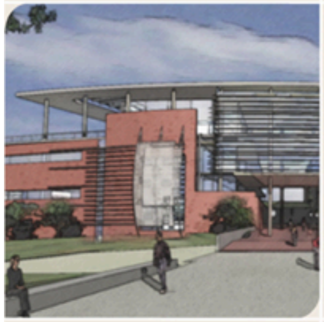

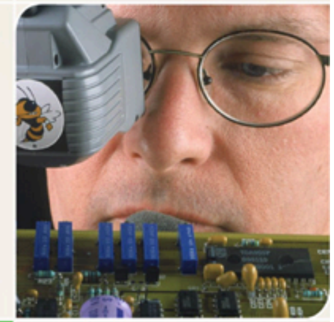

Opportunistic Computing: A New Paradigm for Scalable Realism on Many-Cores

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Advised by Santosh Pande

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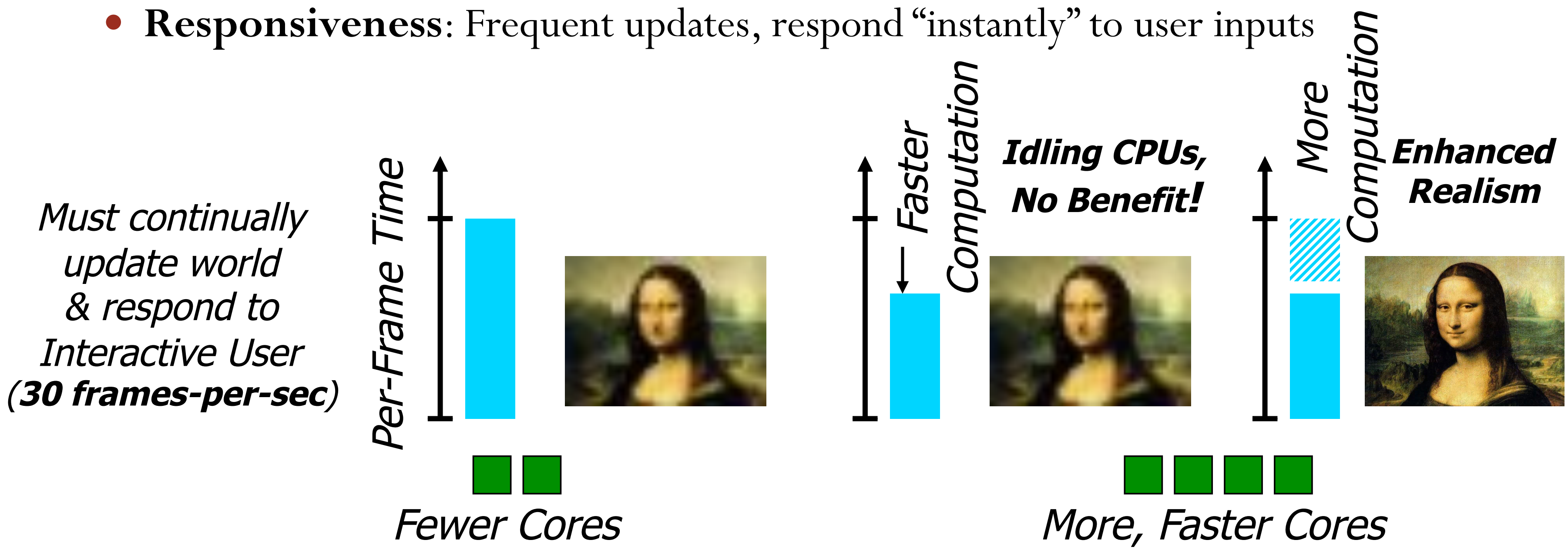
Cores galore

- When single-core was the norm
  - Applications would naturally improve (with frequency)
- With multi-cores
  - Task/data parallelism is used but not always scalable
- With many-cores
  - Well-structured applications can scale
  - What of the others?

Cores will be wasted

Speedup Is Not Always the End-Goal

- **Immersive Applications** intend to provide the *richest, most engrossing experience* possible to the *interactive* user
  - Gaming, Multimedia, Interactive Visualization
- With growing number of cores, or increasing clock-frequencies
  - These applications want to do *MORE,* not just do it *FASTER*
- Design goal: **maximize Realism**
  - **Sophistication in Modeling**: Most detail in render/animation
  - **Responsiveness**: Frequent updates, respond "instantly" to user inputs



How do we Maximize Realism?

