Quantitative Verification of Embedded Software: The GameTime Approach

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Verification "=" Synthesis

- Different from a definitional and complexity-theoretic viewpoint
- Similar from the viewpoint of algorithmic solution

- Synthesis in Verification
  - The hard parts of verification involve synthesis "sub-tasks"
- Verification in Synthesis
  - Synthesis typically involves a verification check (e.g., equivalence checking for circuits)

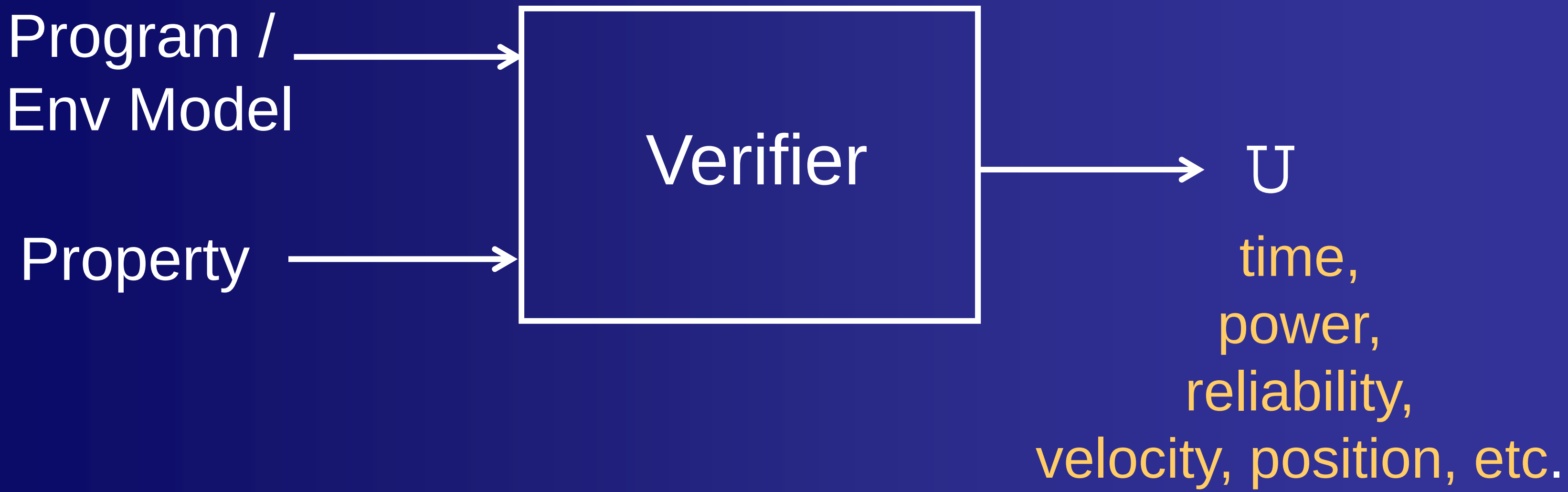
S. A. Seshia, "Sciduction: Combining Induction, Deduction, and Structure for Verification and Synthesis", DAC 2012

Artifacts Synthesized in Verification

- Inductive / auxiliary invariants
- Auxiliary specifications (e.g., pre/post-conditions, function summaries)
- Environment assumptions / E interface specifications
- Abstraction fun odels
- Interpol
-
- te lemmas for compositional ning
- Theory lemma instances in SMT solving
- …

EVERYTHING IS A SYNTHESIS PROBLEM!

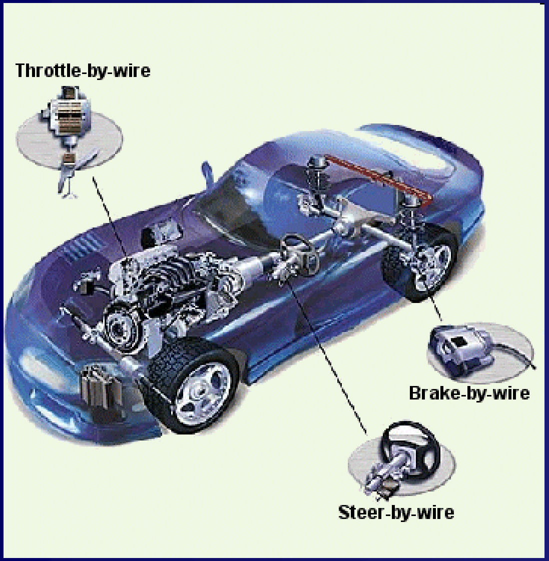
Quantitative Verification of Embedded Software



