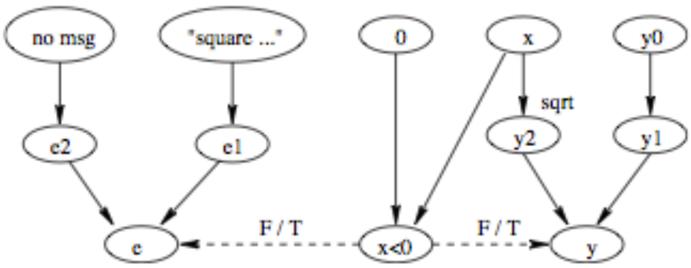
- D in conditional Branches
    - blockI; if P then A else B

      with different y definitions for A and B
    - Build sequential subgraph for each branch
        - blockI; A, with output marked as y1
        - blockI; B, with output marked as y2
    - Build selector predicate subgraph for P with context blockI; P
    - Selector to select between A/B branch,
        - y in the selector node
        - y1 and y2 as data inlink
        - P as control inlink
        - match control and data inlink values
- N-way branch: Similar, but with N-way selectors and corresponding labeling

Building DDG

- Branching with empty "else"

- Special alert: still two choices
    - one updated, one unchanged
  - Selector still needed
- Branching with multiple OVs
  - CFG subgraph for each OV
  - Same control predicated used as inlinks to multiple selectors
  - Example: Fig 11.7 (p.194)



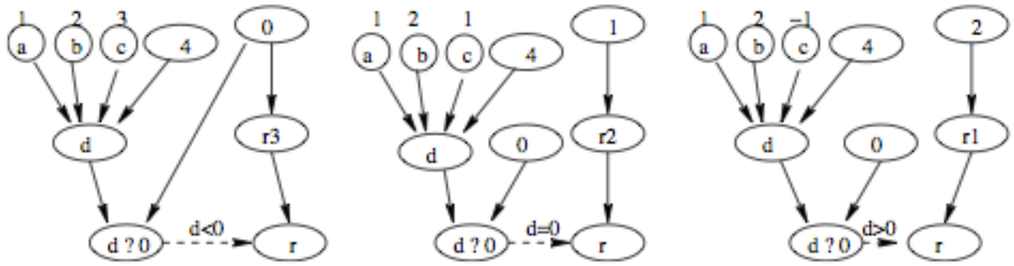
DFT and Loops

- Essential vs nonessential loops
  - Essential: mostly nondeterministic
  - Nonessential iteration/loops
    - most deterministic loops
    - due to language/system limitations
    - example: sum over an array
- Loop testing in DFT
  - Treat loop as a computational node
  - Unfold/unwind once or twice
  - Similar to one or two if's
  - Test basic data relation

    but not all (loop) boundary values

Defining Data Slices

- Data slice: data item and all information needed to determine its value
- No data selector involved) 1 slice
- Single data selector
  - n slices for an n-way selector
  - example: Fig 11.8 (p.195)



Sensitization in DFT

- Test one slice at a time
    - Test cases: (input-variable, value) pairs to compute a slice
    - Combining (sub)slices
    - Focus on variables in tested slice only
    - Use default values for other variables

    (still need in our sequential machines)
- Combining multiple selectors
    - an M-way and an N-way selector
    - independent: not in other's slice

    (not used to define each other)

