HELIOS
Execution Optimization For Link Discovery

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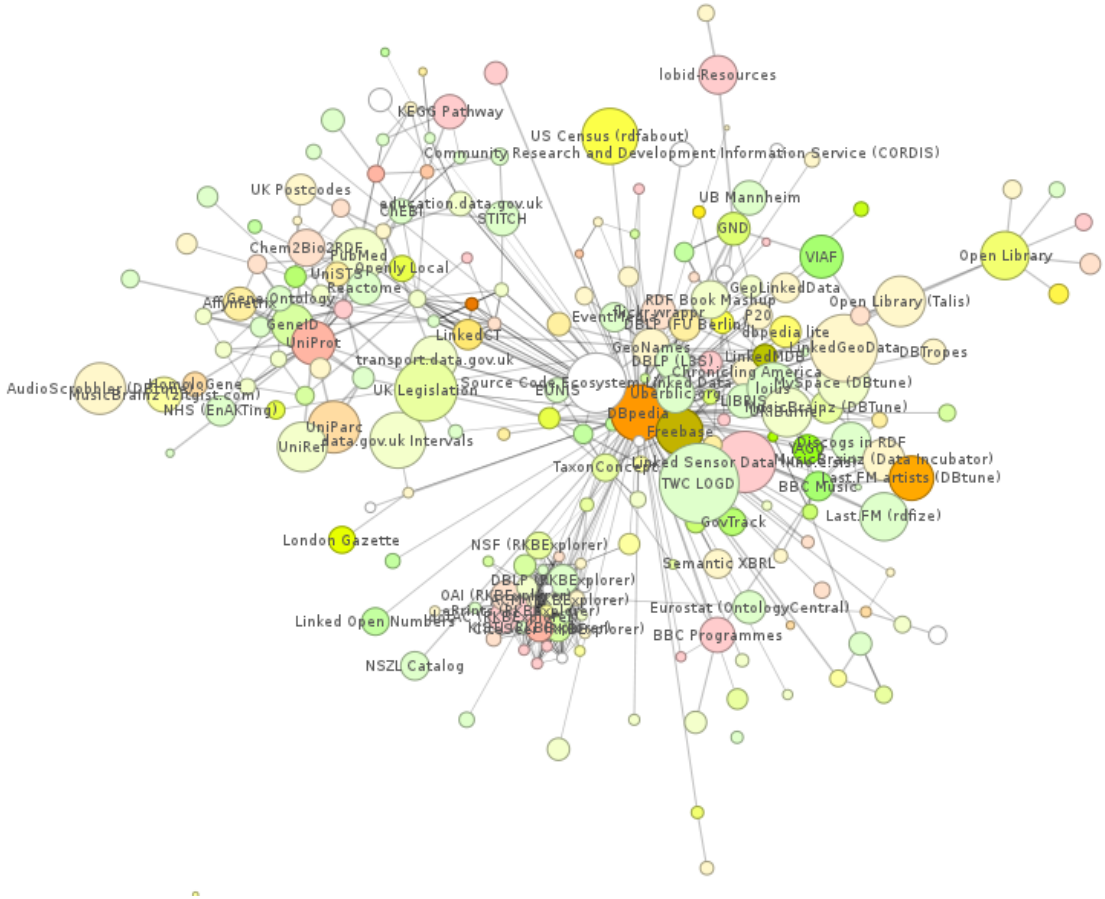
Why Link Discovery?