Models include quantitative parameters

Results only as accurate as the model (parameters)

Example: Deadline Properties

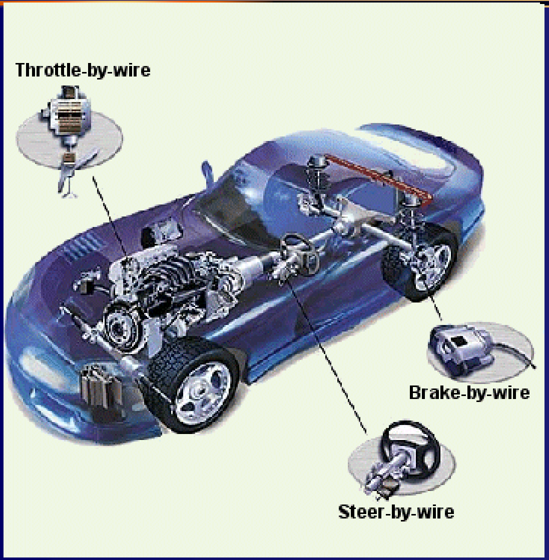


Does the brake-by-wire software task always actuate the brakes within 1 ms?

Safety-critical real-time embedded systems

Need to perform Timing Analysis

Challenge in Timing Analysis



Does the brake-by-wire software always actuate the brakes within 1 ms?

NASA's Toyota UA report (2011) mentions:
"*In practice…there are significant limitations*"
(in the state of the art in timing analysis).

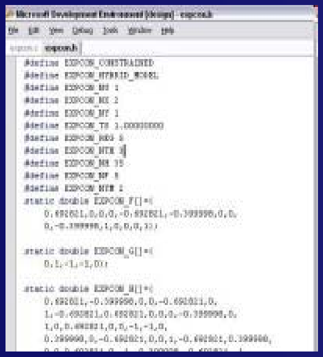
CHALLENGE: ENVIRONMENT MODELING

Need a good model of the *platform*
(processor, memory hierarchy, network, I/O devices, etc.)

This Talk

- What makes Timing Analysis Hard
- The GameTime Approach
  - Learning Program-Specific Environment Model
    - *Inductive Synthesis*
- Generalization: Induction + Deduction
  - Several applications in Verification & Synthesis

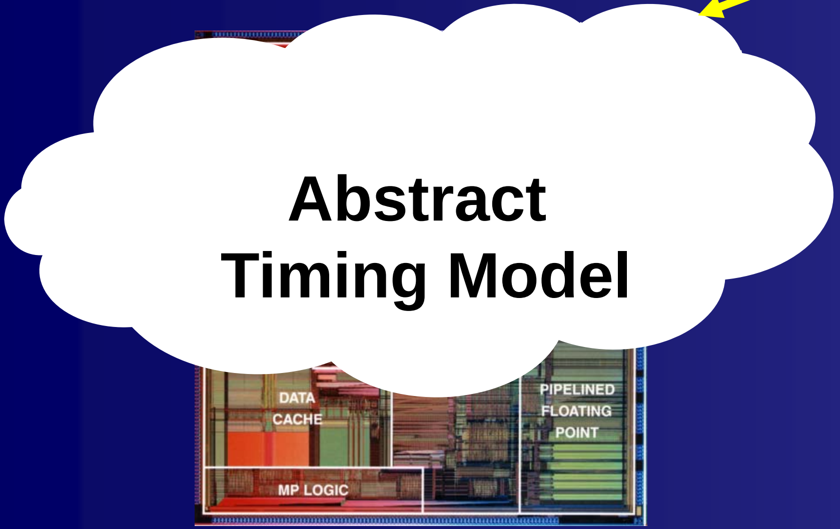
Current State-of-the-art for Timing Analysis


