32nd IEEE Real-Time and Embedded Technology and Applications Symposium

Generative Profiling for Soft Real-Time Systems

and its Applications to Resource Allocation

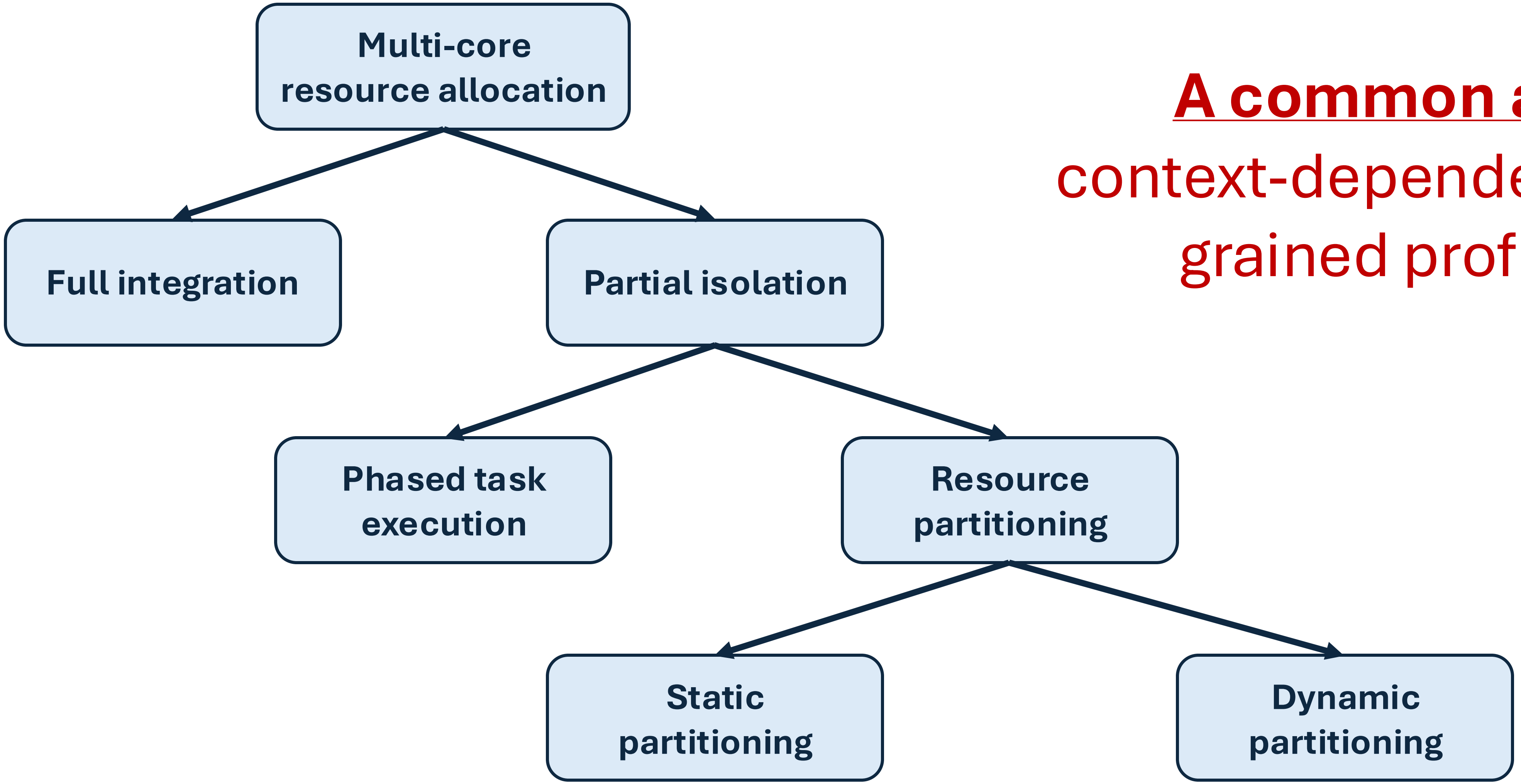
Georgiy A. Bondar, **Abigail Eisenklam**, Yifan Cai, Robert Gifford,
Tushar Sial, Linh Thi Xuan Phan, Abhishek Halder

Penn
University of Pennsylvania

UC Santa Cruz

Iowa State University

Multi-Core Resource Allocation

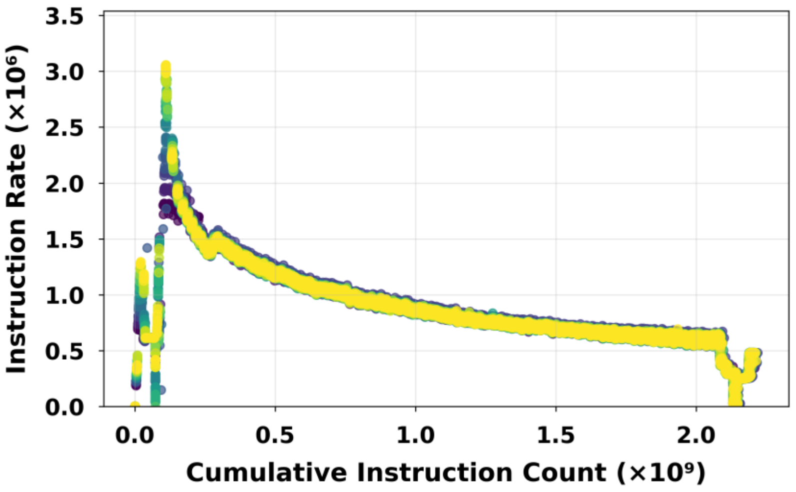


<u>A common aid:</u>

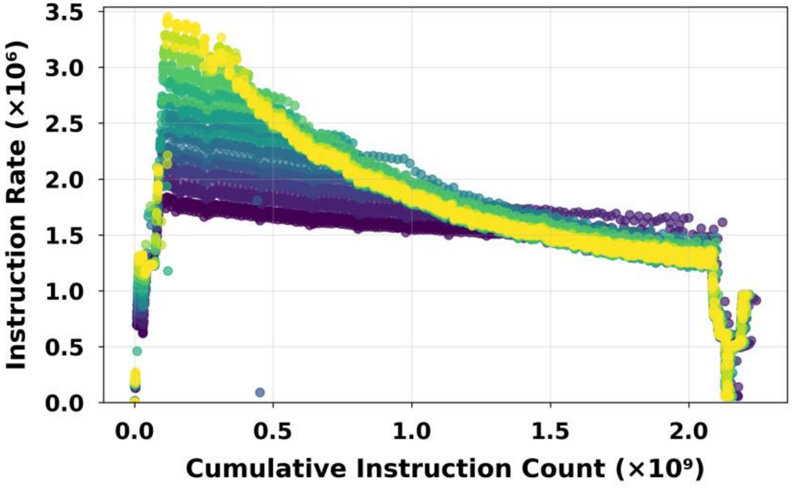
context-dependent fine-grained profiles

Context-Dependent Fine-Grained Profiles

PARSEC benchmark:
`canneal`



10% of LLC + MemBW



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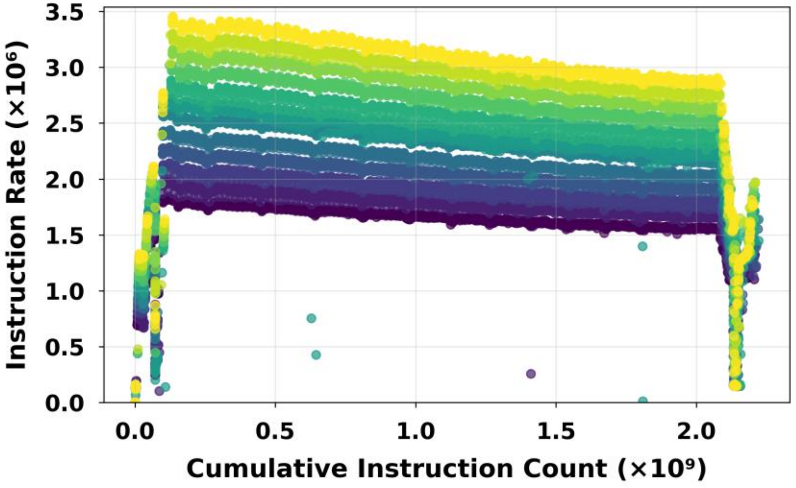


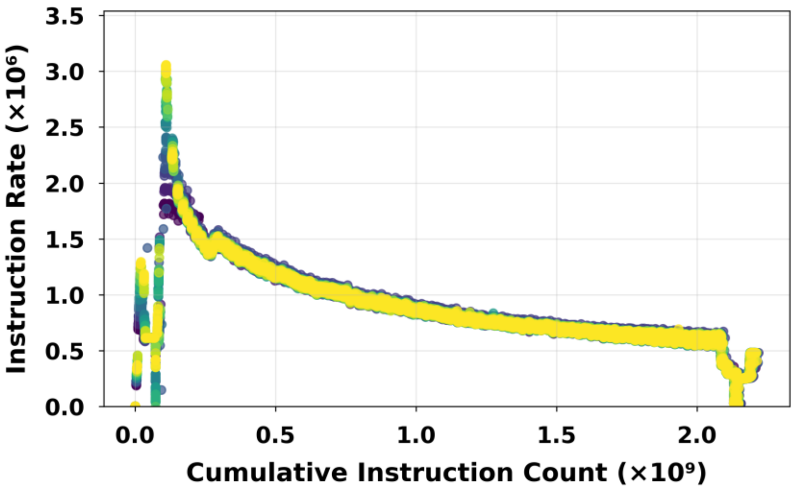
50% of LLC + MemBW

1.2 GHz  2.3 GHz

Context-Dependent Fine-Grained Profiles

PARSEC benchmark:
`canneal`

Profile for resource context:
(LLC, MemBW, CPUFreq) = (4 MB, 280 MB/s, 2.3 GHz)