1. Fourth principle
2. Links are central for
   - Cross-ontology QA
   - Data Integration
   - Reasoning
   - Federated Queries
   - ...
3. Current topology of the LOD Cloud
   - 62+ billion triples
   - $\approx$ 0.5 billion links
   - Mostly `owl:sameAs`



Formal Definition

Definition (Link Discovery)

- Given sets S and T of resources and relation $\mathcal{R}$
- Find $M = \{(s, t) \in S \times T : \mathcal{R}(s, t)\}$

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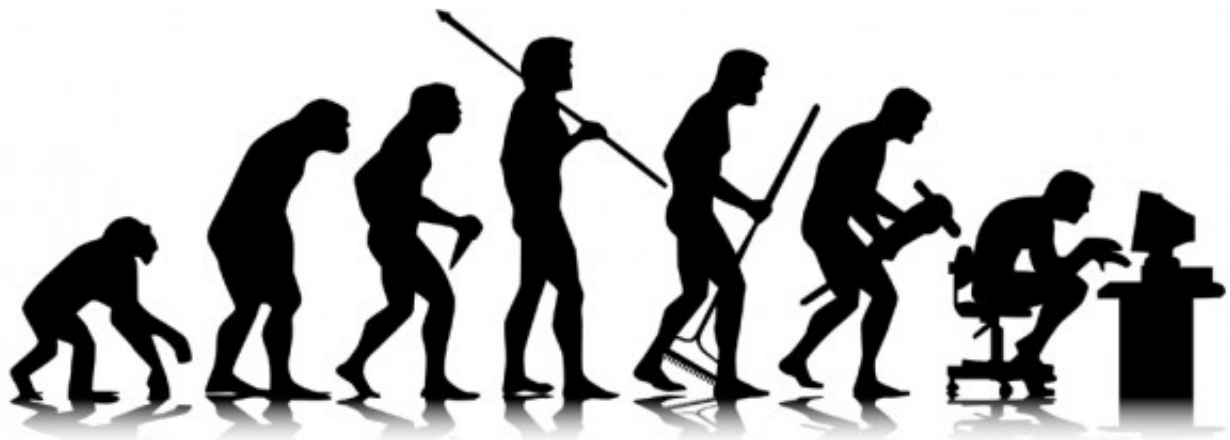
- Automatic computation of M most commonly difficult
- Too tedious for manual evaluation on large knowledge bases



Normal Form for Link Specifications

Definition (Link Discovery (Approximation))

- Find $M' = \{(s, t) \in S \times T : \sigma(s, t) \geq \theta\}$

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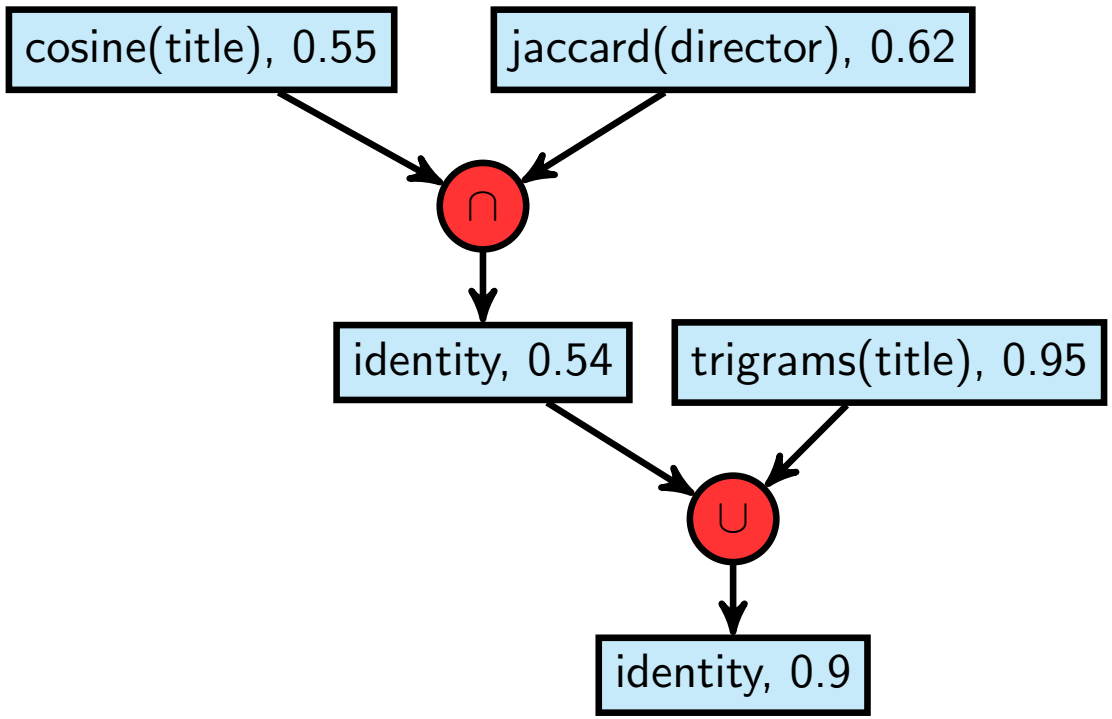

