An Introduction to the DES (Discrete Event System) Analyzer: A Performance Analysis and Timing Verification Tool for Concurrent Digital Systems

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Developers and documentation

- Developers (2005 - present)
  - Peggy B. McGee: design and implementation
  - Steven M. Nowick: project management

- Documentation
  - Peggy B. McGee, Steven M. Nowick and E.G. Coffman Jr., “Efficient Performance Analysis of Asynchronous Systems Based on Periodicity," in *Proceedings of the 3rd IEEE/ACM/IFIP International Conference on Hardware/Software Codesign and System Synthesis (CODES+ISSS ’05), pages 225-230, Sept. 2005.*
  - Peggy B. McGee and Steven M. Nowick, “An Efficient Algorithm for Time Separation of Events in Concurrent Systems," in *Proceedings of the 2007 IEEE/ACM International Conference on Computer-Aided Design (ICCAD ’07), Nov. 2007.*

Download site

- Accessible on the web from:
  http://www1.cs.columbia.edu/∼nowick/asynctools
- Package includes:
  - Tool binaries
    - Currently, Linux version only
  - Introduction and tutorial slides (this document)
  - Benchmark examples
  - Other documentation
    - Tool setup instructions (README)
    - Related conference publications
    - Related conference presentation slides

Outline

- The DES Analyzer:
  - Introduction
  - Tool flow overview
- Background on modeling
- Overview of analysis methods
- Tool features
- Tutorial: Design examples and hands-on tutorial
  - Using *des-tse:* Time separation of events (TSE) analysis
    - Example 1a: FIFO ring
    - Example 1b: Micropipeline
  - Using *des-perf:* Performance analysis
    - Example 2: Micropipeline
- Conclusions

The DES Analyzer:

Introduction & tool flow overview

The DES Analyzer: Goals and Applications

- Overall goal:
  - A CAD package for analyzing the timing behavior of digital concurrent systems
    - Asynchronous systems
    - Mixed-timing systems, e.g. GALS
- Applications
  - Performance analysis
    - Finds *average*-case system latency and throughput
    - Finds *worst* and *best*-case system latency and throughput
  - Timing verification
    - Identifies violations of system-level timing constraints
  - Optimization
    - Finds system performance bottlenecks
    - Identifies impossible ordering of events
      - Increases don't-care space for synthesis

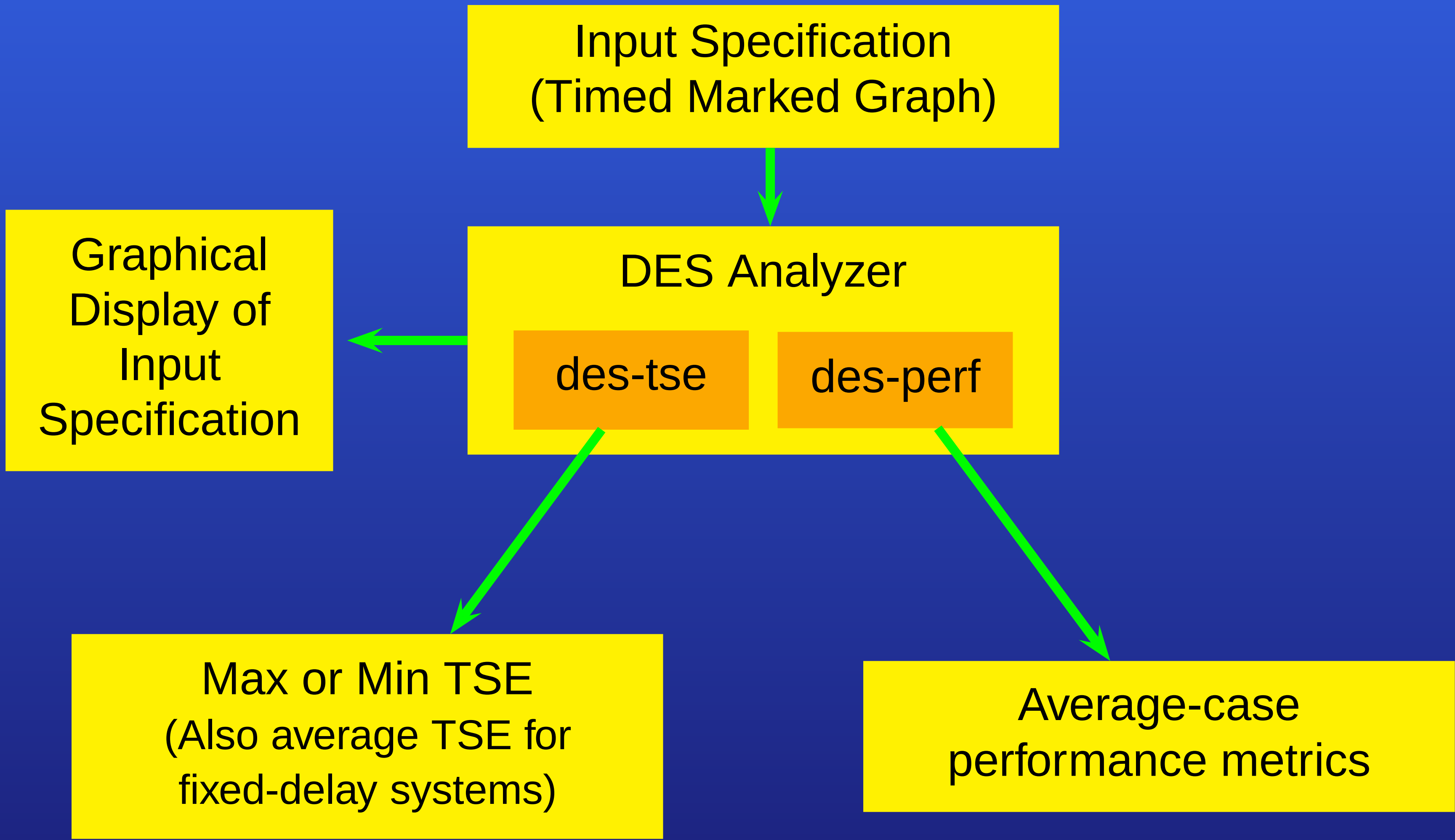
The DES Analyzer: Scope

- Scope:
  - Assumes repetitive systems
    - System interacts with environment continuously
  - Assumes systems modeled with concurrent graphs
    - Currently supports *marked graphs*, a sub-class of Petri nets
  - Handles two types of delay models
    - Bounded delays = lower and upper bounds *(for des-tse)*
      - special case: Fixed delays = single delay number
    - Exponential distributions *(for des-perf)*
  - Currently only handles choice-free systems
    - Support for systems with choice planned in future releases