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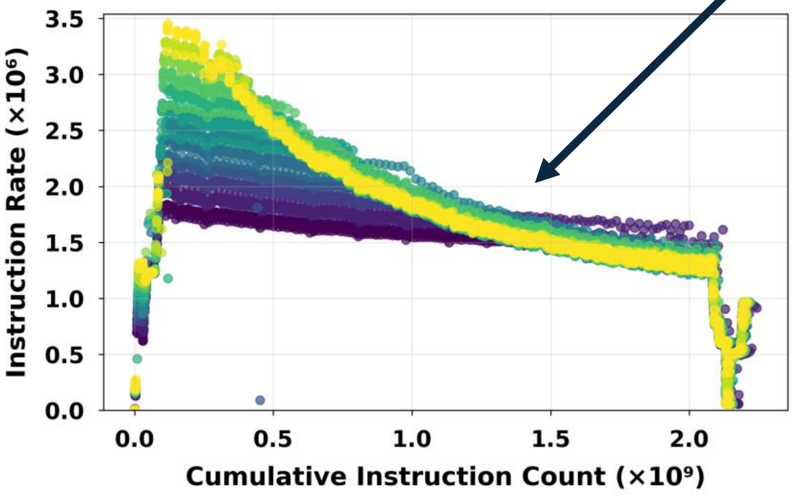

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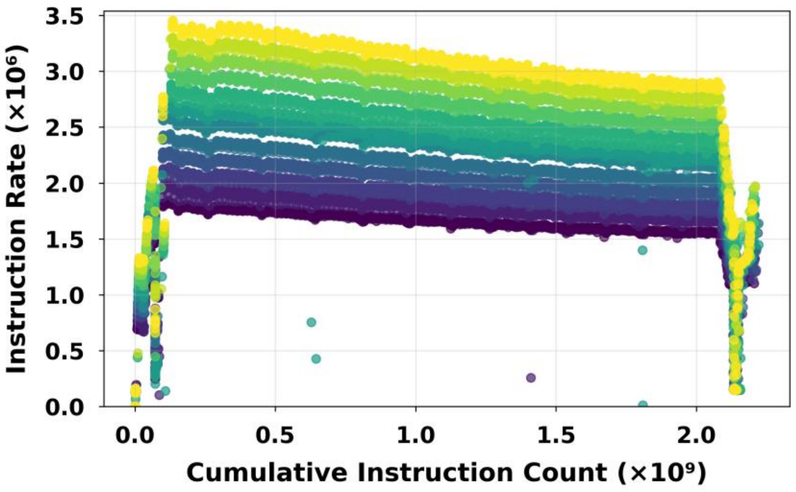

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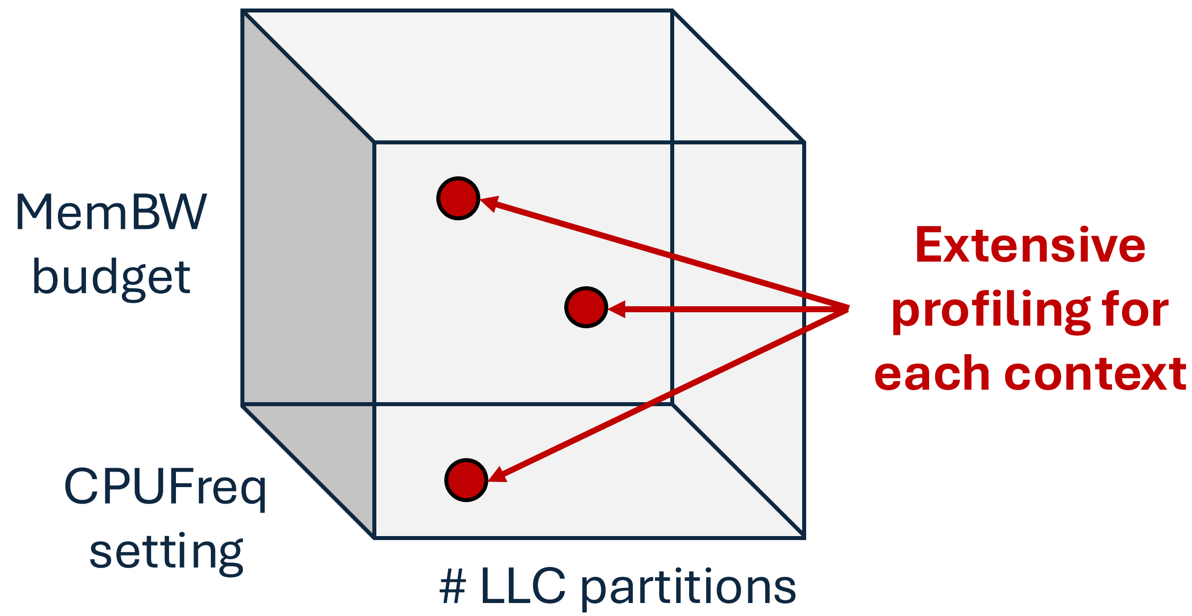
Challenges and Limitations of Existing Approaches

Measurement only	Static/hybrid approaches

The space of possible resource contexts is large



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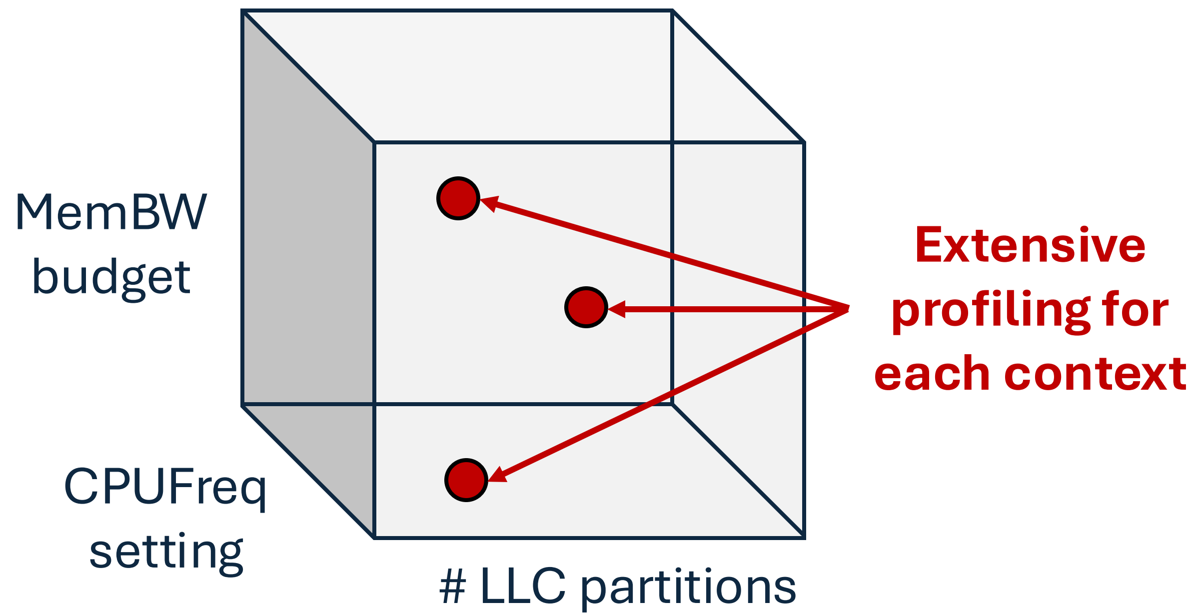
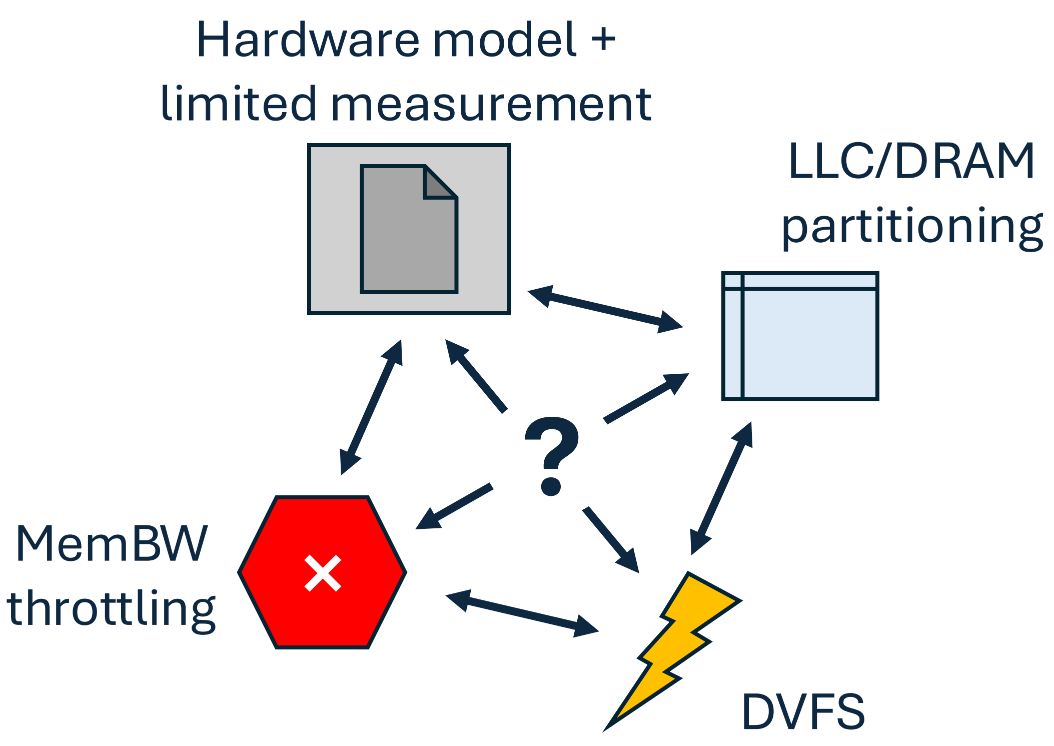
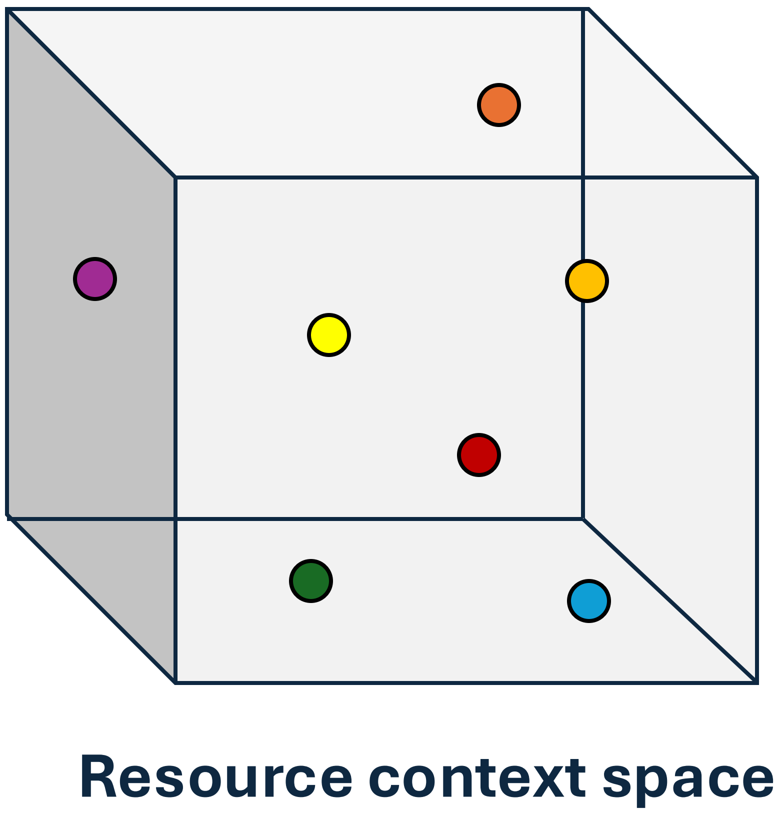