Microsoft Development Environment [design] - expcon.h
File Edit View Debug Tools Window Help
expcon.h

```
#define EXPCON_CONSTRAINED
#define EXPCON_HYBRID_MODEL
#define EXPCON_NU 1
#define EXPCON_NX 2
#define EXPCON_NY 1
#define EXPCON_TS 1.00000000
#define EXPCON_NDS 5
#define EXPCON_NTR 3
#define EXPCON_NR 15
#define EXPCON_NP 5
#define EXPCON_NTM 2
static double EXPCON_F[]={
    0.692821,0,0,0,-0.692821,-0.399998,0,0,
    0,-0.399998,1,0,0,0,1};

static double EXPCON_G[]={
    0,1,-1,-1,0};

static double EXPCON_H[]={
    0.692821,-0.399998,0,0,-0.692821,0,
    1,-0.692821,0.692821,0,0,0,-0.399998,0,
    1,0,0.692821,0,0,-1,-1,0,
    0.399998,0,-0.692821,0,0,1,-0.692821,0.399998,
```



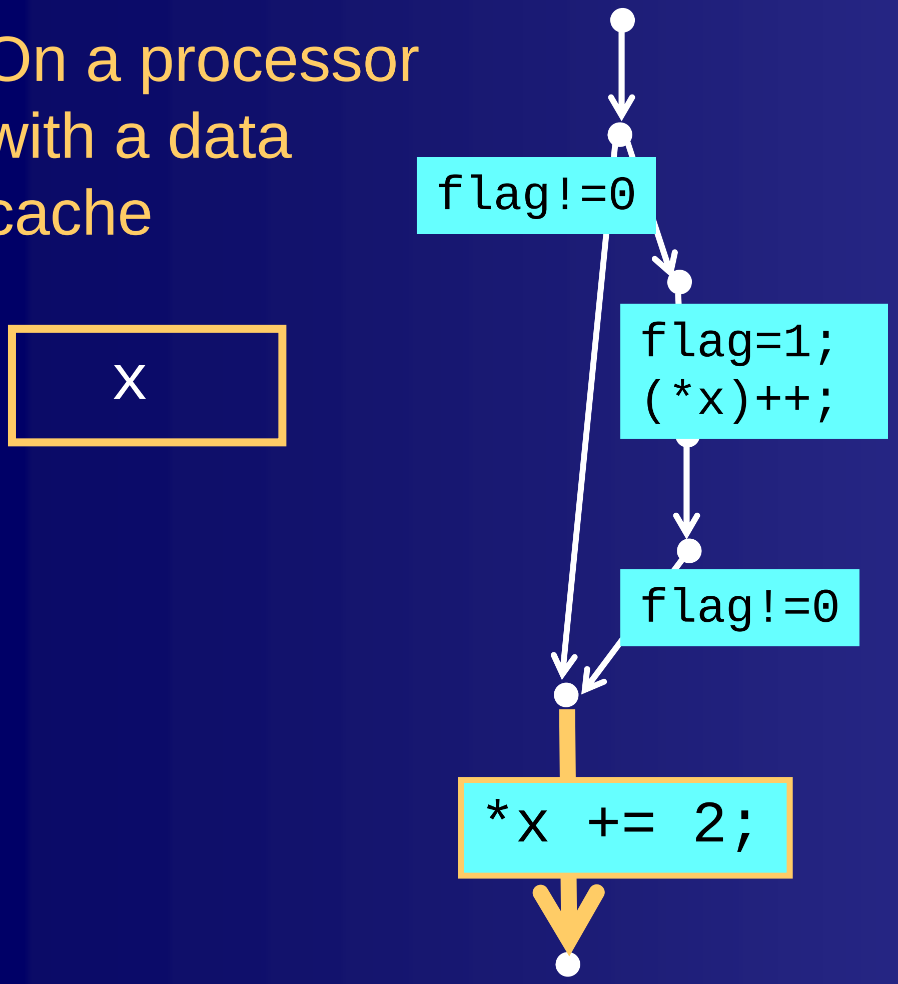
- Program = Sequential, terminating program
- Runs uninterrupted

PROBLEM:
Takes <u>several man-months</u> to construct!
Also: limited to extreme-case analysis