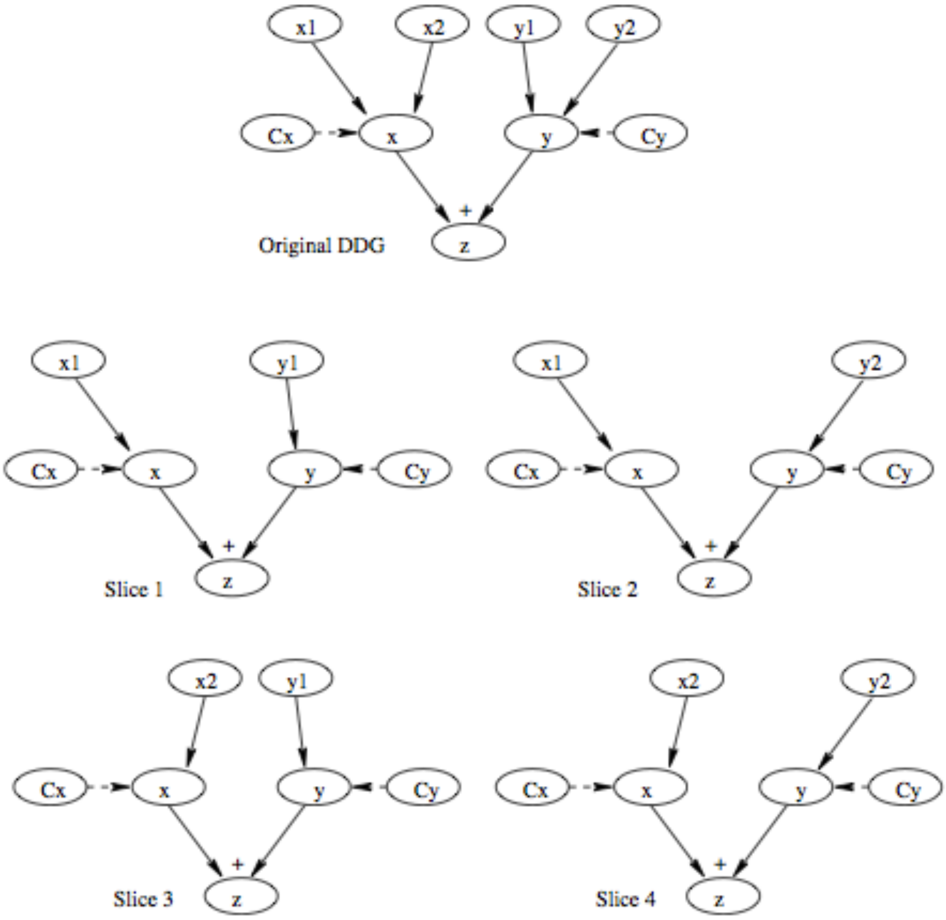
        - direct combination: M x N slices