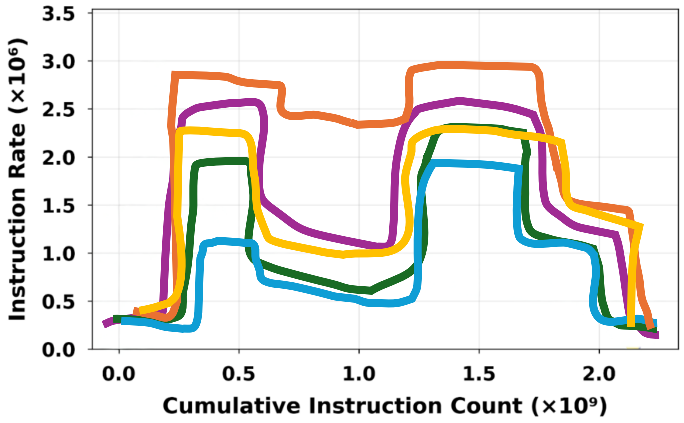
Complex interactions are challenging to model

Our Objective



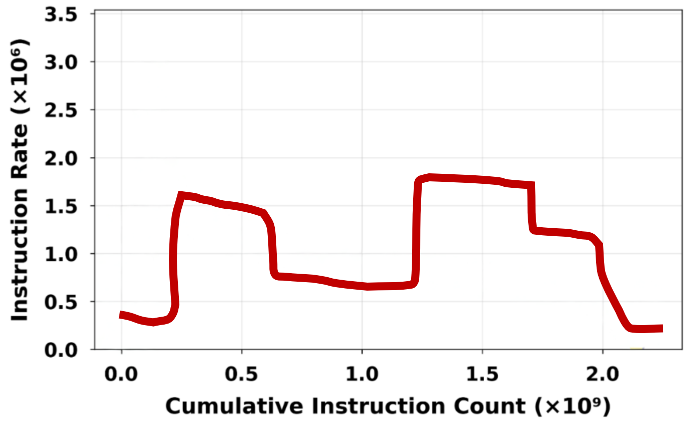
Given:

Sparse set of known resource contexts = { ● ● ● ● ● ● }



Learn:

Unknown context: ●



Desired Properties

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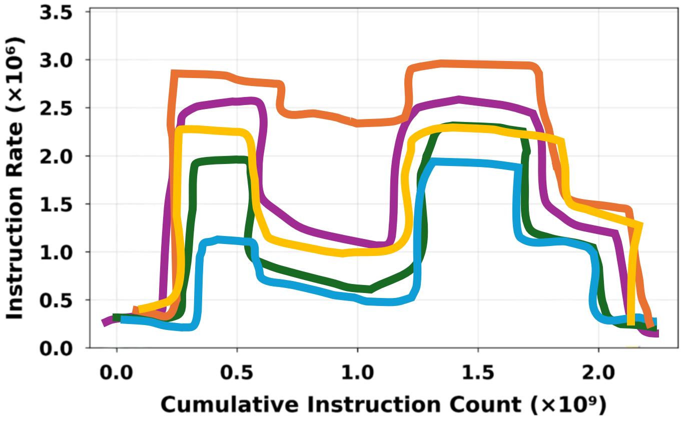
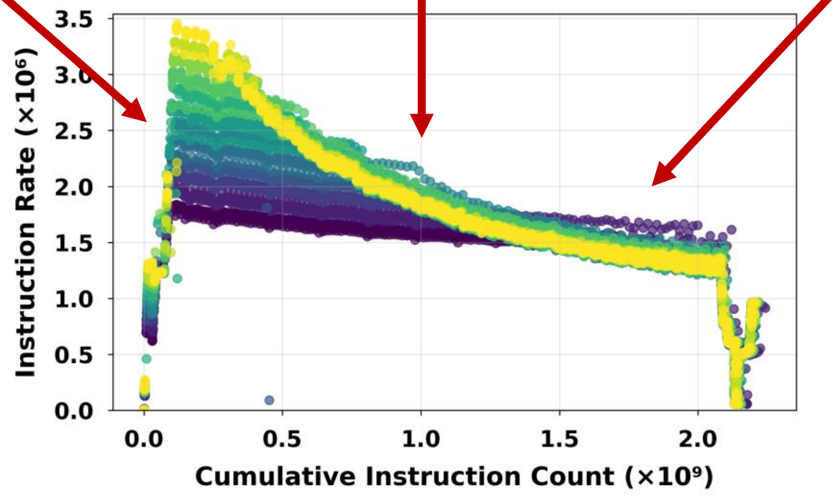


Property 1:

Consistency with known observations

Desired Properties

Linear effect
Nonlinear effect
No effect



20% of LLC + MemBW

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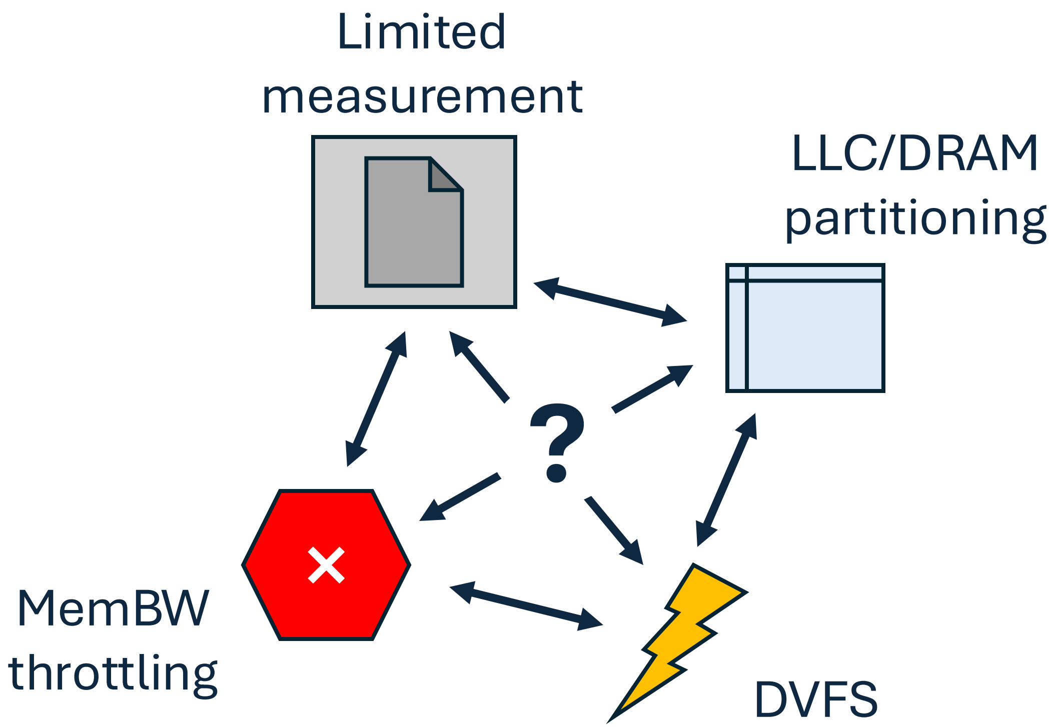
Property 2:
Nonparametric
(no distributional assumptions)