Using multi-cores to maximize realism

Two complementary techniques

#1: N-version Parallelism
Speed up hard-to-parallelize algorithms with high probability

- Applies to algorithms that have a diversity of ways to execute
- Basic Intuition: Randomized Algorithms (but not limited to them)

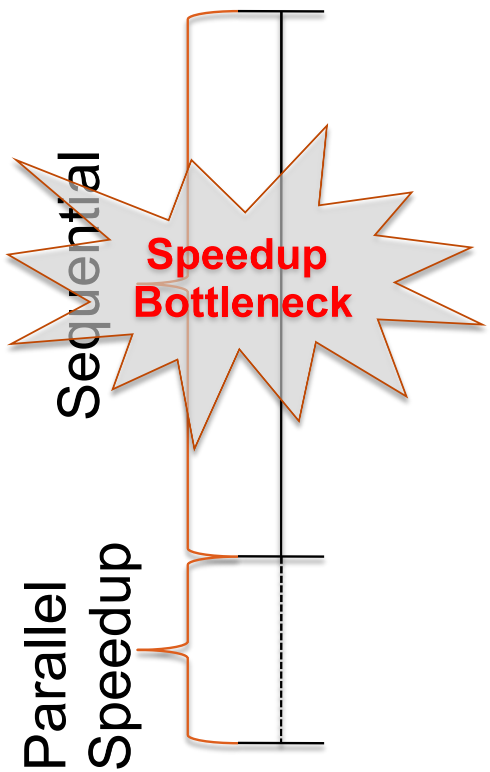
#2: Scalable Soft Real-Time Semantics (*SRT*)
Scale application semantics to available compute resources

- Applies to algorithms whose execution time, multi-core resource requirements and sophistication are parametric
- Basic Intuition: Real-Time Systems (but with different formal techniques)

Unified as *Opportunistic Computing Paradigm*:
N-version creates slack for **SRT** to utilize for Realism

#1
N-Version Parallelism:
Speedup Sequential Algorithms with High Probability

Bottleneck for Speedup

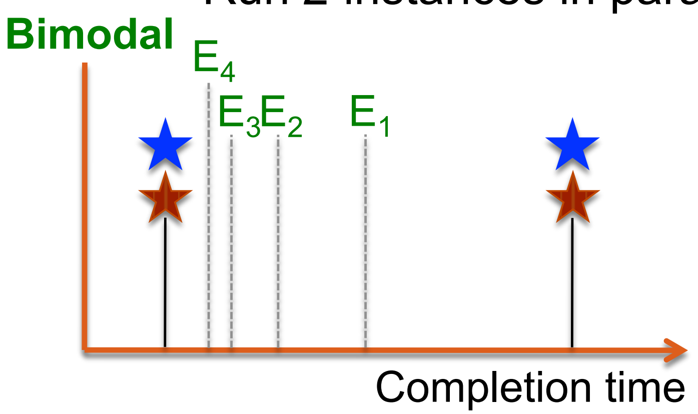


- Applications still have significant sequential parts
  - Stagnation in processor clock frequencies makes sequential parts the major bottleneck to speedup (Amdahl's Law)
- A reduction in *expected execution time* for sequential parts of an application will provide more slack to improve realism