    ~ sequential concatenation in CFG

    - nesting: M + N (cid:0) 1 combined slices

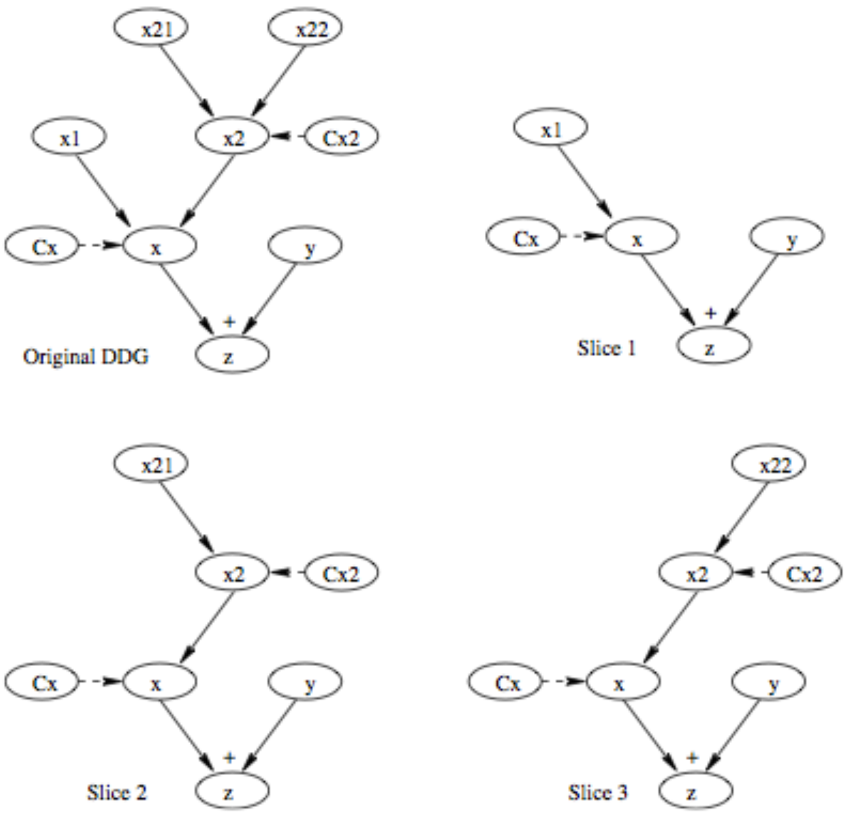
    ~ nesting in CFG

Sensitization in DFT



- Example: Fig 11.9 (p.196)
    - independent selectors for x and y
    - 2 x 2 = 4 combined slices

Sensitization in DFT



- Example: Fig 11.10 (p.197)
    - x2-selector nested in x-selector
    - 3 combined selectors

Sensitization in DFT

- Handling correlations/connections in DFT
- Correlations/connections in unconditional definitions
    - Nothing special need to be done
    - Computational results affected by the shared variables and constants
    - Slice selections not affected
- Correlations/connections in data selectors

  ~ correlated CFT conditions

    - Show up in selector control predicates
    - Correlations captured by shared variable and constants in predicate sub-slices
    - Easily detected, and more easily handled than in CFT

Other Activities in DFT

- Default/random value setting
  - Not affecting the slice
  - But may affect other executions
  - DFT slices has better separation and focus than CFT paths
  - Automated support
- Outcome prediction:

  only need relevant variables in the slice

  (simpler than CFT!)

- Path vs. slice verification:

  (similar, but more powerful and more work, so more need for automated support)

DFT vs CFT

- Comparing with CFT:
  - Independent models
  - DFT closer to specification

    (what result, not how to proceed)

  - More complex, and more info.

    => limit data flow complexity

  - Essential vs. accidental dependencies
  - Loop handling limitations
- Combine CFT with DFT
  - Use in hierarchical testing
  - Nesting, inner CFT & outer DFT
  - CFT for loops

    (then collapse into a single node in DFT)

  - Other combinations to focus on items of concern

DFT vs Others

- Relation to other testing techniques
  - Usage and importance of features

    => similar to Markov OPs

  - Synchronization (example later) in transaction flow testing (TFT)
  - Compare to I/O relations in BT

1 stage vs multiple/different stages

- Beyond software testing
    - Data verification/inspection
    - Data flow machines as oracle?
    - DDG in parallel programs/algorithms
        - help parallelize/speed-up tasks

DFT: Other Issues

- Applicability: (in addition to CFT)
    - Synchronization
    - OO systems: abstraction hierarchies
    - Integration testing
        - communication/connections
        - call graphs
- Need automated support
    - Graph models from (pseudo)programs
    - Sensitization: default setting, etc.
    - Path/slice verification
    - Execution support

DFT in Synchronization Testing

- Correct output produced
    - Input and expected output
    - What we did already in DFT
- Synchronization of arrivals (timing)
    - Input in different arriving orders
    - Example with two way synchronization
        - nothing arrives => no output
        - one arrives => no output
        - two arrive (3 cases: A-B, B-A, AB)

          => correct token generated
    - Combination with correct tokens

DFT: Synchronization Testing

- Multi-way synchronization testing

    - similar: correct output and timing
    - more cases: combinatorial explosion
    - solution: simplify via stages
- Multi-stage synchronization
    - solves combinatorial explosion problem
    - input grouping possibilities
    - in-group synchronization and then cross-group synchronization
    - example: 4-way synchronization
    - shares idea of hierarchical testing