Desired Properties



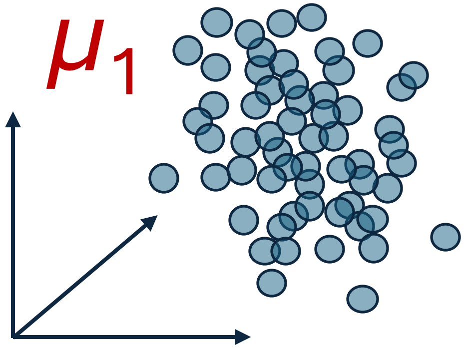
<u>Property 3:</u>
Statistical guarantee of accuracy

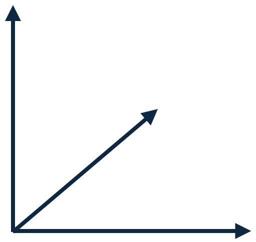
Talk Outline

- **Technique Background**
- Solving for MSBs
- Conditional MSBs
- Profile Generation
- Evaluation

The Bimarginal Schrödinger Bridge (SB) Problem

- **Given:** distributions μ_1 and μ_2 corresponding to times t_1 and t_2
- **Desired:** the highest probability distribution-valued path $t \rightarrow \mu_t$ parameterized by $t \in [t_1, t_2]$





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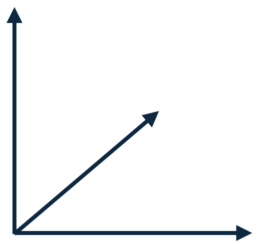

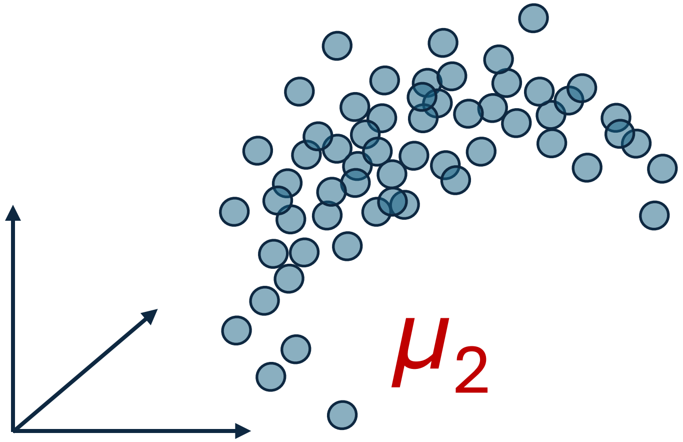

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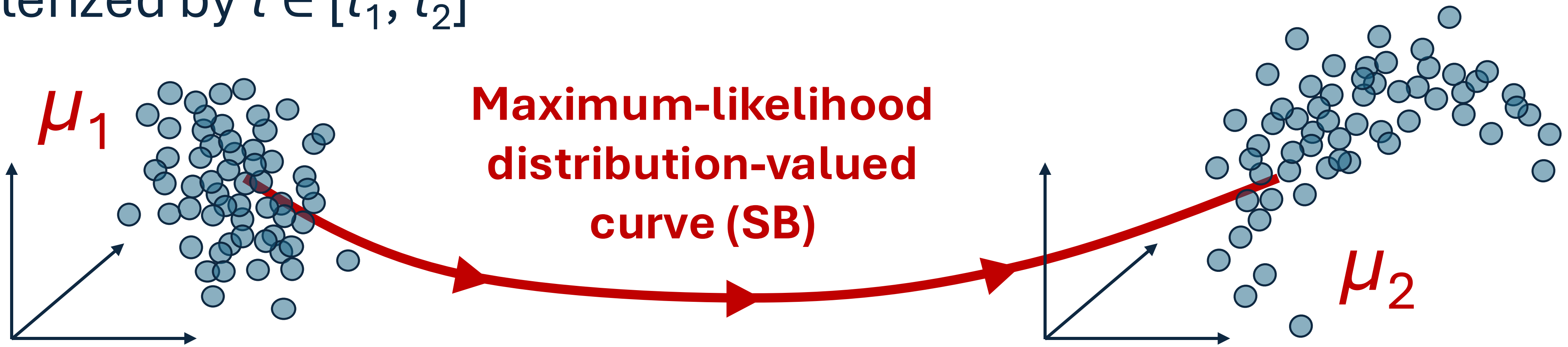

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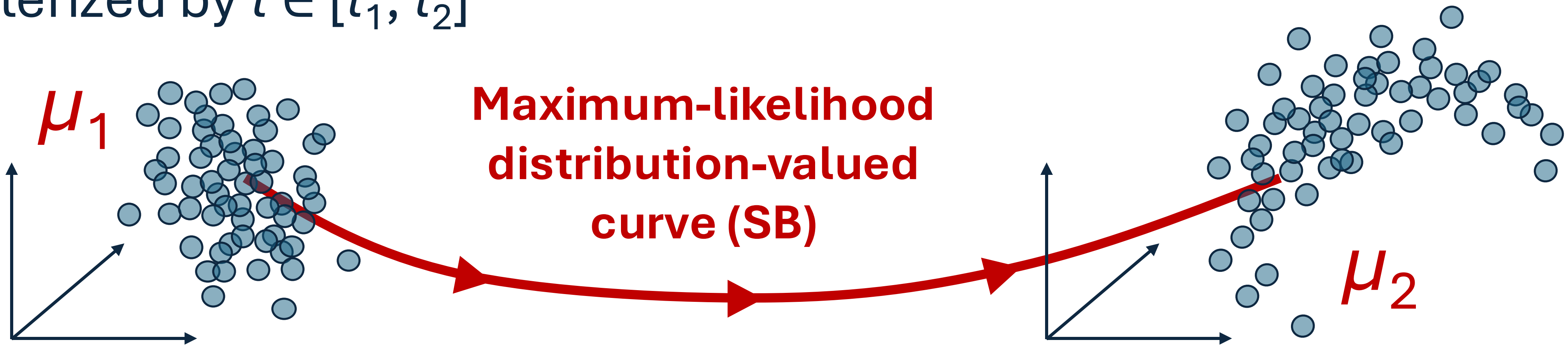

- Originated in 1931-1932 in the works of Schrödinger [1] [2]
- Recent applications in generative AI and stochastic control

[1] E. Schrödinger. Über die Umkehrung der Naturgesetze. Verlag der Akademie der Wissenschaften in Kommission bei Walter De Gruyteru Company, 1931.
[2] E. Schrödinger. Sur la théorie relativiste de l'électron et l'interprétation de la mécanique quantique. In Annales de l'I. H. P., 1932.

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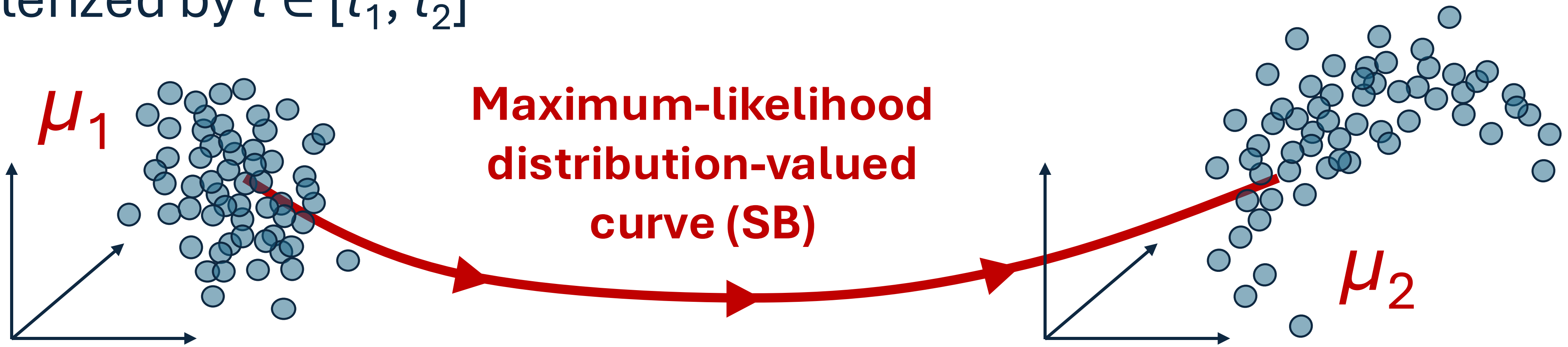

Property 1:
Consistency with known observations

Property 2:
Nonparametric (no distributional assumptions)

Property 3:
Statistical guarantee of accuracy

SB Formulation for Fixed Resource Context β

- Model program behavior as a vectorial stochastic process, conditioned on a resource context

Time-varying execution state $\longrightarrow$ $\xi(t) \mid \beta$ $\longleftarrow$ **Resource context**