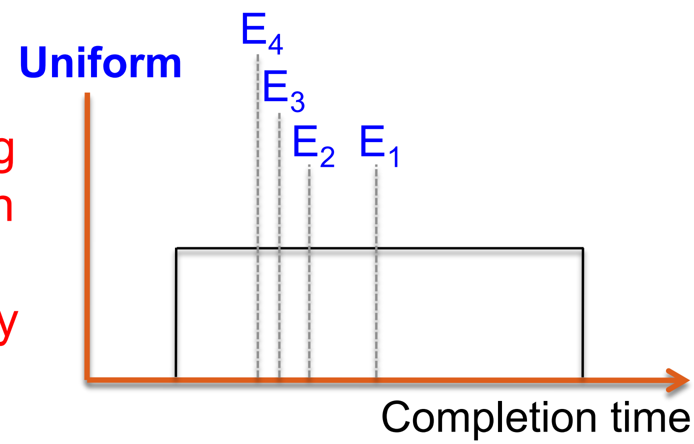
Intuition

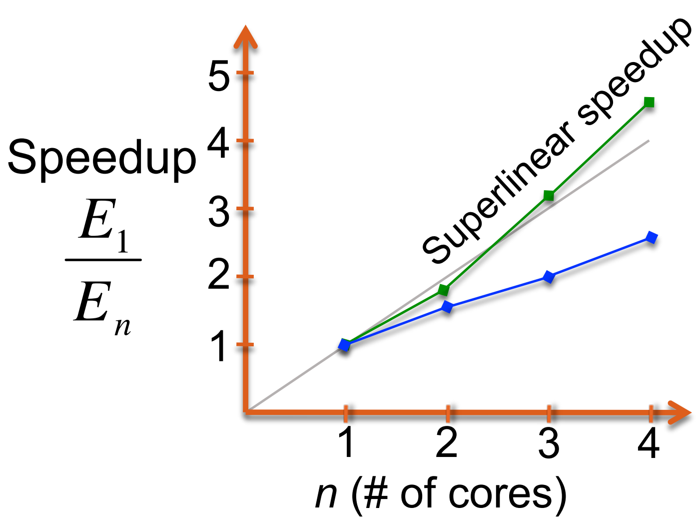
- Algorithms making random choices for a fixed input lead to varying completion times

Run 2 instances in parallel under isolation



Fastest among 2 is faster than average with high probability





- Big opportunities for expected speedup with increasing *n*
- Tradeoff $S = \frac{E_1}{E_n} \leftrightarrow n$
- Wider spread ➔ more speedup

Efficient parallelism $e = \frac{S_n}{n}$

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Learning

- Repeatedly invoked kernels
- Learns the PDF
- Assumes stability condition

$$PDF[A(I_j)] \approx PDF[A(I_{j-1}) \ldots A(I_{j-M})]$$

- Determine expected speedup and optimal efficiency

Culling

- Launch as many as possible
- Provide monitoring capabilities
- Periodically cull non-performing ways

- Does not directly calculate the efficiency but indirectly influences it

N-version parallelism in C/C++

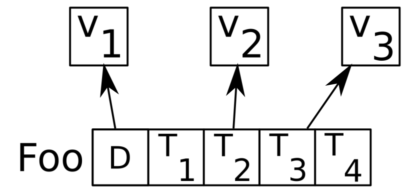
```
int a[];
void f(Input) {
    int b = …;
    a[k] = …;
}
```

C++ can eliminate API wrappers

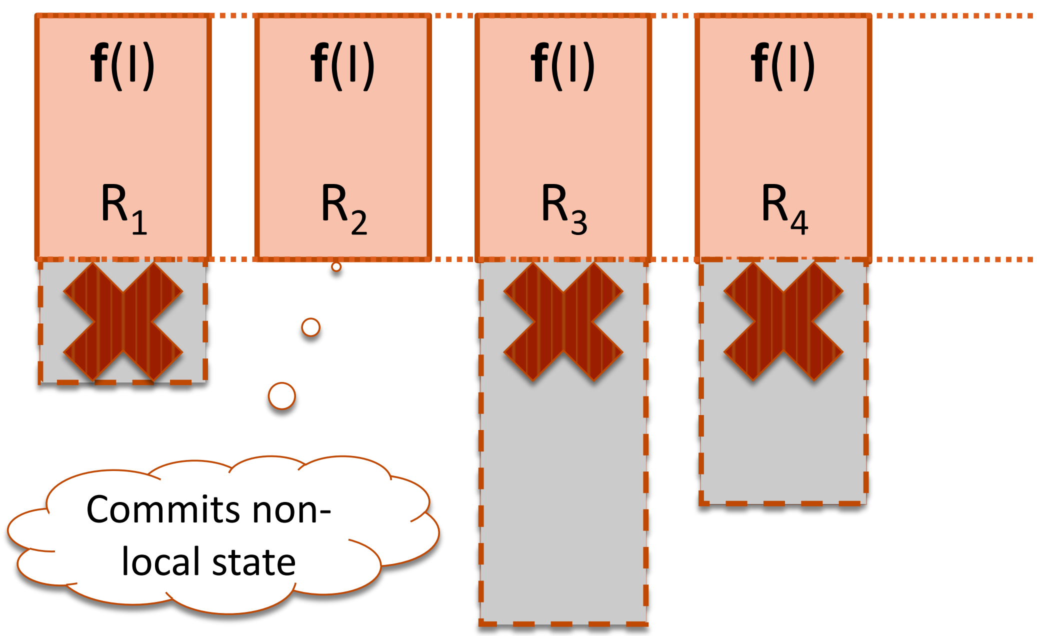
Shared<int> a[];