The DES Analyzer: Tool package

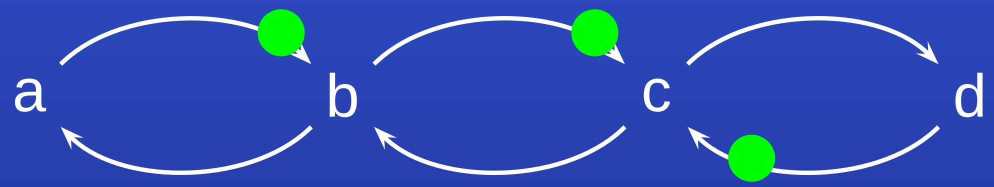
- Two analysis tools under the package:
  1. des-tse
     = *T*ime *S*eparation of *E*vents analysis
     - For *bounded-delay* systems = min/max delay bounds
     - Special case: *fixed-delay* systems = single delay number
     - Applications:
       - Timing verification
       - *Best-* and *worst-case* performance analysis
       - *Average*-case performance analysis
         - for fixed-delay systems only
  2. des-perf
     = *Perf*ormance analysis
     - For *stochastic-delay* systems (exponential distributions)
     - Applications:
       - *Average*-case performance analysis

The DES Analyzer: Tool flow overview



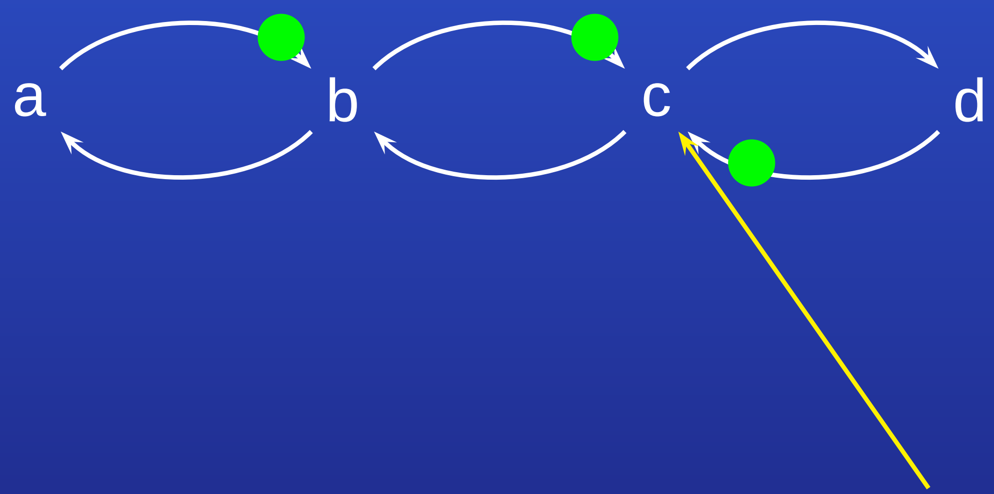
Background on modeling

Background on modeling: Marked graphs



[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, ’71]