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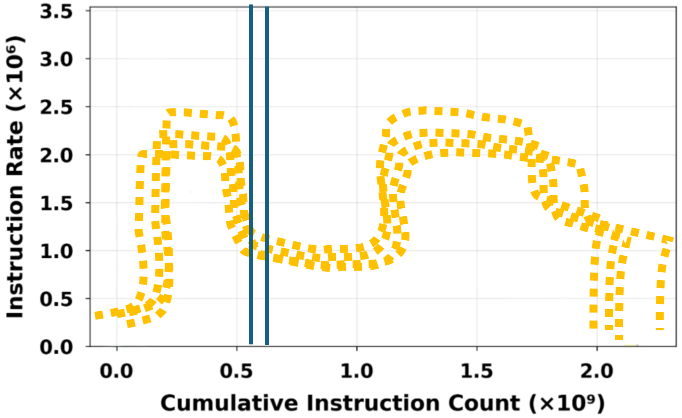
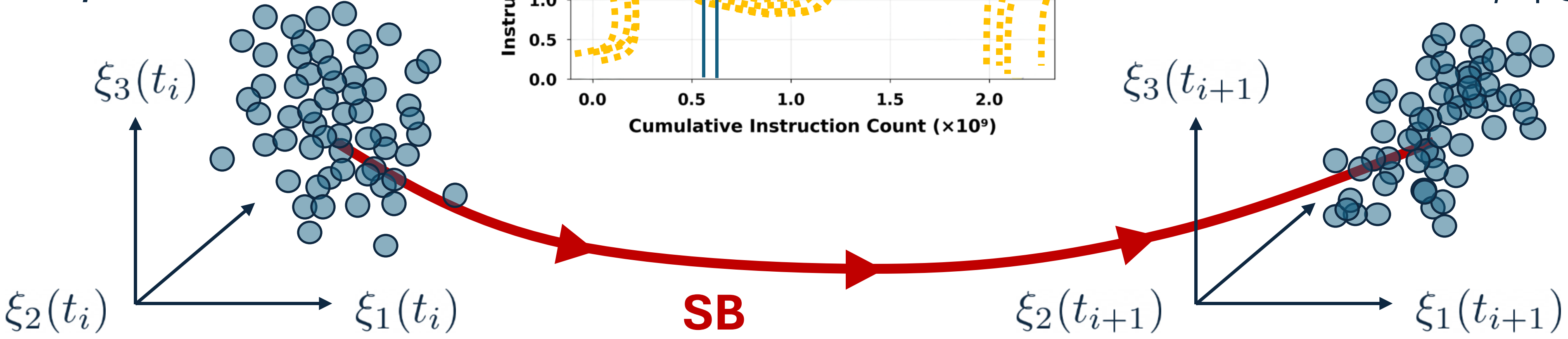
Time-varying execution state → $\xi(t) \mid \beta$ ← **Resource context**



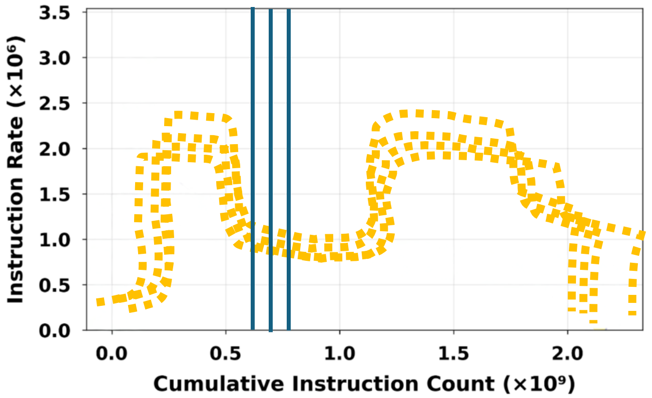
Measurements of ξ at t_i given β = ●

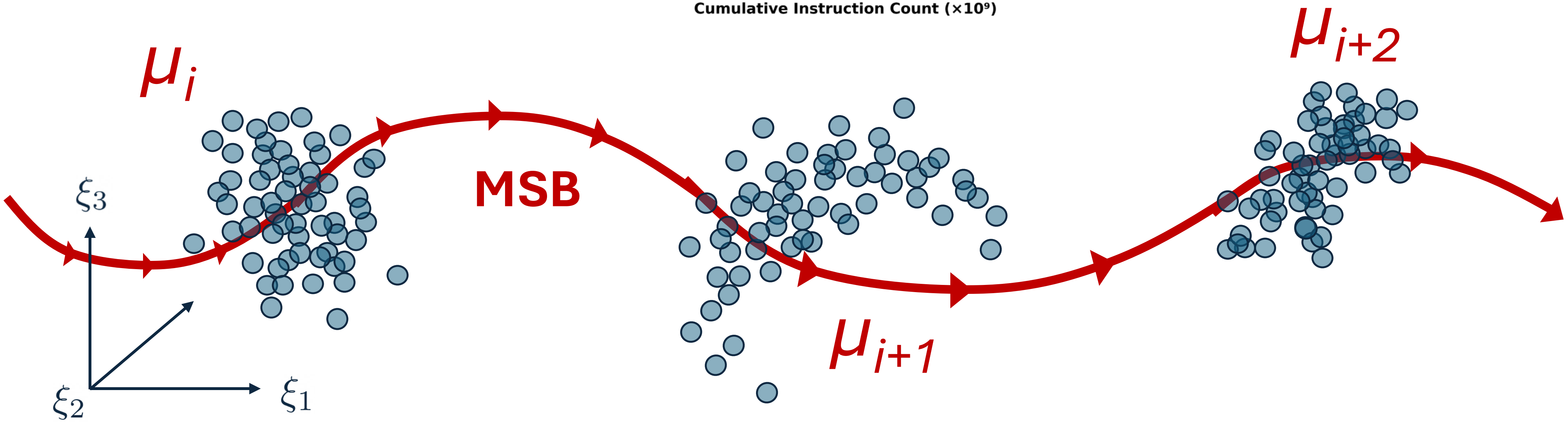
Measurements of ξ at t_{i+1} given β = ●



Multimarginal Schrödinger Bridge (MSB)

- SB naturally extends to more than two consecutive distributions $\{\mu_\sigma\}_{\sigma\in[\![s]\!]}$





Talk Outline

- SB Background
- **Solving for MSBs**
- Conditional MSBs
- Profile Generation
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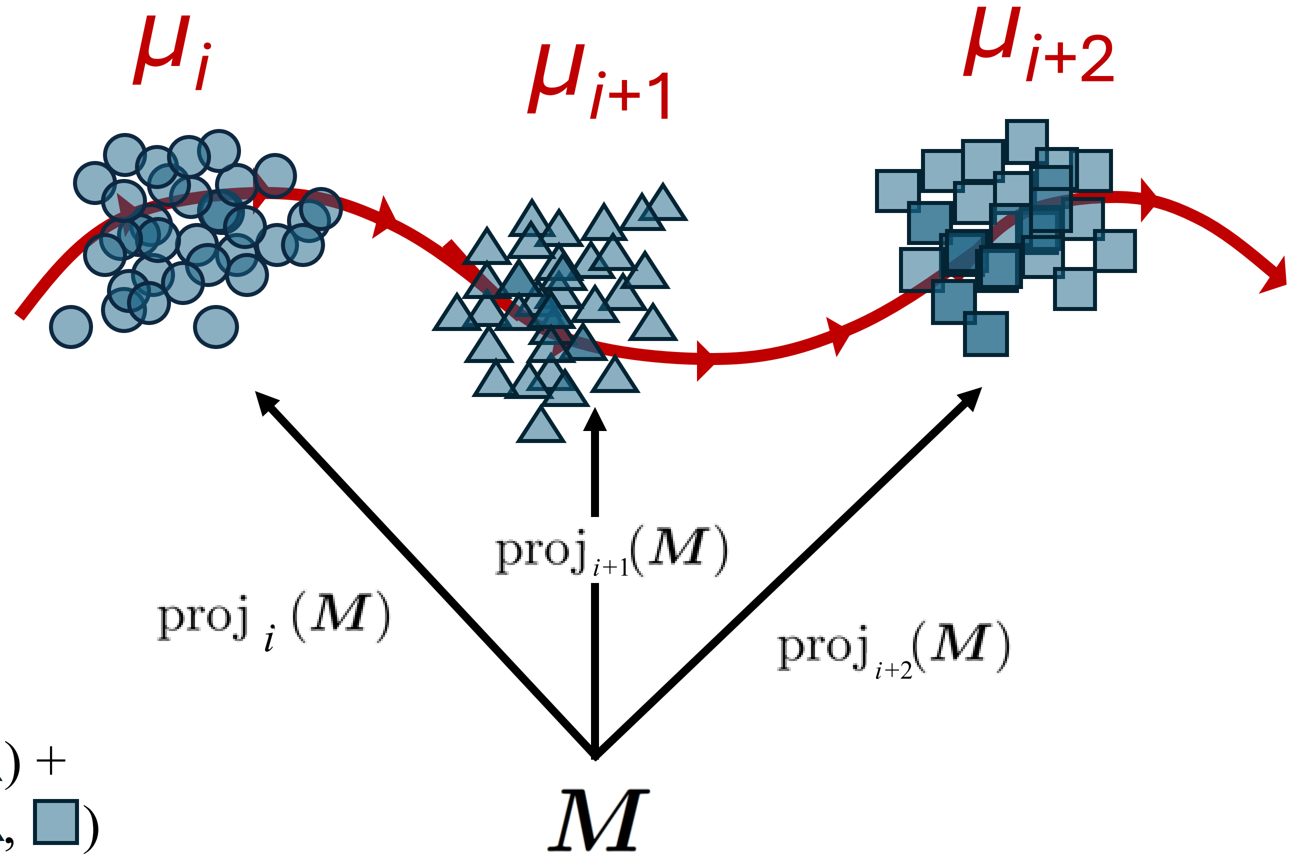
Solving for Multimarginal Schrödinger Bridges

- Idea: MSB is a tensor $\boldsymbol{M}$ with $\{\mu_\sigma\}$ as marginals.
- Find cost + entropy minimizing $\boldsymbol{M}_{\text{opt}}$

$$\min_{\boldsymbol{M} \in (\mathbb{R}^n)^{\otimes s}_{\geq 0}} \langle \boldsymbol{C} + \varepsilon \log \boldsymbol{M}, \boldsymbol{M} \rangle$$

$$\text{subject to} \quad \text{proj}_\sigma(\boldsymbol{M}) = \boldsymbol{\mu}_\sigma \quad \forall \sigma \in [\![s]\!]$$

$\boldsymbol{C}$ (○, △, □) = pairwise-Euclidean-cost(○, △) + pairwise-Euclidean-cost(△, □)



Solving for Multimarginal Schrödinger Bridges

<u>ε > 0</u>

- Strictly convex program
- Strong Lagrange duality
- **P3: Statistical guarantee: max. likelihood**

n^s decision variables

$$\min_{\boldsymbol{M} \in (\mathbb{R}^n)^{\otimes s}_{\geq 0}} \quad \langle \boldsymbol{C} + \varepsilon \log \boldsymbol{M}, \boldsymbol{M} \rangle$$

$$\text{subject to} \quad \mathrm{proj}_\sigma(\boldsymbol{M}) = \boldsymbol{\mu}_\sigma \quad \forall \sigma \in [\![s]\!]$$

P1: Consistency with known observations

P2: Unique, nonparametric solution guaranteed in linear time!