Local state: leave as is

Non-local state: wrap with API call



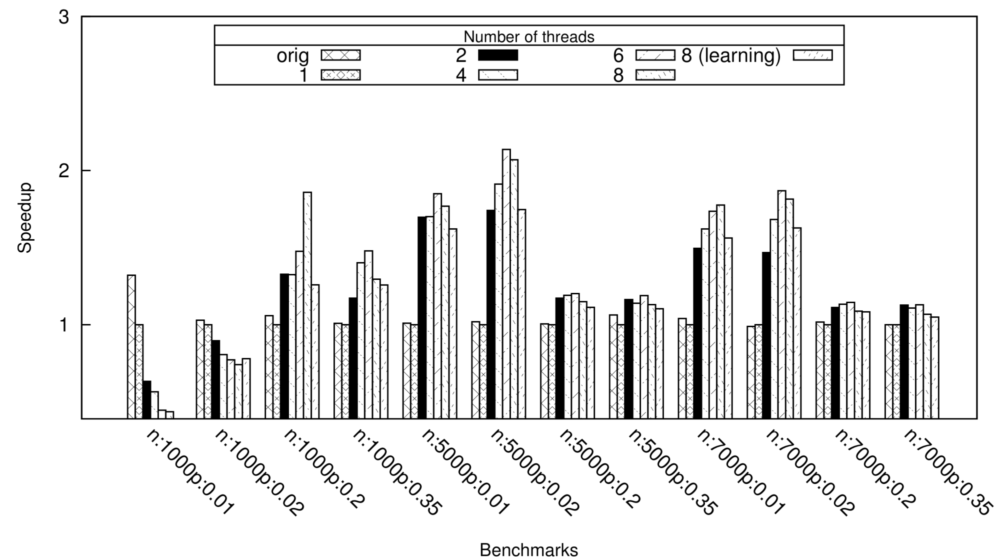
Render each instance side-effect free



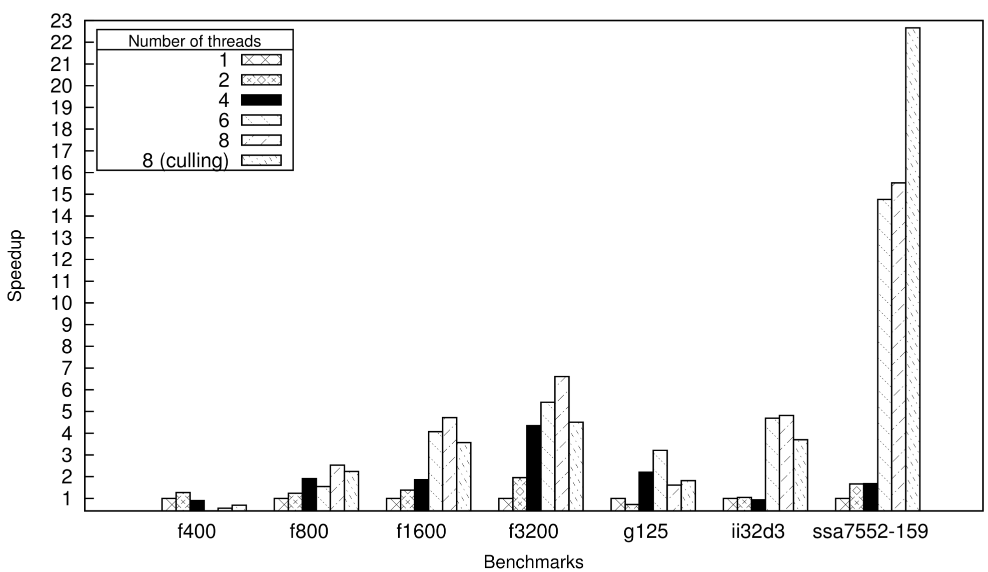
Start n-versions

n-versions completion time

Results: low overhead runtime provides good speedup



Hamiltonian benchmark



WalkSAT benchmark

Status and current research

- C++ framework implemented and tested
- How **broad** is the class of algorithms that would benefit?
- Exploration of the **balance** between n-version and traditional parallelism
  - Efficiency becomes a crucial measure
  - N-version can complement already parallel applications due to lower memory footprint
- Exploration of other performance metrics
  - Pick-the-best instead of pick-the-fastest (**quality of result**)

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#2
Scalable Soft Real-Time Semantics (SRT):