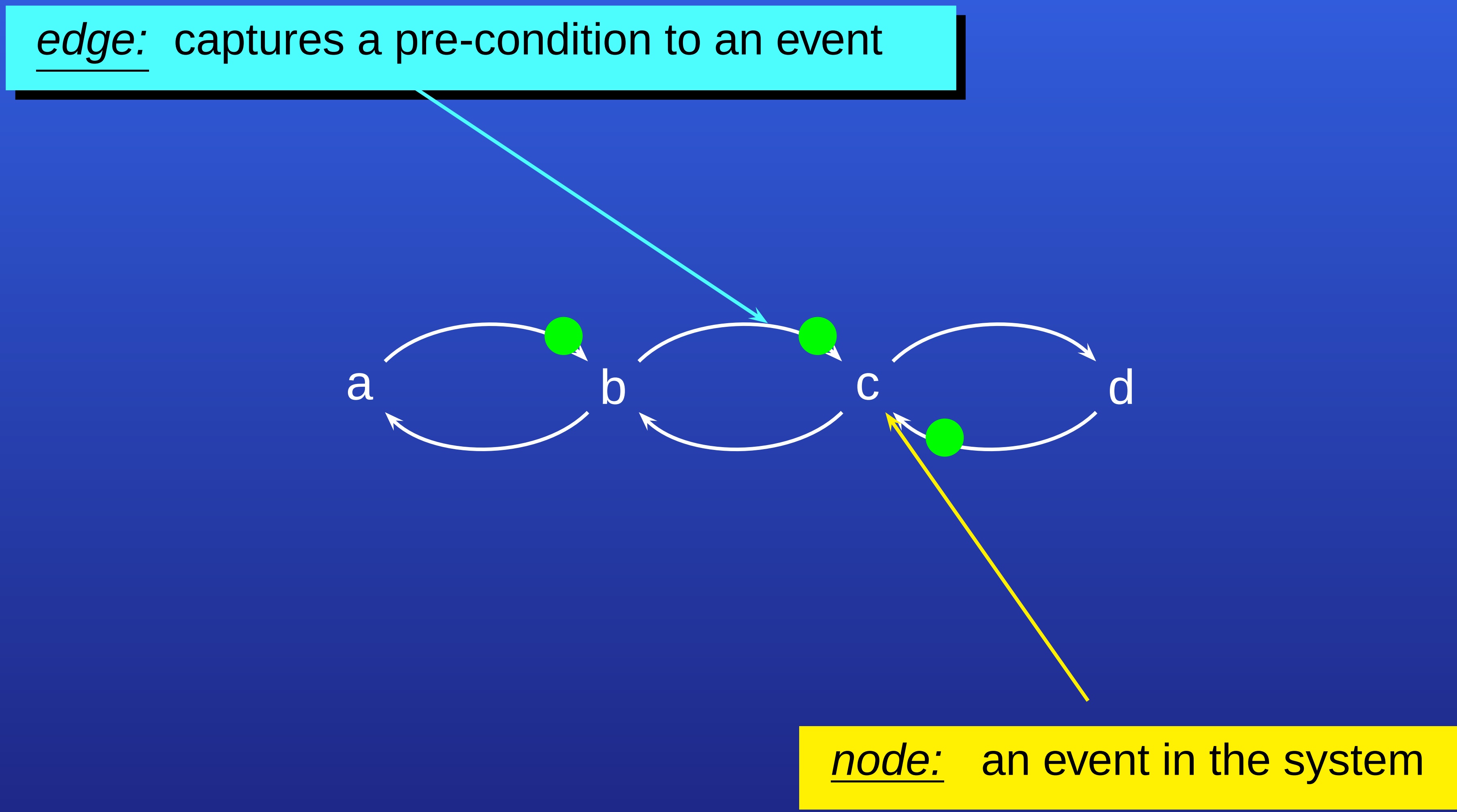
Background on modeling: Marked graphs



node: an event in the system

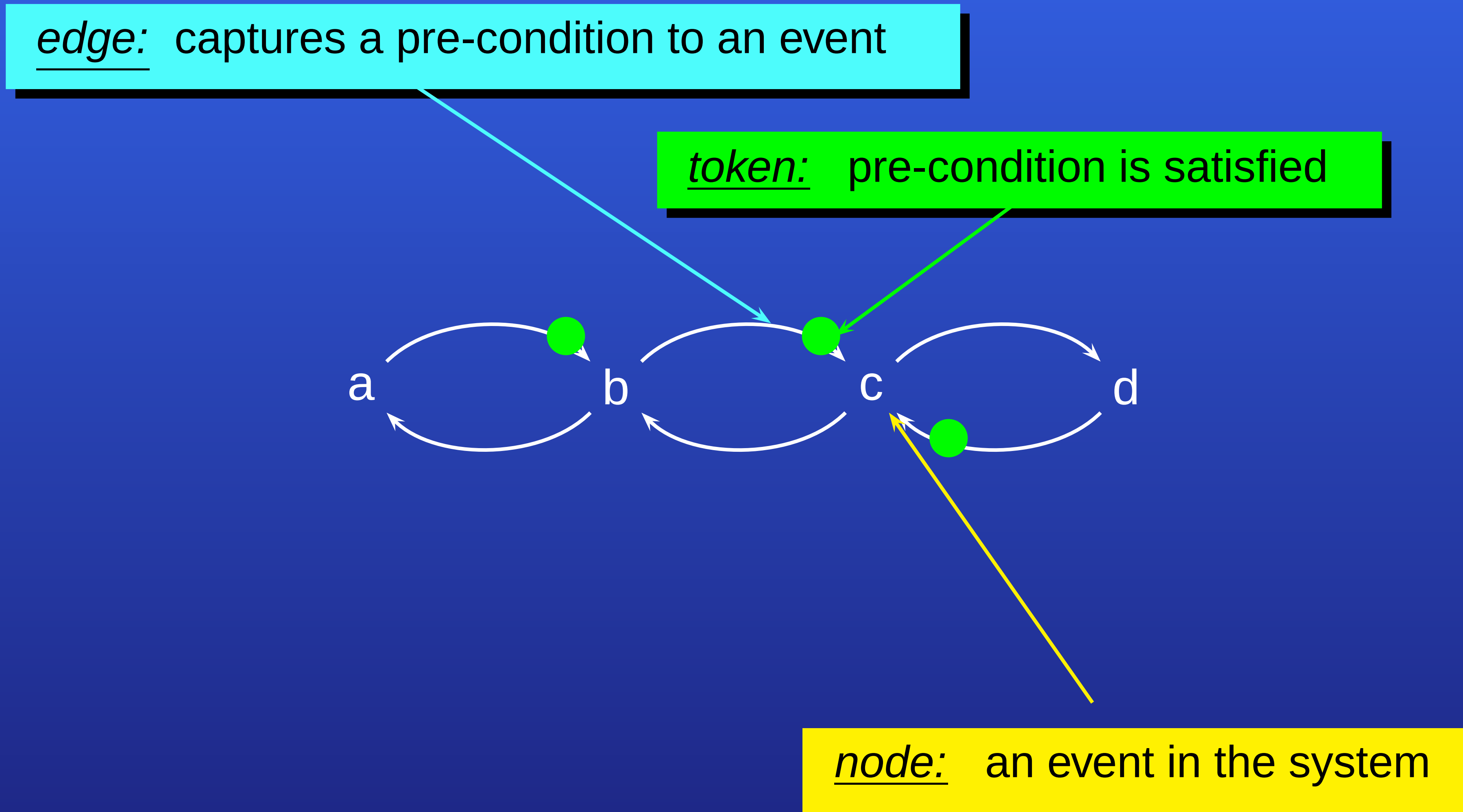
[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, '71]

Background on modeling: Marked graphs



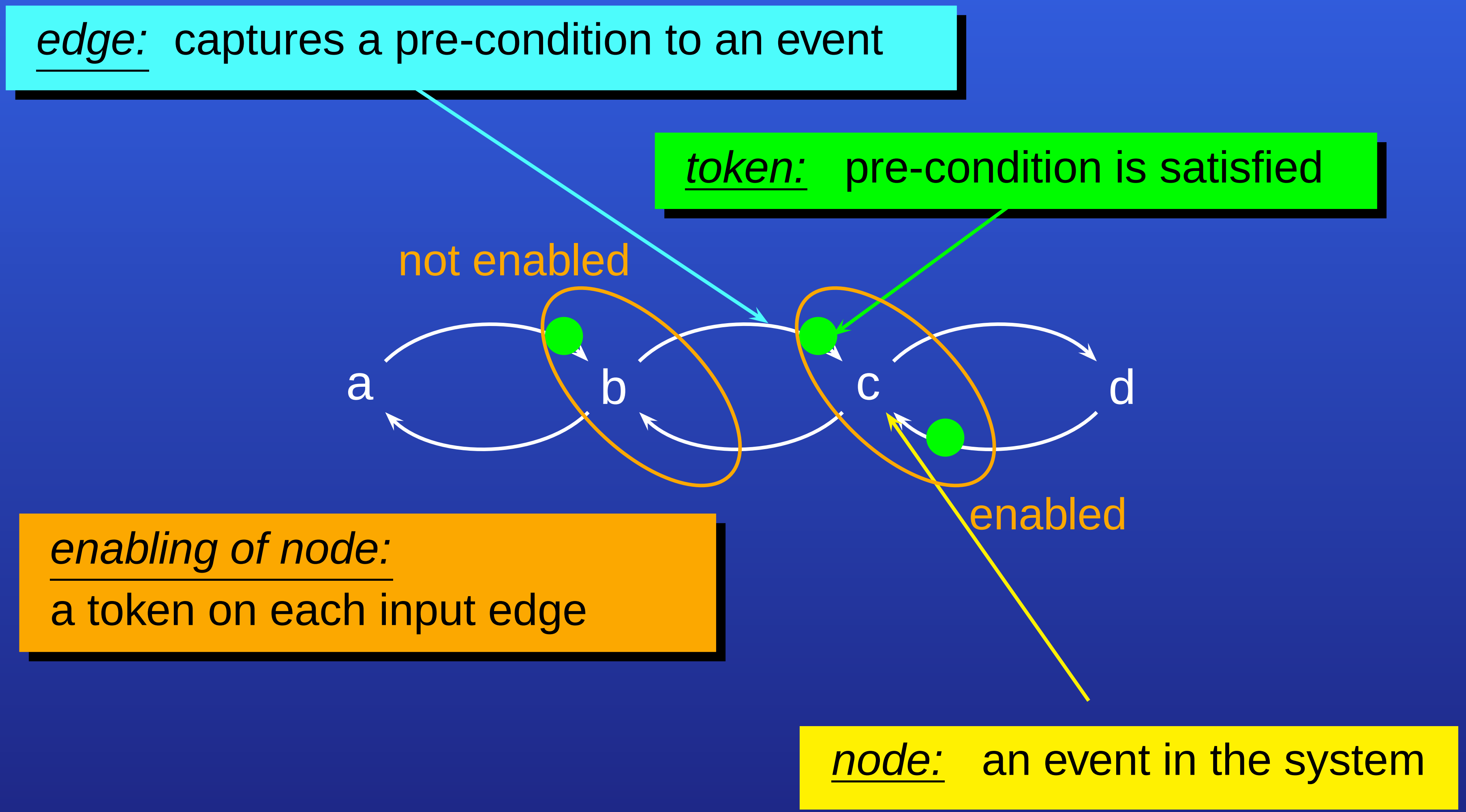
[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, '71]