- Environment = Single-core Processor + Instruction/Data Cache

Complexity of a Timing Model: Path Space x Platform State Space

On a processor with a data cache



Program CFG unrolled to a DAG

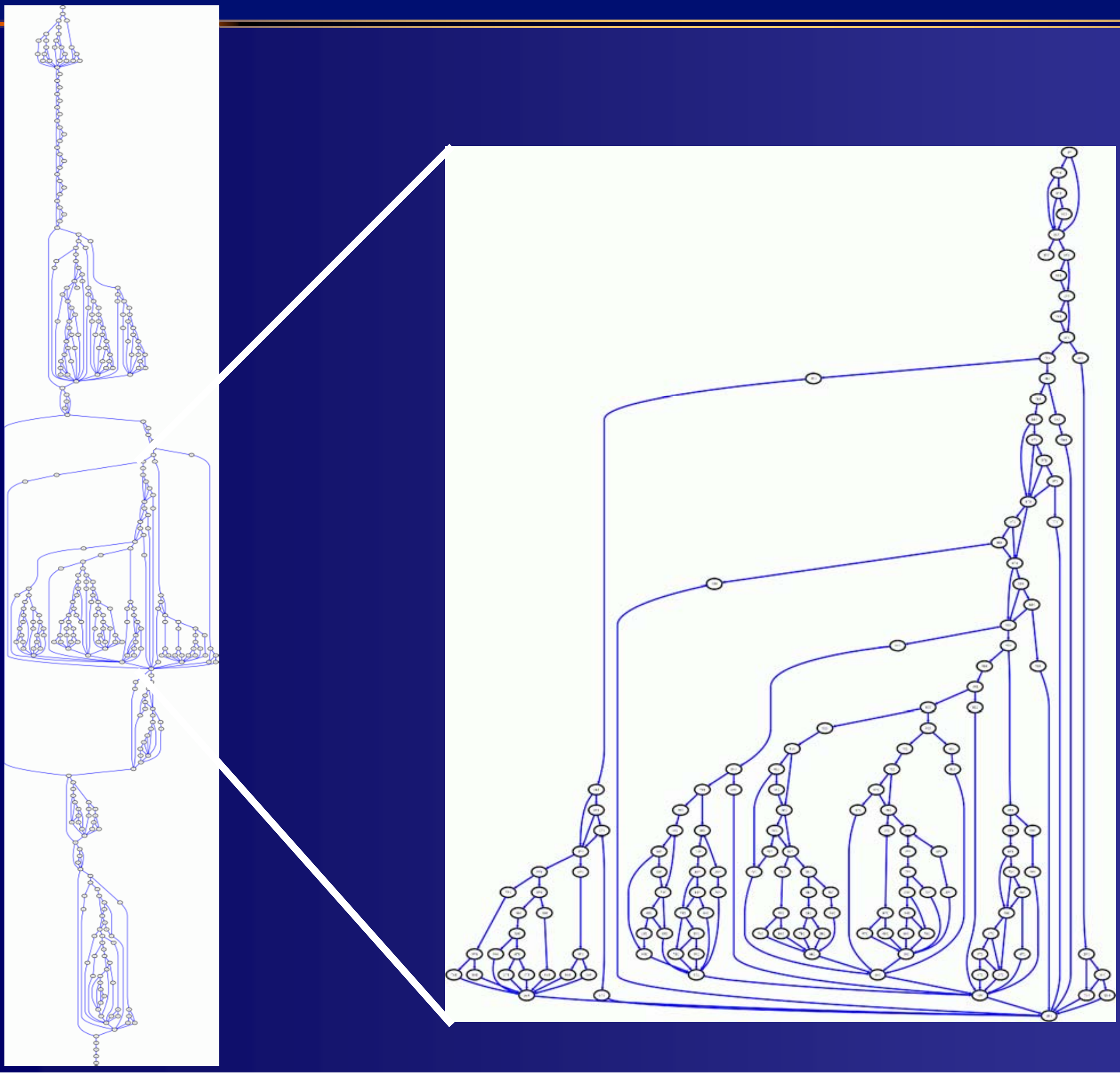
Timing of an edge (basic block) depends on:

- **Path** it lies on
- Initial **platform state**

Challenges:

- Exponential number of paths and platform states!
- Lack of visibility into platform state