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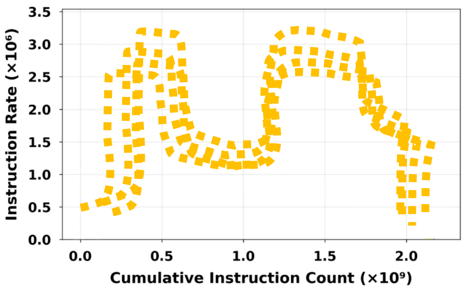
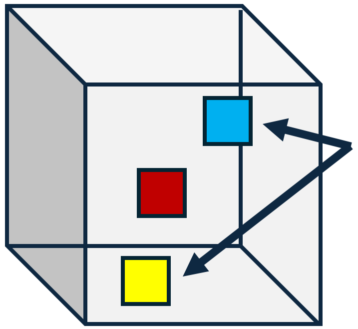
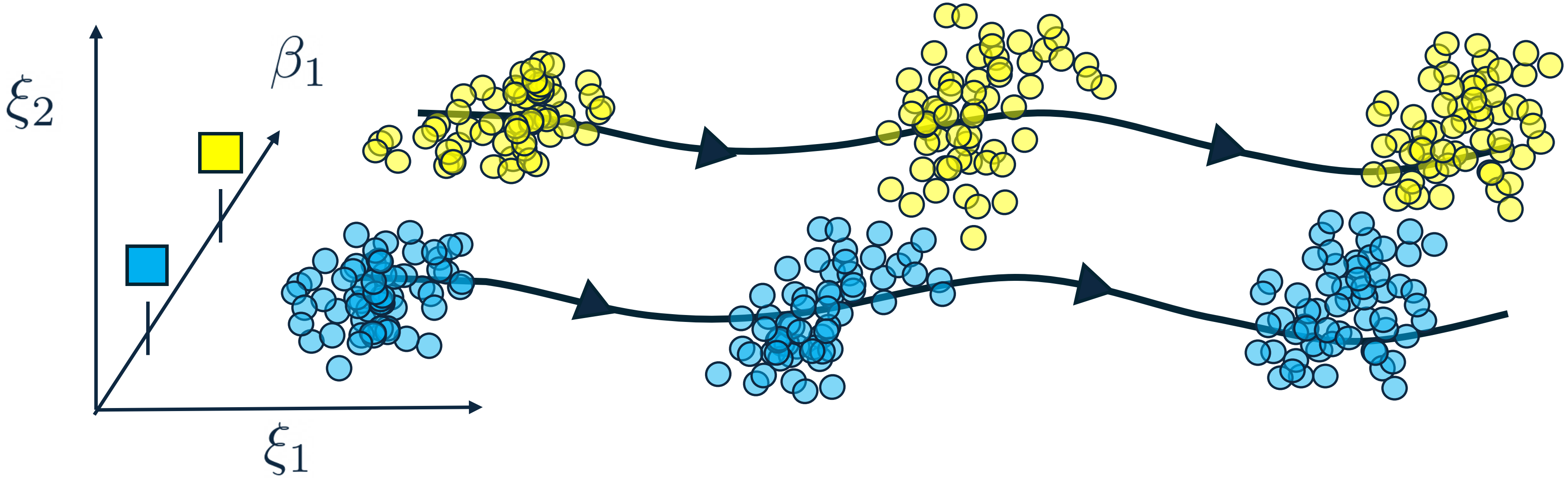
Inputs to Conditional MSBP