Scale Application Semantics to
Available Compute Resources

Applications with Scalable Semantics

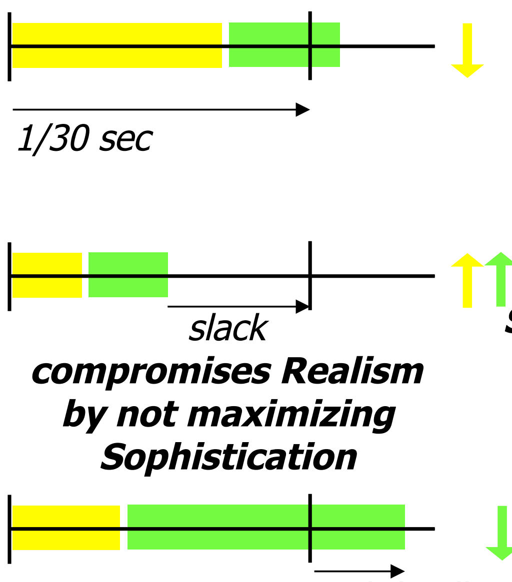
- Games, Multimedia Codecs, Interactive Visualization
  - Possess scalable semantics

Game
AI **Physics**

Game-Frames at approx. 30 fps

Characteristic 1
User-Responsiveness is Crucial.
➔ Model/Algorithmic Complexity must be suitably adjusted / bounded

Frame Time



Frame# 0 - 10
Scale down *AI complexity*: think-frequency, vision-range

Frame# 50 - 60
Scale up *AI & Physics complexity*: sim time-step, effects modeled

compromises Realism by not maximizing Sophistication

Frame# 80 - 90
Scale down *Physics complexity*

Missed deadline significantly
Responsiveness Affected

Characteristic 2
Dynamic Variations in Execution Time over Data Set.
➔ To preserve Responsiveness while maximizing Sophistication, *Continually Monitor* Time and *Scale* Algorithmic Complexity (semantics)

Scaling Semantics in Monolithic Applications

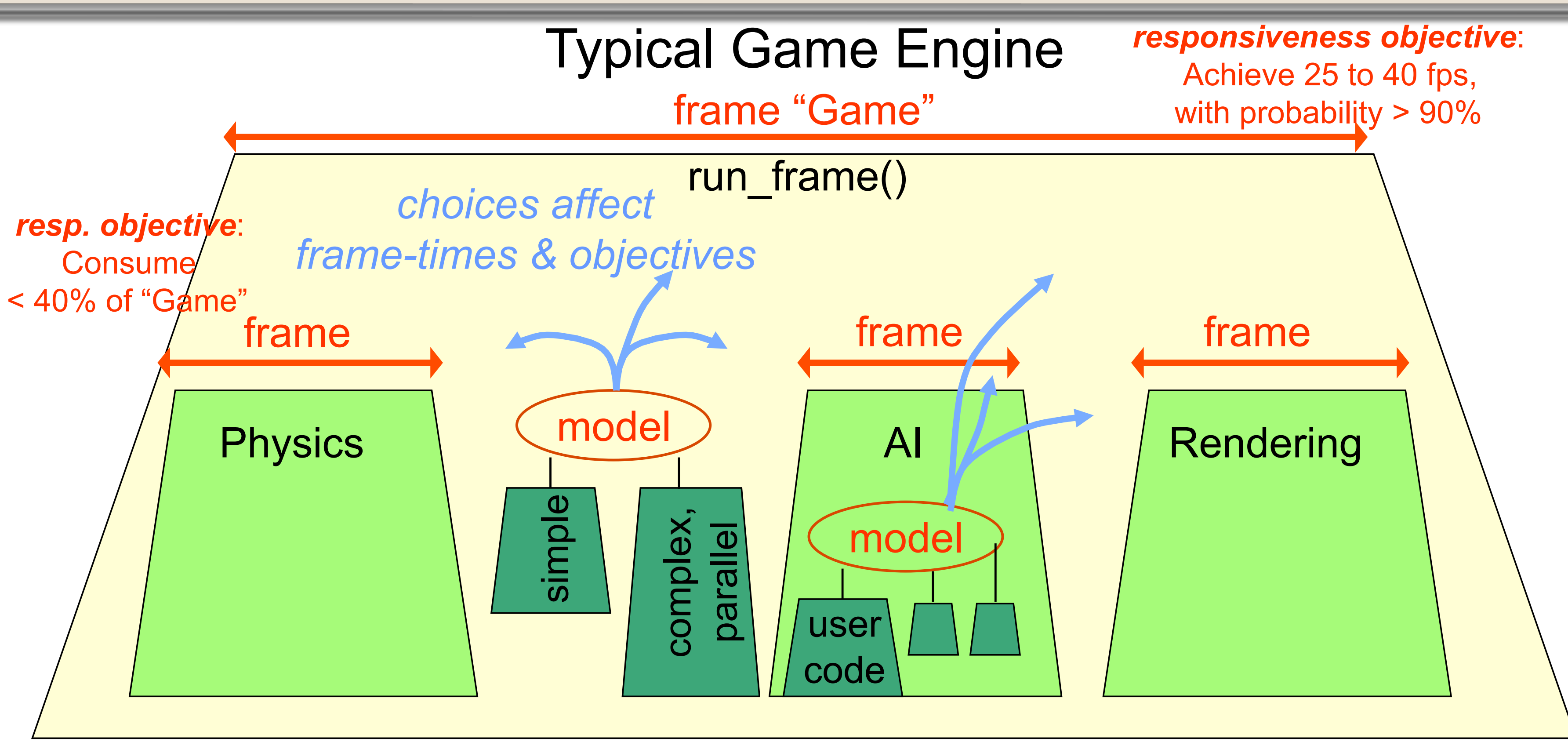
- Challenge for Monolithic Applications
  - C/C++/Java do not express user-responsiveness objectives and scalable semantics