Example: Automotive Window Controller



~ 1000 lines of C code

~ 10^{16} paths

Outline

- What makes Timing Analysis Hard
- The GameTime Approach
  - Learning Program-Specific Environment Model
    - *Inductive Synthesis*
- Generalization: Induction + Deduction
  - Several applications in Verification & Synthesis

Our Approach and Contributions

[ICCAD ’08, ACM TECS’12]

Model the estimation problem as a Game

- Tool vs. Platform

- Measurement-based, but minimal instrumentation
  - Perform *end-to-end* measurements of selected (linearly many) paths on platform
- Learn Environment Model
  - Similar to online shortest path in the ‘bandit’ setting
- Online, randomized algorithm: GameTime
  - Theoretical guarantee: can predict worst-case path with arbitrarily high probability under model assumptions
- Uses satisfiability modulo theories (SMT) solvers for test generation

The Game Formulation

- Complexity '=' Path Space x Platform State Space
  (controllable) (uncontrollable)

- Model as a 2-player Game: Tool vs. Platform
  - Tool selects program paths
  - Platform 'selects' its state (possibly adversarially)

- Questions:
  - What is a good class of platform models?
  - How to select paths so that we can learn an accurate platform model by executing those?

Platform Model

Platform selects weights for edges of the CFG

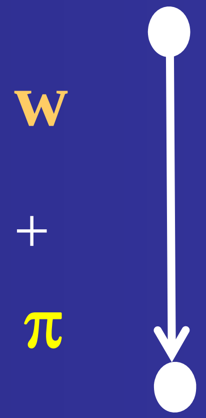
Models path-independent timing

Nominal weight on edge of unrolled CFG

+

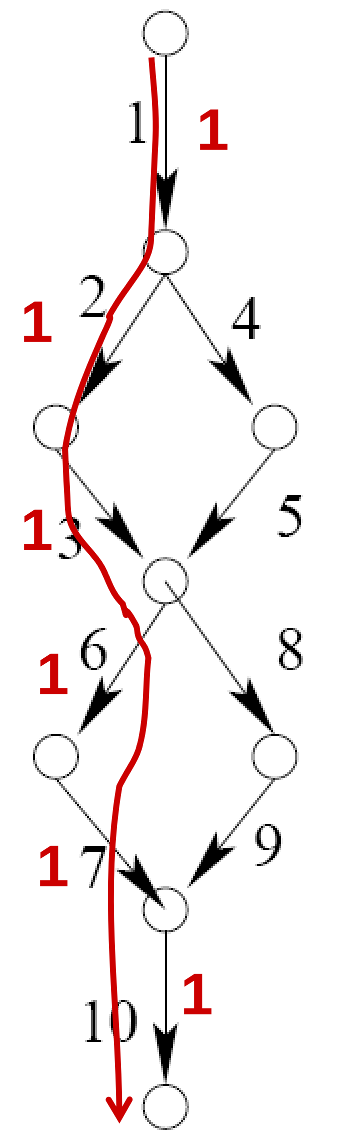
Path-specific perturbation

Models path-dependent timing



A Path is a Vector x 5 {0,1}^{m}

(m = #edges)