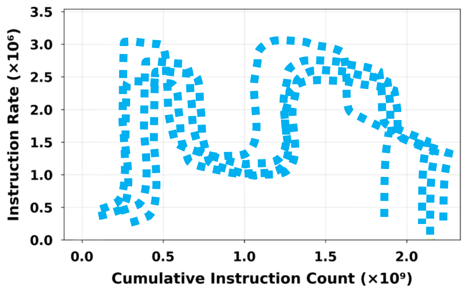




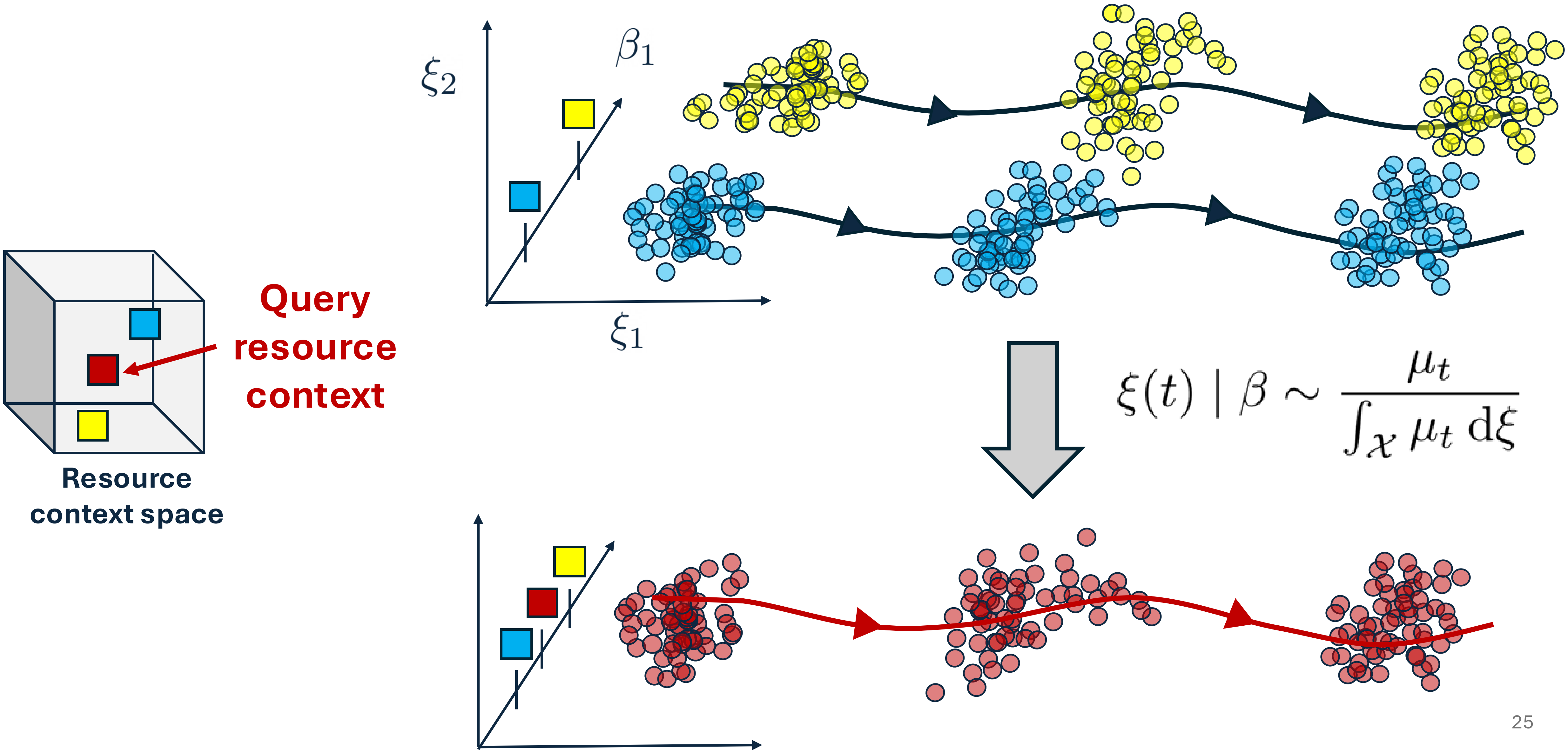
Known resource contexts

Resource context space

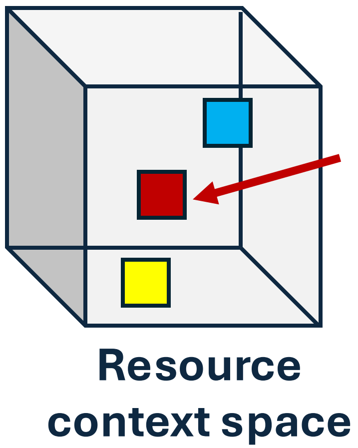




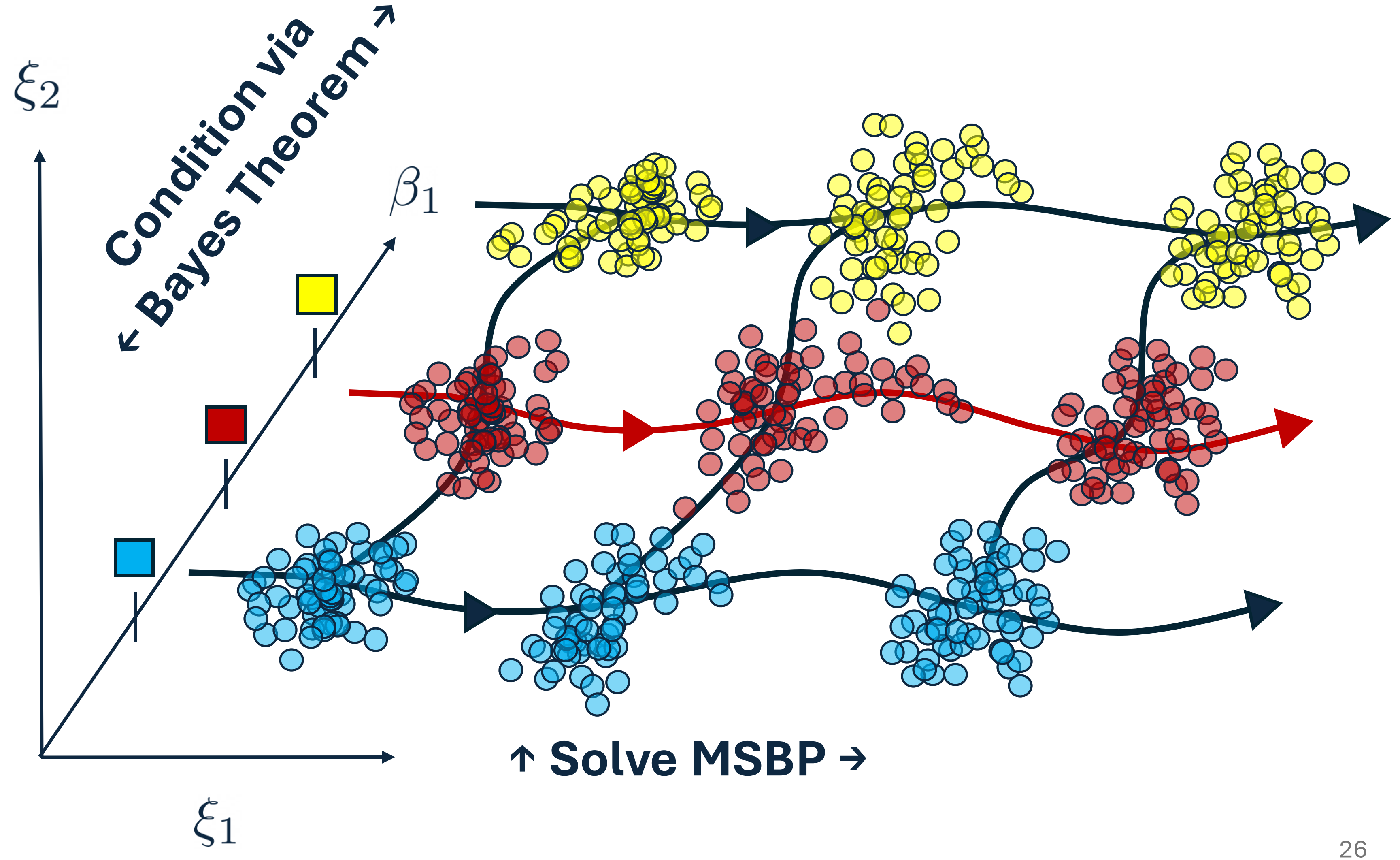
Output of Conditional MSBP



Conditional MSBP Summary



Query
resource
context



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- **Profile Generation**
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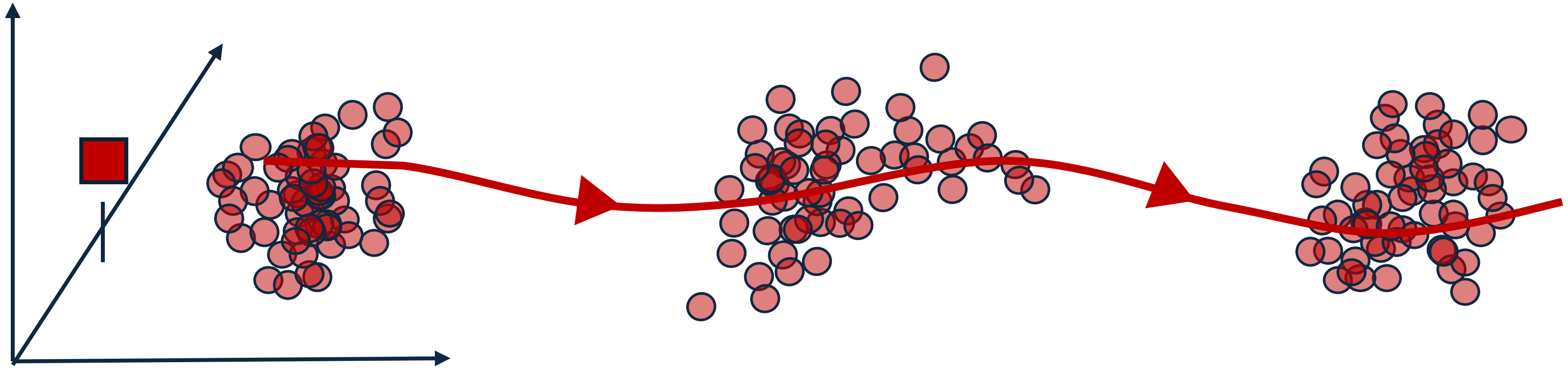
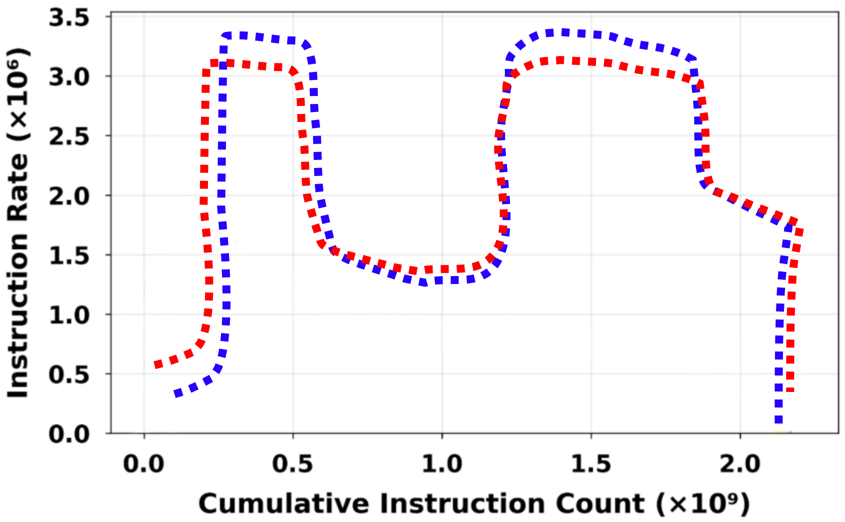
Generating Profiles via Sampling



Sample mean along distribution-valued curve

Sample maximum-likelihood along distribution-valued curve



Talk Outline

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- Conditional MSBs
- Profile Generation
- **Evaluation**