Background on modeling: Marked graphs



[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, ’71]

Background on modeling: Marked graphs

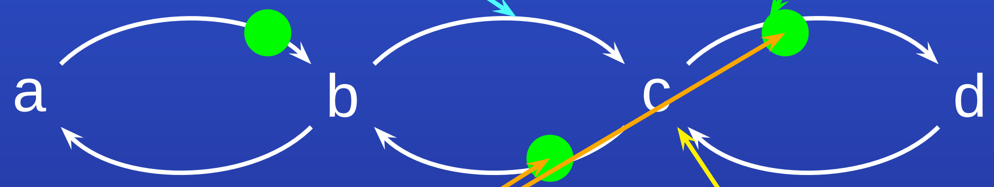


[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, '71]

Background on modeling: Marked graphs

edge: captures a pre-condition to an event

token: pre-condition is satisfied



firing of node: occurrence of an event

► a token deposited onto each output edge

node: an event in the system

[Commoner, Holt, Even and Pnueli, *Journal of Comput. Syst. Sci*, '71]

Background on modeling: Timed marked graphs

Timed marked graphs =
An extension of marked graphs to include timing information

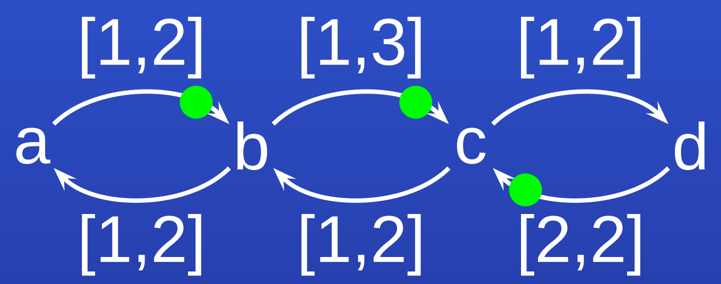
Each *edge* or *node* in the marked graph assigned a *delay*

- Types of delay models:
  - Probabilistic distribution, e.g. exponential distribution
  - Bounded delay = lower and upper bounds
    - Special case: fixed delay = single delay number

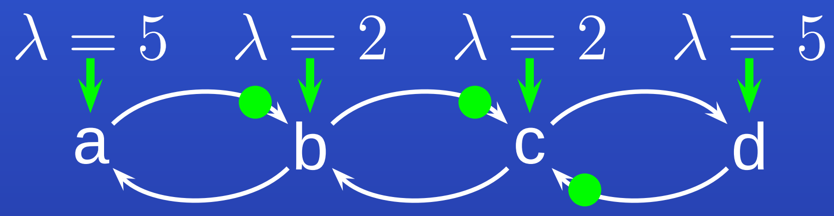
Background on modeling: Timed marked graphs

For the DES Analyzer:

For des-tse:



For des-perf



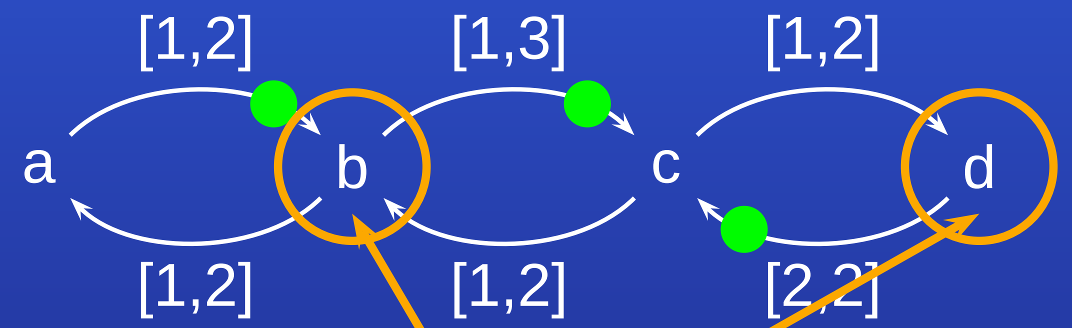
Bounded delays on *edges*

Exponentially-distributed delays on *nodes*
(λ = Mean of delay distribution)

Overview of analysis methods

des-tse: TSE analysis overview

Key concept: Capture *exact timing behavior* of system for timing verification



Example: Find maximum TSE between two consecutive firings of nodes b and d

des-tse: TSE analysis overview

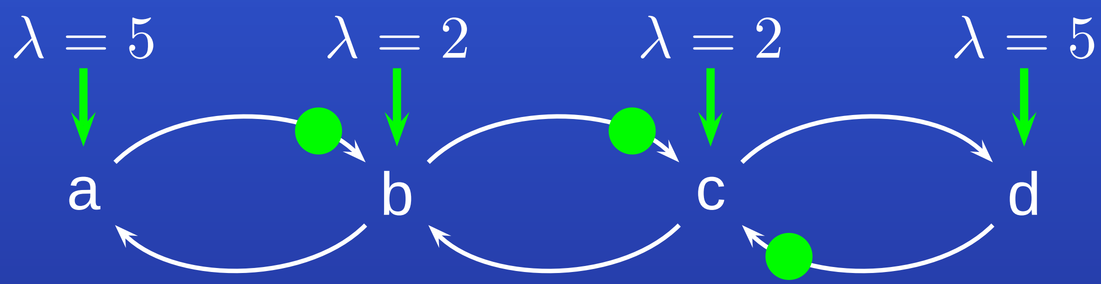
- Evaluates entire time evolution of system analytically
  - System operates in two phases: *“ramp-up”* and *“steady state”*
  - Tool considers timing behavior in both phases
- For fixed-delay systems
  - *Critical cycles* drive asymptotic timing behavior
  - *Critical paths* = longest paths from critical cycle to each node
    - Determine relative firing time of system events
    - Find TSE from relative firing time of events
- For bounded-delay systems
  - Re-cast as two fixed-delay problems
  - Solve individually and combine results