$$\boxed{x1 = (1,1,1,0,0,1,1,0,0,1)}$$

$$x2 = (1,0,0,1,1,0,0,1,1,1)$$

$$x3 = (1,1,1,0,0,0,0,1,1,1)$$

$$x4 = (1,0,0,1,1,1,1,0,0,1)$$

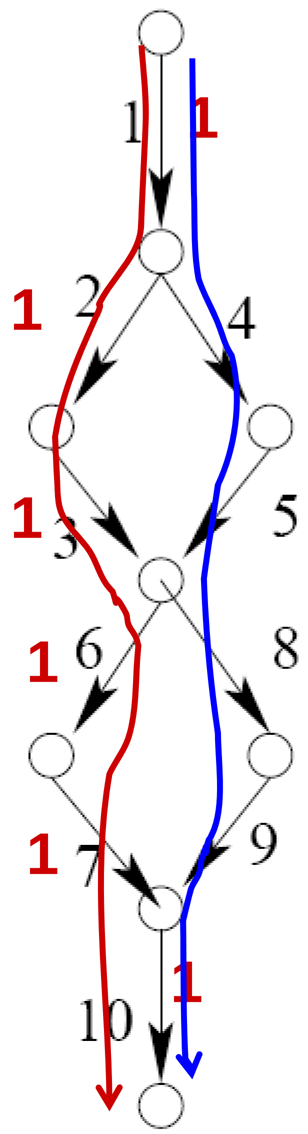
<u>Insight:</u>

Only need to sample

a Basis

of the space of paths

Basis Paths



$x1 = (1,1,1,0,0,1,1,0,0,1)$

$x2 = (1,0,0,1,1,0,0,1,1,1)$

$x3 = (1,1,1,0,0,0,0,1,1,1)$

$x4 = (1,0,0,1,1,1,1,0,0,1)$

$x4 = x1 + x2 - x3$

#(basis paths ‰ m

< 200 basis paths for automotive controller

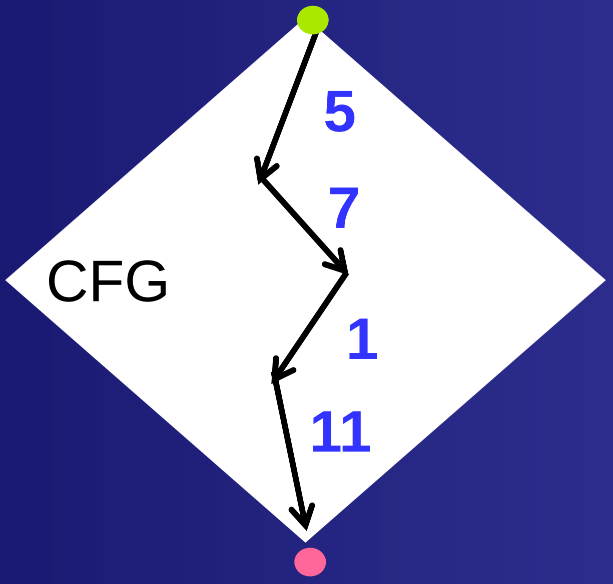
Useful to compute certain special bases called "barycentric spanners"

Timing Analysis Game (Our Model)

Played over several rounds $t = 1, 2, 3, \ldots, \tau$

At each round t:

Tool picks x_t



Platform picks w_t

Platform picks $\pi_t(x_t)$

(-1, -1, -1, -1)