- Our Approach
  - Let **Programmers** specify *responsiveness policy* and *scaling hooks* using SRT API
  - Let **SRT Runtime** determine *how* to achieve policy by manipulating provided hooks

- SRT API enables programmers to specify policy and hooks
  - Based purely on their knowledge of the **functional design** of individual algorithms and application components
  - Without requiring them to anticipate the **emergent responsiveness behavior** of interacting components

- SRT Runtime is based on **Machine Learning** and **System Identification** (Control Theory), enabling Runtime to
  - *Infer* the structure of the application
  - Learn *cause-effect* relationships across application structure
  - *Statistically predicts* how manipulating hooks will scale semantics in a manner that best achieves desired responsiveness policy

Case Study: Incorporating SRT API & Runtime in a Gaming Application



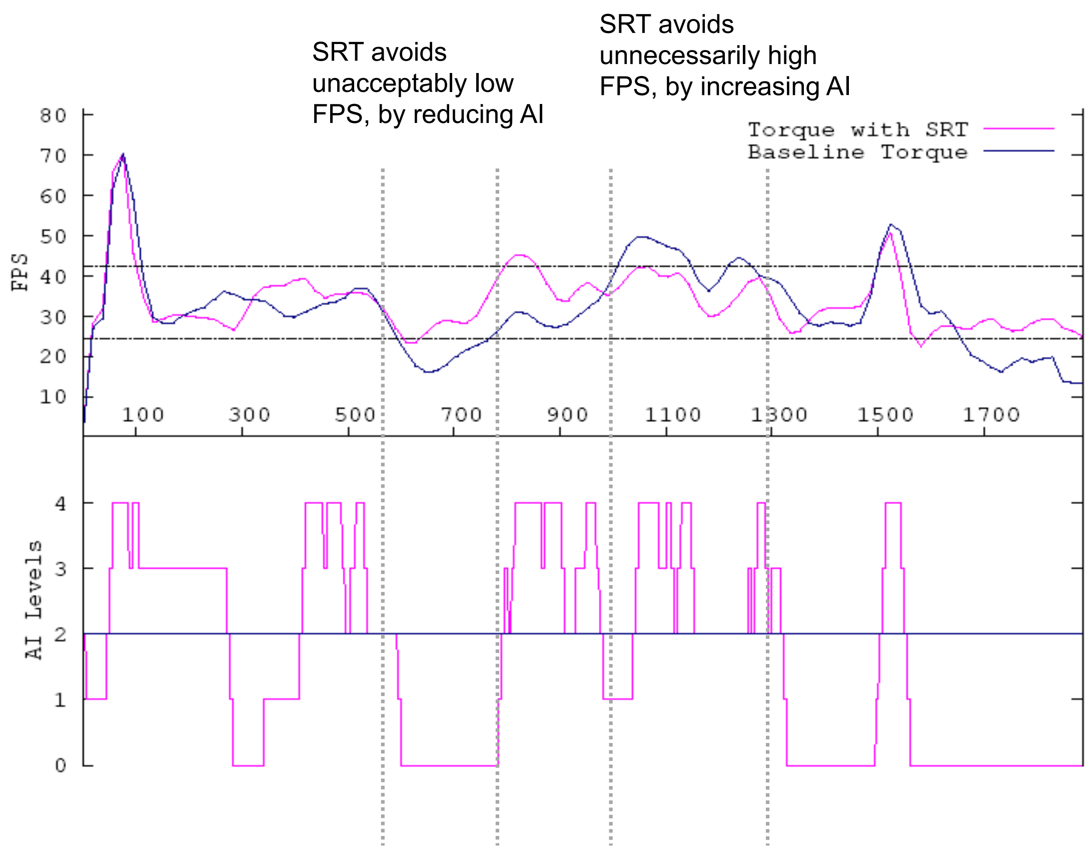
SRT Runtime

- Monitors frame
- Learns Application-wide ***Average Frame Structure***
- Chooses between user-codes in model