For details, see accompanying ICCAD’07
- *Conference publication*
- *Presentation slides*

des-perf: Performance analysis overview

Key concept: Derive *asymptotic timing behavior* of system using Markovian analysis

λ = Mean delay at node (assumes exponential distribution)



Given timed marked graph:

- Gives asymptotic state distribution
  - Can be further processed to give performance metrics
  - *Example:* average delay(d,b) = 4.8 time units

des-perf: Performance analysis overview

- Evaluates asymptotic timing behavior of system analytically
  - Gives average performance metrics of system at steady-state
- System state transition dynamics captured in a *Markov chain*
  - Markov transition probabilities derived from delay distributions
- Efficient method based on *periodic properties* of system for:
  - Constructing the Markov chain
  - Solving the Markov chain

For details, see accompanying CODES'05
- *Conference publication*
- *Presentation slides*

Tool features

Tool features: Command line input

- Commands to run the tools:
  - > des-tse [input_filename] [options]
  - > des-perf [input_filename] [options]

  Input file format and tool options *same* for des-tse and des-perf

- Input file =
  - Text description of timed marked graph

- Outputs
  - Analysis results
    - Printed onto the standard output
    - Can be piped to a text file for further analysis
  - (Optional) graphical display of input specification

Tool features: Tool options

- “-o *output_filename*"
  - Optional feature: displaying input specification
    - Given input specification, generates a graphical display
      - Graphical display described in text format
      - Viewable in a third-party tool: dotty
        - Viewer can be downloaded from the AT&T website http://www.research.att.com
- “-no_processing"
  - Overrides tool default by performing no analysis
    - Useful when used together with the “-o" option
      - For generating graphical display only
- “-help”
  - Prints “help” information of the commands

Tool features: Input format

- Format of input specification = text file

- Each line in input text file prefixed with an identifier:
  - #
    - The rest of the line is ignored by tool front-end
    - Used for comments
  - .node_list
    - Declares list of all nodes in the marked graph
      example: .node_list a b c d
    - Must be the first line in the input files
      - Excluding comments

Tool features: Input format (cont'd)

- Each line in input text file prefixed with an identifier (cont'd)
  - .edge:
    - Specifies an edge
    - *for des-perf:* followed by input and output nodes of edge
      Example: .edge a b
    - *For des-tse:* followed by input and output nodes of edge
      - Plus three additional arguments:
        - Lower delay bound
        - Upper delay bound
        - 1 (if there is a token on the edge), or 0 (otherwise)

      Example: .edge a b 3.5 5.2 1

Tool features: Input format (cont'd)

- Each line in input text file prefixed with an identifier (cont'd)
  - .init
    - Used in des-tse only
    - Specifies the firing time of enabled nodes at initialization
      Example: .init a 0
  - .check
    - Used in des-tse only
    - Specifies two nodes to check TSE for
      Example: .check a b
    - Alternatively, specifies all nodes
      Example: .check all
  - .node
    - Used in des-perf only
    - Specifies the mean of the delay distribution of a node
      Example: .node a 3.5

Tutorials

0. Getting started

1. TSE analysis with des-tse

Example 1a: FIFO ring

Example 1b: Micropipeline

2. Performance analysis with des-perf

Example 2: Micropipeline

Tutorial 0: Getting started

Tutorial 0: Getting started

Step 1: Making sure the tool is set up

- Make sure the tool and path for the DES Analyzer are set up:
  - Follow the instructions from the README file
- Test the set-up by running the tool with the “-help” option:

  $>$ des-tse -help

  or

  $>$ des-perf -help

  You should see the following output display:

```
Usage: des-tse [input_file] [-o output_file] [-no_processing]

input_file         Filename of input marked graph specification.

-o output_file     Graphical display option.
                   Converts input specification to ".dot" format for display
                   with the dotty viewer and writes to output filename.

-no_processing     Option to perform no analysis. When used with the
                   "-o" option, prints graphical display only.
```

Tutorial 0: Getting started

Step 2: Setting up the dotty viewer (Optional)

- Check if “dotty” is already installed in your environment:
  > which dotty
- If the tool is not found in your path, download the tool from:
  http://www.research.att.com
- Follow the instruction from the tool website to setup the tool.

Tutorial 0: Getting started

Step 3: Copying tutorial files

- Make a new directory for running the tutorials:
  For example:
  $>$ mkdir DES
- Go to it:
  $>$ cd DES
- Create a subdirectory for each of the two tutorials:
  $>$ mkdir tutorial1
  $>$ mkdir tutorial2
- Copy the example input files to the tutorial directories:
  $>$ cp $DES_HOME/examples/des-tse/micropipeline.txt tutorial1/.
  $>$ cp $DES_HOME/examples/des-tse/fifo_ring_run1.txt tutorial1/.
  $>$ cp $DES_HOME/examples/des-tse/fifo_ring_run2.txt tutorial1/.
  $>$ cp $DES_HOME/examples/des-perf/micropipeline.txt tutorial2/.

  $DES_HOME = location of the downloaded DES Analyzer CAD Package

Tutorial 1: TSE analysis with des-tse

Example 1a: FIFO ring

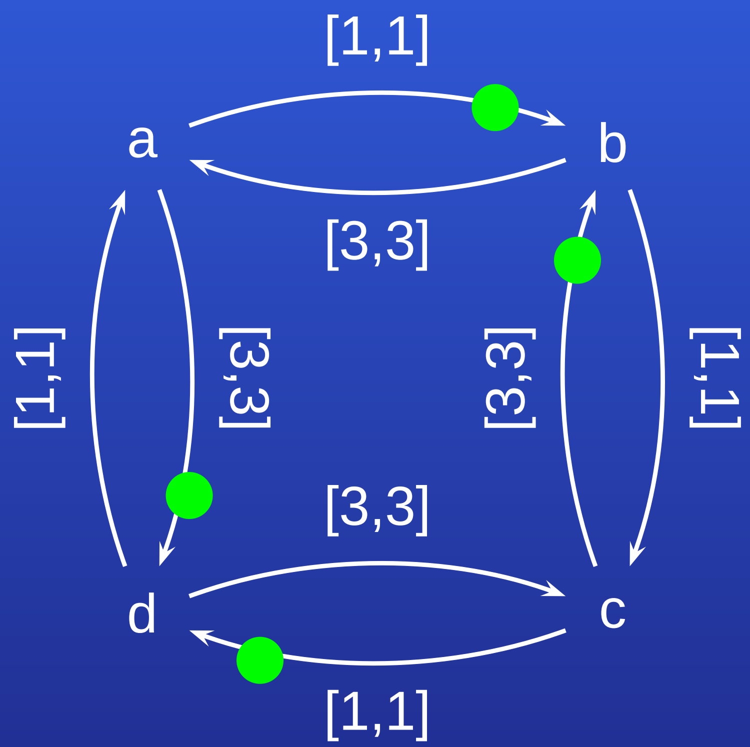
Tutorial 1: TSE analysis with des-tse

- Example 1a: FIFO ring

- In this tutorial we shall learn how to:
  - *Step 1:* Specify a marked graph input for the des-tse tool
  - *Step 2:* Display the input specification graphically
  - *Step 3:* Run TSE analysis
  - *Step 4:* Specify initial conditions of the system
    - and learn how initial conditions affect TSE results
  - *Step 5:* Perform different TSE queries on the system