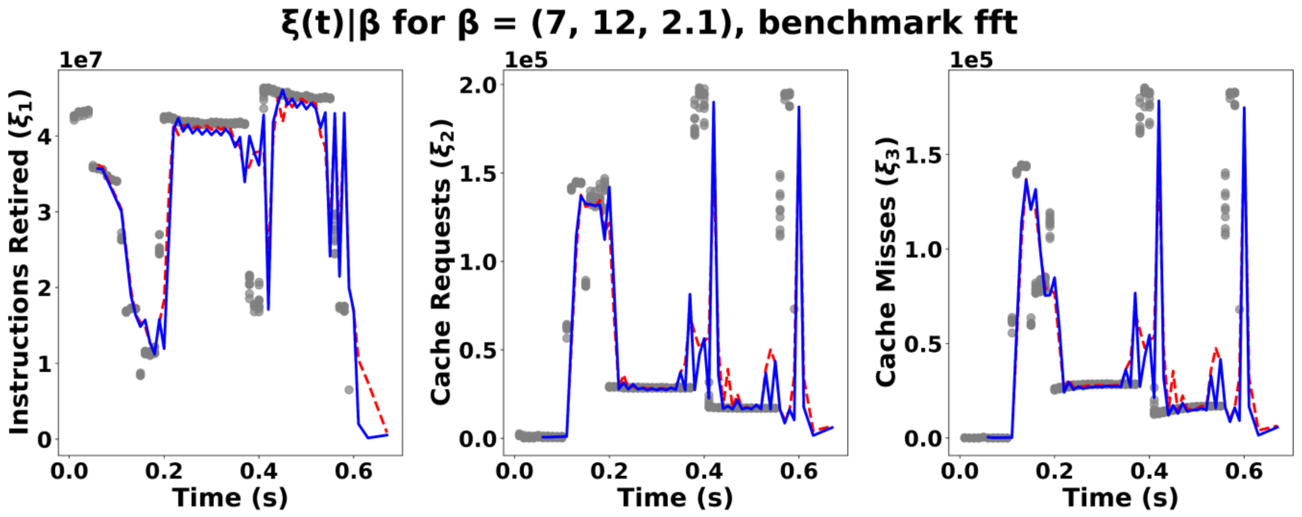
Evaluation Setup

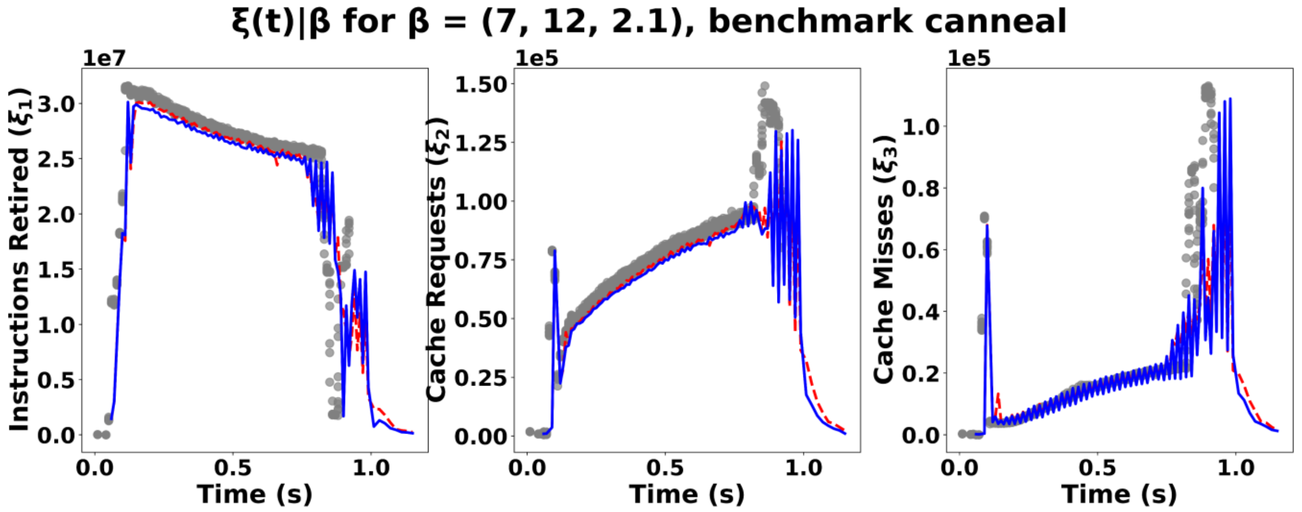
- **Benchmarks:** Single-threaded PARSEC with input `simsmall`
- **Hardware:** Intel Xeon E5-2618L v3 processor
- **Resource contexts (4560 unique β):**
  - CAT for LLC partitioning (β_1)
  - MemGuard for memory bandwidth regulation (β_2)
  - DVFS for CPU frequency scaling (β_3)
- **Measured/generated execution state:**
  - Instructions retired (ξ_1)
  - LLC requests (ξ_2)
  - LLC misses (ξ_3)

Mean vs. Maximum-Likelihood

- Visualized **mean** and **maximum likelihood** generative profiles overlaid on **empirical profiles**

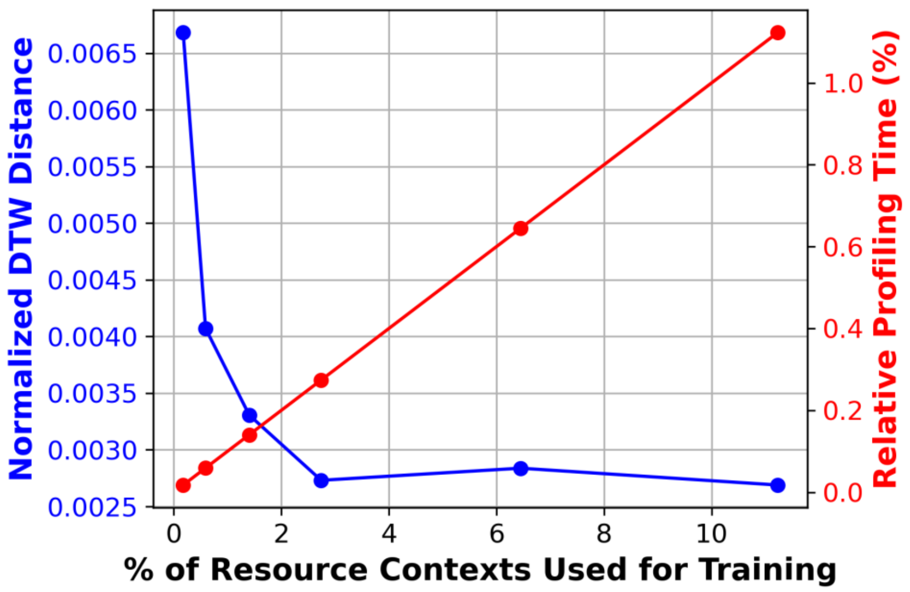
- Resource context unknown to solver: $\beta = (7, 12, 2.1)$





Sparsity Evaluation

- How many resource contexts should be empirically profiled to obtain accurate generative profiles?



- **Accuracy metric:** normalized Dynamic Time Warping (DTW) distance

Accuracy Evaluation vs. Baseline

- **Baseline:** interpolation between known resource contexts

	Baseline	Generative	Improvement
blackscholes	0.0429	0.0343	20.0%
bodytrack	0.0437	0.0375	14.2%
canneal	0.0227	0.0027	88.1%
dedup	0.0321	0.0191	40.5%
fft	0.0508	0.0478	5.9%
fluidanimate	0.0357	0.0275	23.0%
radiosity	0.0404	0.0380	5.9%
streamcluster	0.0549	0.0418	23.9%

- Does this level of improvement in the DTW distance matter?

Case Study

- **DNA [3]:** phase-aware dynamic cache and memory bandwidth allocator that uses fine-grained context-dependent profiles
- **DVFS-DNA (this case study):** extension of DNA that selects minimal CPU frequency for each phase and resource context

[3] R. Gifford, N. Gandhi, L. T. X. Phan, and A. Haeberlen. DNA: Dynamic resource allocation for soft real-time multicore systems. In RTAS, 2021.

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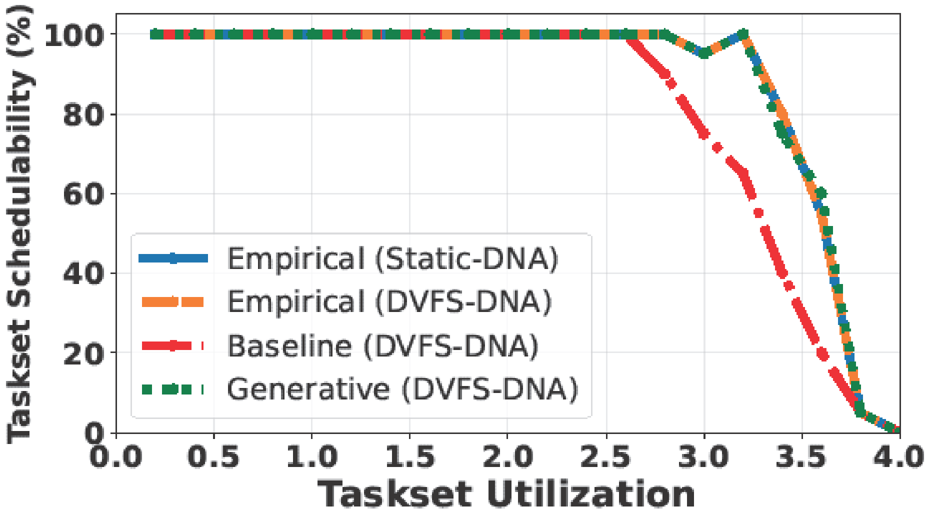

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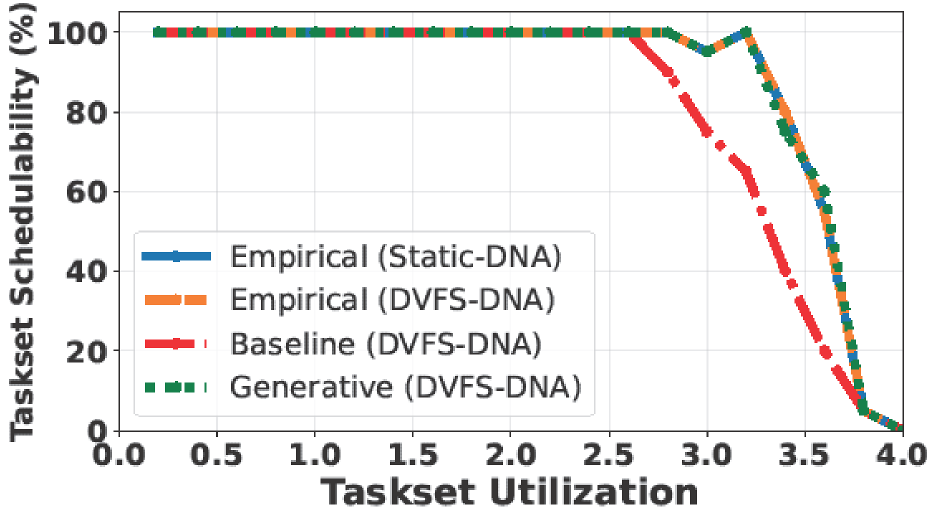

DVFS-DNA energy reduction:
18.1% with empirical profiles
14.8% with generative profiles

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Reduction in Profiling Time per Benchmark

	Total Time (hrs)	# Empirical Profiles
Empirical	231	456,000
Baseline	0.64	1,250
Generative	1.14	1,250

Conclusion

- We presented context-dependent fine-grained **generative profiling**
- Properties:
  - No parametric assumptions
  - Extends to arbitrary resource context and execution state dimensions
  - Consistency with known observations
  - Maximum-likelihood guarantee
- Experimental findings:
  - Orders of magnitude reduction in profiling time
  - Generates profiles for unseen resource contexts with high accuracy
  - Maintains real-time performance in a case study

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