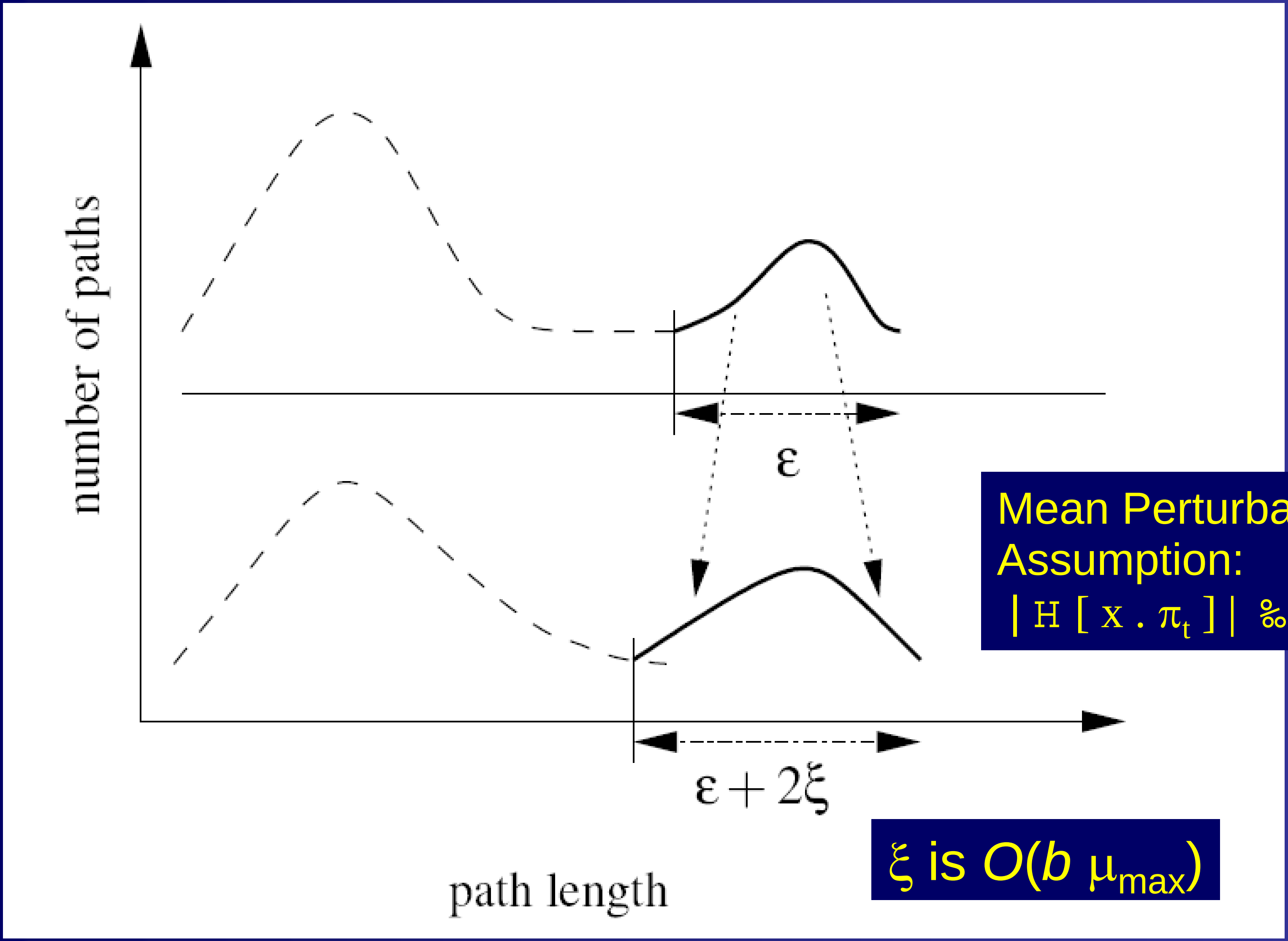
Tool observes $l_t = x_t f(w_t + \pi_t)$

(5+7+1+11) - 4 = 20

At round τ : Tool makes prediction (longest path x^*_τ)

- Tool wins iff its prediction is correct

Theorem about Estimating Distribution (pictorial view)



Mean Perturbation Assumption: ; x 5 *Paths* | H [x . π_t] | ‰ μ_{max}

ξ is $O(b\ \mu_{max})$

Some Experimental Results

(details in ICCAD'08, ACM TECS, FMCAD'11 papers)

- GameTime is Efficient
  - E.g.: 7 x 10^{16} total paths vs. < 200 basis paths
- Accurately predicts WCET for complex platforms
  - I & D caches, pipeline, branch prediction, …
- Basis paths effectively encode information about timing of other paths
  - Found paths 25% longer than sampled basis
- GameTime can accurately estimate the distribution of execution times with few measurements
  - Measure basis paths, predict other paths

Recent Results

- Timing analysis of **interrupt-driven** programs [FMCAD 2011]
  - Idea: context-bounded analysis + GameTime

- **Energy estimation** on embedded devices
  - Use GameTime algorithm with iCount hardware [P. Dutta et al.]

Generalizing the GameTime Approach

- Identify "Synthesis Sub-task" in verification
  - Environment Modeling
- Make a Structure Hypothesis
  - $w + \pi$ model for the platform
- Use Inductive Inference
  - learning from measurements
- Combine with Deductive Reasoning
  - SAT/SMT solving for test generation

S. A. Seshia, "Sciduction: Combining Induction, Deduction, and Structure for Verification and Synthesis," Tech. report, UCB/EECS, May 2011 & DAC 2012.

Induction + Deduction + Structure
Other Projects

- **Switching logic synthesis** for hybrid systems
  - For safety and optimality
  - [Jha et al., ICCPS 2010, EMSOFT 2011]
- **Program synthesis**, malware analysis
  - [Jha et al., ICSE 2010]
- **Synthesizing fixed-point code** from floating-point specifications
  - [Jha & Seshia, 2011]
- Controller **synthesis from temporal logic**
  - [Li et al., MEMOCODE 2011]
- **Hardware verification**
  - [Brady et al., FMCAD 2011]