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

FIFO ring: marked graph model [McGee et al., ICCAD'07]



This example has *fixed delay* on all edges
(e.g. [1,1] = fixed-delay of 1)

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 1: Specifying the marked graph input

- Go to the ‘tutorial1’ directory created in Step 0
- Take a look at the file fifo_ring_run1.txt

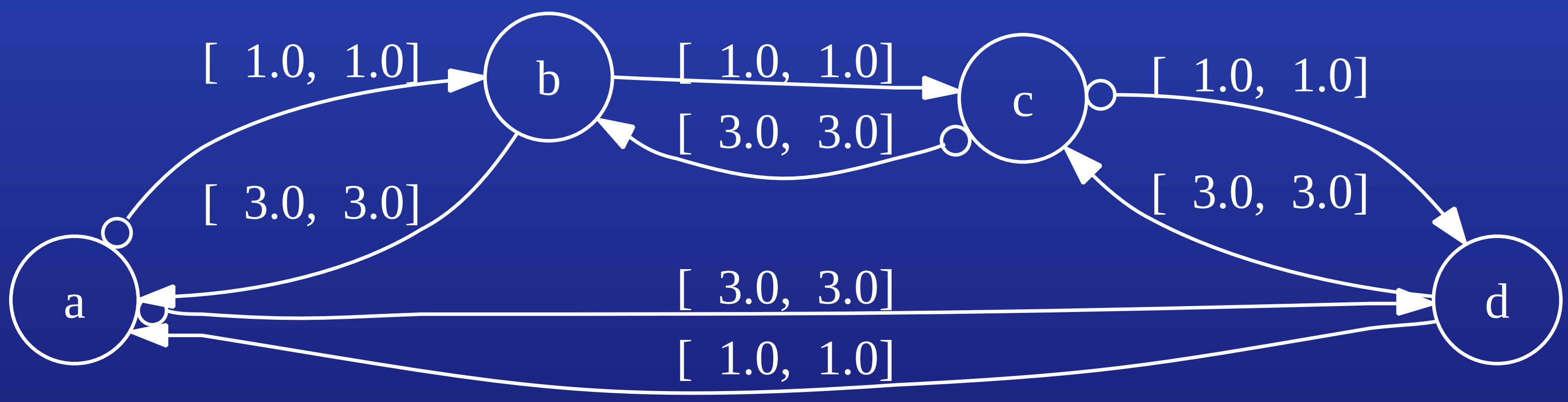
```
# list of nodes in graph
.node_list a b c d

# edge specification: .edge <input node> <output node> <min delay> <max delay> <has token?>
.edge a b 1 1 1
.edge b a 3 3 0
.edge b c 1 1 0
.edge c b 3 3 1
.edge c d 1 1 1
.edge d c 3 3 0
.edge d a 1 1 0
.edge a d 3 3 1

# initial firing time of enabled nodes
.init b 0
.init d 0

# TSE pairs to check
.check b d
```

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 2: Displaying the input specification

- Generate a graphical output:
  > des-tse fifo_ring_run1.txt -o fifo_ring.dot -no_processing
- Display it:
  > dotty fifo_ring.dot

  A window should pop up to display the following:



Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 3: Running TSE analysis

- Run the tool:
  $>$ des-tse fifo_ring_run1.txt
- Look at the output:

```
Event pair    Max TSE    Min TSE
---------------------------------------
(b,d)         6.0        0.0
```

- The result table shows the maximum and minimum
  - TSE between all consecutive firings of events b and d
    - From initialization to steady-state

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 4: Specifying different initial conditions

- Take a look at both files:

  fifo_ring_run1.txt
  fifo_ring_run2.txt

- The two files specify the same design
  - with *same initial marking* = placement of tokens
  - but *different initial firing times* of enabled nodes
    - tokens can have different "lag" times at initialization
      = time before it contributes to the firing of nodes
    - node fires only when all input tokens arrive
      → initial firing time of node = Max. of lag times of input tokens
    - user specifes actual firing time of enabled nodes at initialization
      - system time starts at $t = 0$

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 4: Specifying different initial conditions

- Note the difference between the two specifications:

```
...
# initial firing time of
# enabled nodes
.init b 0
.init d 0
...
```

Run 1

nodes b and d fire at the same time (at $t = 0$)

```
...
# initial firing time of
# enabled nodes
.init b 0
.init d 2
...
```

Run 2

node b fires at $t = 0$
node d fires at $t = 2$

System time $t = 0$ at startup

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 4: Specifying different initial conditions

- Run des-tse on both files and note the difference in results:
  - > des-tse fifo_ring_run1.txt
  - > des-tse fifo_ring_run2.txt
- Result of Run 1:

```
Event pair    Max TSE    Min TSE
--------------------------------------
(b,d)         6.0        0.0
```

- Result of Run 2:

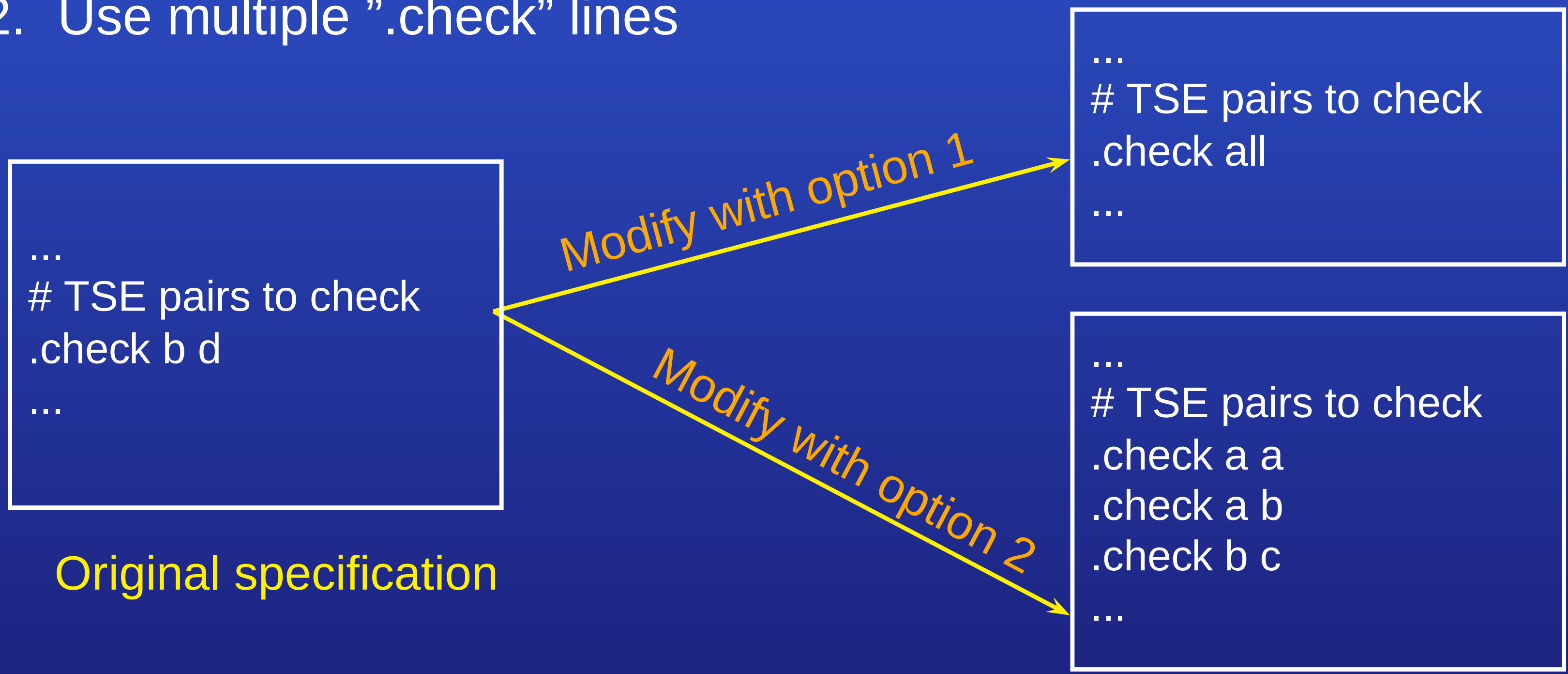
```
Event pair    Max TSE    Min TSE
--------------------------------------
(b,d)         2.0        2.0
```

Note the significant difference in TSE results:
caused by different initial conditions

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 5: Performing different TSE queries

- Modify input files to perform TSE queries on different event pairs
- Two options:
  1. Use ".check all" to query TSE for all event pairs
  2. Use multiple ".check" lines



Original specification

Tutorial 1: TSE analysis with des-tse
- Example 1a: FIFO ring

Step 5: Performing different TSE queries

- Try out different options, run des-tse and observe results
- Example output from using ".check all" with fifo_ring_run2.txt:

```
Event pair     Max TSE     Min TSE
--------------------------------------
(a,a)          8.0         4.0
(a,b)          5.0         1.0
(a,c)          2.0         2.0
(a,d)          3.0         3.0
(b,a)          3.0         3.0
(b,b)          8.0         4.0
(b,c)          5.0         1.0
(b,d)          2.0         2.0
(c,a)          2.0         2.0
(c,b)          3.0         3.0
(c,c)          8.0         4.0
(c,d)          5.0         1.0
(d,a)          5.0         1.0
(d,b)          2.0         2.0
(d,c)          3.0         3.0
(d,d)          8.0         4.0
```

Tutorial 1: TSE analysis with des-tse

Example 1b: Micropipeline

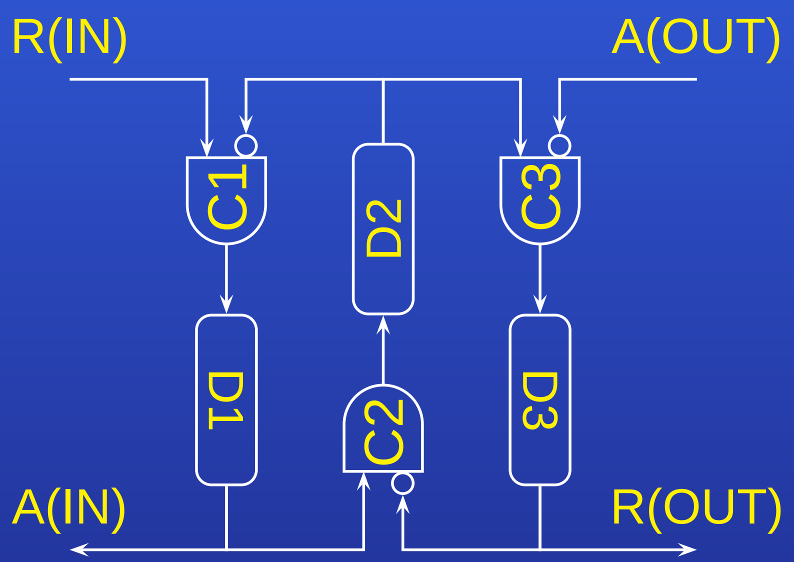
Tutorial 1: TSE analysis with des-tse

- Example 1b: Micropipeline

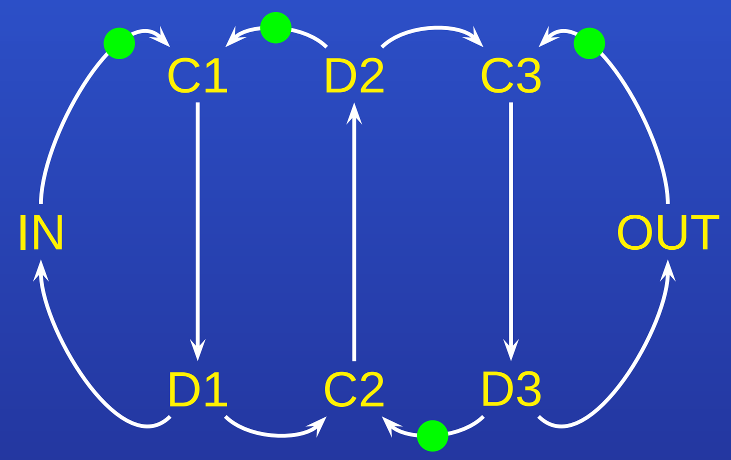
- In this tutorial we shall:
  - Look at a bounded-delay system
  - Run TSE analysis using the same steps as in Tutorial 1

Tutorial 1: TSE analysis with des-tse
- Example 1b: Micropipeline

Micropipeline design [Sutherland, Comm. of the ACM, '89]



Circuit diagram



Marked graph model
(Delays not shown)