- Learns & Caches statistical relations:

- **Reinforcement Learning**: Which models predominantly affect which objectives? *(infer complex relationships, slowly)*
- **Feedback Control**: Adjust choices in models (simple, medium, complex, ...) to meet objectives *(fast reaction)*

Torque Game Engine: Measured Behavior



objective: 25 to 42 fps

Conclusion

- Maximizing Realism is underlying design goal for an important class of applications
  - Speedup is only one enabling factor
- Realism provides avenues to utilize multi/many-cores, over and above traditional task and data parallelism techniques
- We introduced two complementary techniques that utilize extra cores for maximizing Realism
  - **N-versions Parallelism**: Creates slack on hard to parallelize code
  - **Semantics Scaling SRT**: Utilizes dynamically available slack to maximize realism

Thank you!

- Questions?

Reference: R. Cledat, T. Kumar, J. Sreeram, S. Pande:
Opportunistic Computing: A New Paradigm for Scalable Realism, HotPar 2009

Backup Slides

What is Realism?

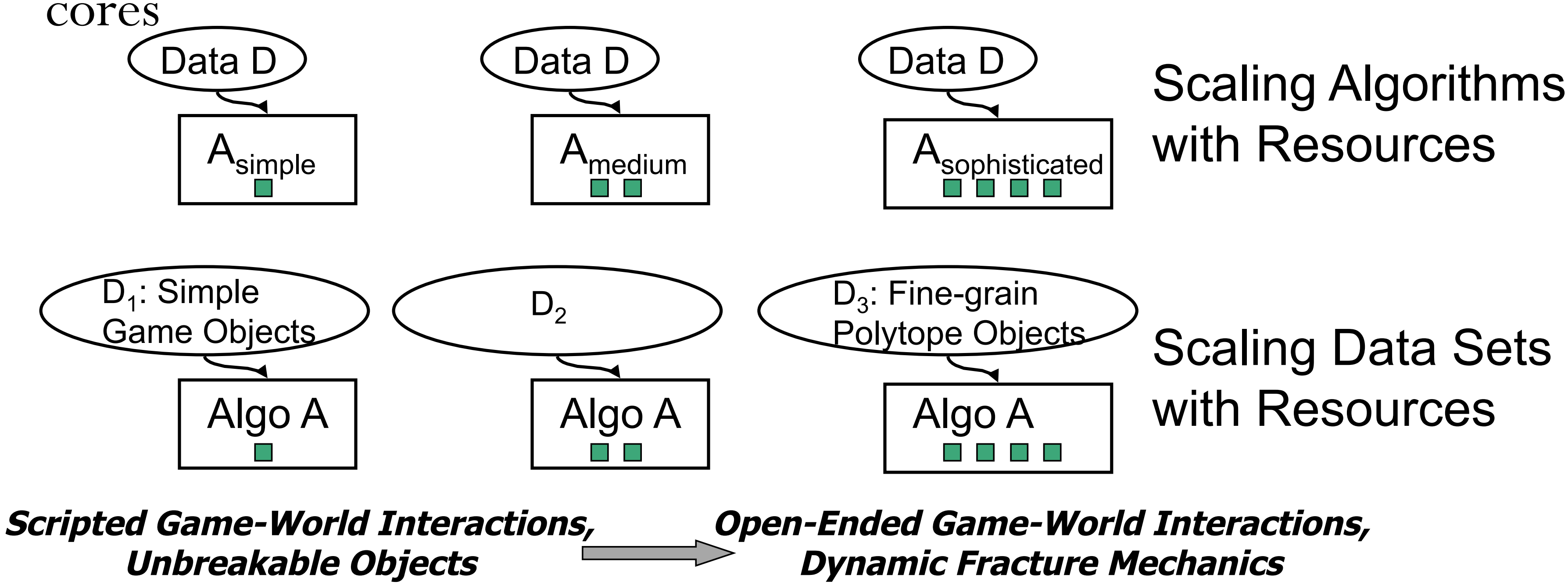
- Realism consists of
  - **Sophistication in Modeling**
    - Example: Render/Animate as highly detailed a simulated world as possible
  - **Responsiveness**
    - Example: Update world frequently, respond "instantly" to user inputs
    - Unit of world update: **Frame**

- Typical Programming Goal
  - Pick models/algorithms of as high a sophistication as possible that can execute within a *frame deadline* of 1/30 seconds

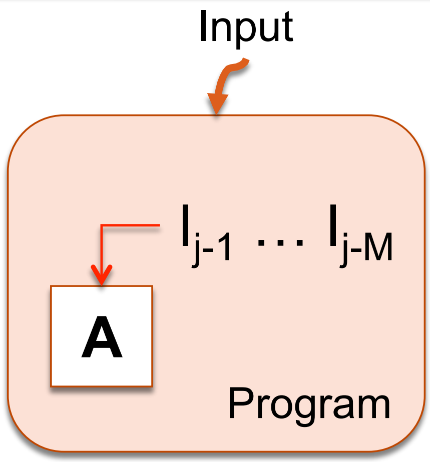
- Flexibility: *Probabilistic Achievement of Realism is Sufficient*
  - Most frames (say, >90%) must complete within 10% of frame deadline
  - Relatively few frames (<10%) may complete very early or very late

Scaling Semantics with Multi-cores

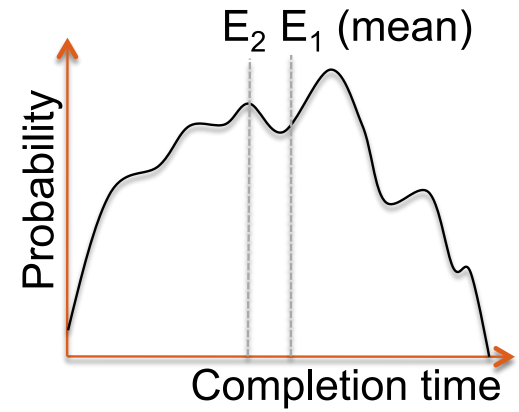
- Traditionally, benefiting from more cores required breaking up the same computation into more parallel parts
  - Difficult problem for many applications, including gaming and multimedia
- Scalable Semantics provide an *additional* mechanism to utilize more cores



Application Use Scenario



- **Goal**: Find the reasonable n to reduce expected completion time of $PDF[A(I_j)]$



- **Need** knowledge of $PDF[A(I_j)]$ to compute the speedup S
  - **Determine** $PDF[A(I_{j-1})\ldots A(I_{j-M})]$ How do we do this?
  - **Assume** $PDF[A(I_j)] \approx PDF[A(I_{j-1})\ldots A(I_{j-M})]$ (stability condition)
    - Stability condition gives predictive power When will this hold?

We want to determine the speedup S and the number of concurrent instances n on $A(I_j)$ from PDF with *no prior* knowledge of the underlying distribution

PDF and Stability Condition

$$PDF[A(I_j)] \approx PDF[A(I_{j-1}) \ldots A(I_{j-M})]$$

- Holds **statically** over j for inputs of the same "size"
  - Graph algos: $|V|$ and $|E|$
- Holds for **sufficiently slow variations**
  - $|I_{j-M}| \approx \ldots \approx |I_{j-1}| \approx |I_j|$
- Example: TSP for trucks in continental United States
  - Fixed grid size
  - Similar paths

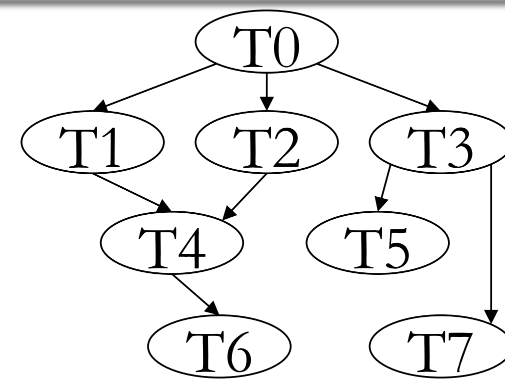
- Randomized algorithms
  - Analytically known PDF
    - Depends on input *size* and *parameters* (referred to as "size")
  - "Size" might be unknown
- Other algorithms
  - PDF is analytically unknown/ intractable

Runtime Estimation

Don't Real-Time Methods Solve This Already?

Games, Multimedia, Interactive Viz

Implement as a Real-Time App



Implement with High-Productivity, Large Scale Programming flows

<u>C, C++, Java: Monolithic App</u>

- 100Ks to Millions of LoC
- No analyzable structure for responsiveness and scaling
- Responsiveness is entirely an ***emergent*** attribute

(currently tuning this is an art)

<u>Real-Time Task-Graph</u>

- Application decomposed into Tasks and Precedence Constraints
- Responsiveness guaranteed by Real-time semantics (hard or probabilistic)

Need a new bag of tricks to Scale Semantics in Monolithic Applications