Tutorial 1: TSE analysis with des-tse

- Example 1b: Micropipeline

Step 1: Specifying the marked graph input

- Go to the tutorial1 directory created in Step 0:
  $>$ cd tutorial1
- Look at the DES input specification file:
  $>$ less micropipeline.txt

```
# list of nodes in graph
.node_list in c1 d1 c2 d2 c3 d3 out

# edge specifications
.edge in c1 5 10 1
.edge c1 d1 1 1 0
.edge d1 in 4 5 0
.edge c2 d2 1 1 0
.edge d2 c1 4 8 1
.edge c3 d3 1 1 0
.edge d3 out 4 5 0
.edge out c3 5 10 1
```

```
# initial firing time of enabled nodes
.init c1 0

# TSE pairs to check
.check in out
```

Tutorial 1: TSE analysis with des-tse
- Example 1b: Micropipeline

Step 2: Displaying the input specification

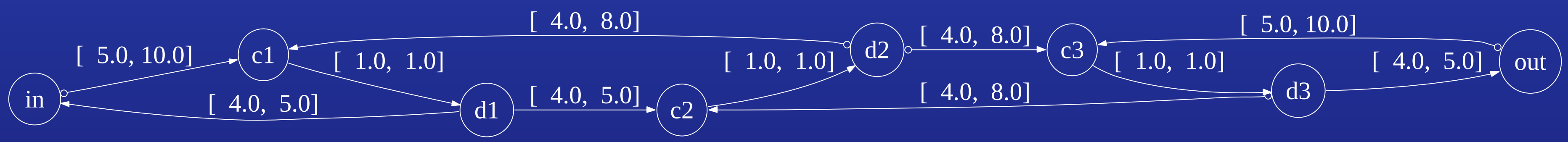
- Generate graphical output:

  > des-tse micropipeline.txt -o micropipeline.dot -no_processing

- Display it:

  > dotty micropipeline.dot

  A window should pop up to display the following:



Tutorial 1: TSE analysis with des-tse
- Example 1b: Micropipeline

Step 3: Running TSE analysis

- Run the tool:
  $>$ des-tse micropipeline.txt
- Look at the output:

```
Event pair     Max TSE     Min TSE
--------------------------------------
(in,out)         13.0        10.0
```

Step 4: Specifying different initial conditions

- Modify the initial conditions in input file as in Tutorial 1
- Run des-tse and observe results

Step 5: Performing different TSE queries

- Modify the TSE query section in input file as in Tutorial 1
- Run des-tse and observe results

Tutorial 2: Performance analysis with des-perf

Example 2: Micropipeline

Tutorial 2: Performance analysis with des-perf
- Example 2: Micropipeline

- In this tutorial we shall learn how to:
  - *Step 1:* Specify a marked graph input for the des-perf tool
  - *Step 2:* Display the input specification graphically
  - *Step 3:* Run performance analysis

Tutorial 2: Performance analysis with des-perf
- Example 2: Micropipeline

Step 1: Specifying the marked graph input

- Go to the tutorial2 directory created in Step 0:
  $>$ cd tutorial2
- Look at the input specification file:
  $>$ less micropipeline.txt

```
# list of nodes in graph
.nodes IN C1 D1 C2 D2 C3 D3 OUT

# edge list:
# .edge <input node> <output node>
.edge IN C1
.edge C1 D1
.edge D1 IN
.edge C2 D2
.edge D2 C1
.edge C3 D3
.edge D3 OUT
.edge OUT C3
```

```
# node list:
# .node <mean delay>
.node IN 10
.node C1 1
.node D1 5
.node C2 1
.node D2 5
.node C3 51
.node D3 5
.node OUT 10
```

Tutorial 2: Performance analysis with des-perf
- Example 2: Micropipeline

Step 2: Displaying the input specification

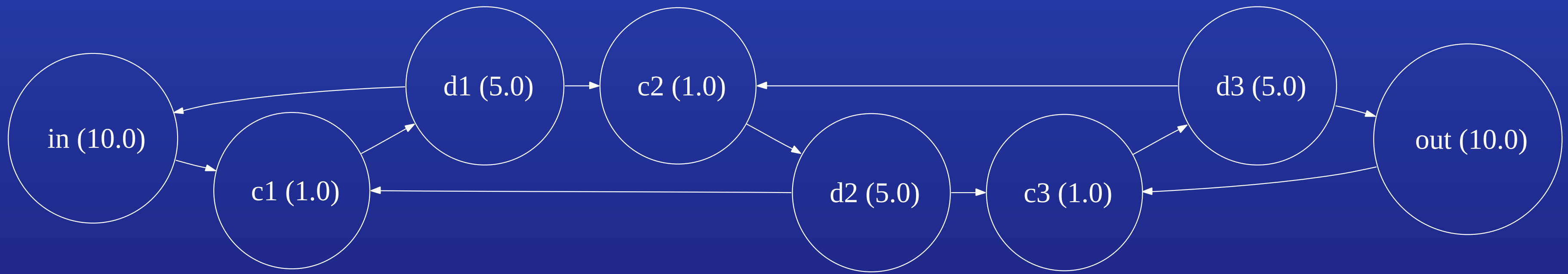
- Generate a graphical output:

  $>$ des-perf micropipeline.txt -o micropipeline.dot -no_processing

- Display it:

  $>$ dotty micropipeline.dot

  A window should pop up to display the following:



Tutorial 2: Performance analysis with des-perf
- Example 2: Micropipeline

Step 3: Run des-perf

- Run the tool:
  > des-perf micropipeline.txt
- Look at the output:

```
SYMBOLIC STATE TABLE
--------------------------------
0 | 56 41 01
1 | 45 23 20 67
2 | 75 45 12
3 | 63 67 41 20
4 | 63 67 41 01
5 | 56 12
6 | 23 01 45 67
7 | 75 45 23 20
8 | 63 75 41 20
9 | 63 67 12
.....
.....
```

```
STATIONARY STATE DISTRIBUTION
--------------------------------
0 | 2.872948e-01
1 | 2.127045e-01
2 | 2.872949e-01
3 | 2.127045e-01
4 | 1.542347e-01
5 | 4.788247e-01
6 | 1.063522e-01
7 | 1.542347e-01
8 | 1.063522e-01
9 | 3.796258e-01
.....
.....
```

Tutorial 2: Performance analysis with des-perf
- Example 2: Micropipeline

Step 3: Run des-perf

- Two sections in the results table
  - Symbolic state table
    - State = a marking in the marked graph
      = placement of tokens on graph edges
    - Output representation:
      - *Column 1:* symbolic state
      - *Column 2:* edges with tokens in the state
  - Stationary state distribution
    - Output representation:
      - *Column 1:* symbolic state
      - *Column 2:* asymptotic probability of state
- Results can be further processed to give other useful results:
  - Average latency, throughput, etc.

Conclusions

- Two analysis tools under the DES Analyzer CAD package
  - des-tse
  - des-perf
- Used in the design flow for concurrent digital systems for
  - Verifying timing correctness
  - Measuring system performance
  - Getting feedback on performance bottlenecks for optimization