- σ can be complex and represented as bi-partite tree
- Atomic elements are **filters** (blue) and **operators** (red)

Why is it difficult?

- **Accuracy**
  - Detection of appropriate filters, thresholds and operators
  - Solutions incl.
    - Unsupervised learning (EUCLID, EAGLE, KnoFuss)
    - Active learning (RAVEN, EAGLE, ActiveGenLink)
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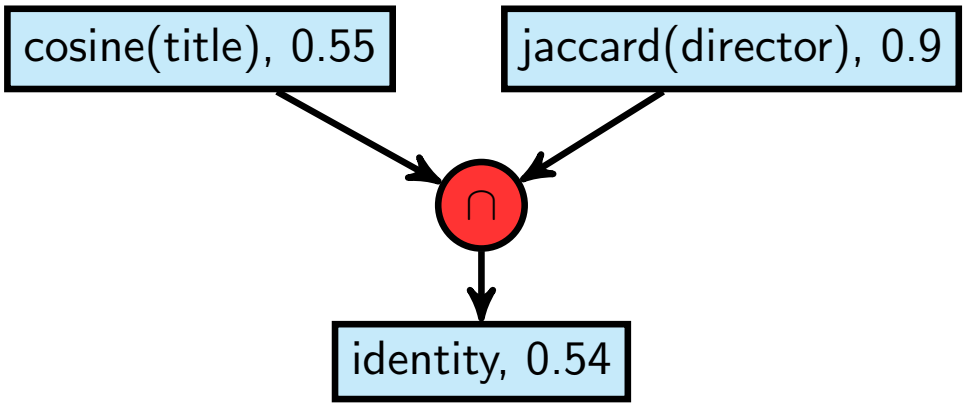
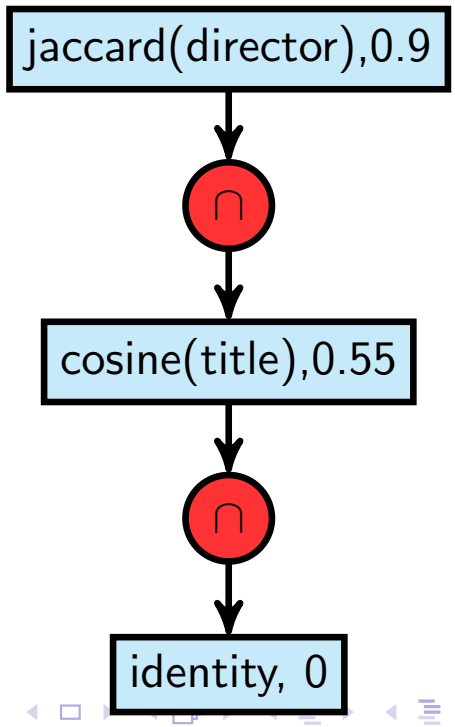
- **Time complexity**
  - Quadratic a-priori runtime
  - So far optimization of runtime for single filters (HR^3, HYPPO, PPJoin+, LIMES)

Execution Optimization

HELIOS

- **Goal**: Optimize runtime for **whole specifications**
- **Approach**:
  1. Rewrite specifications to small equivalent specifications
  2. Optimize execution by finding time-efficient plans

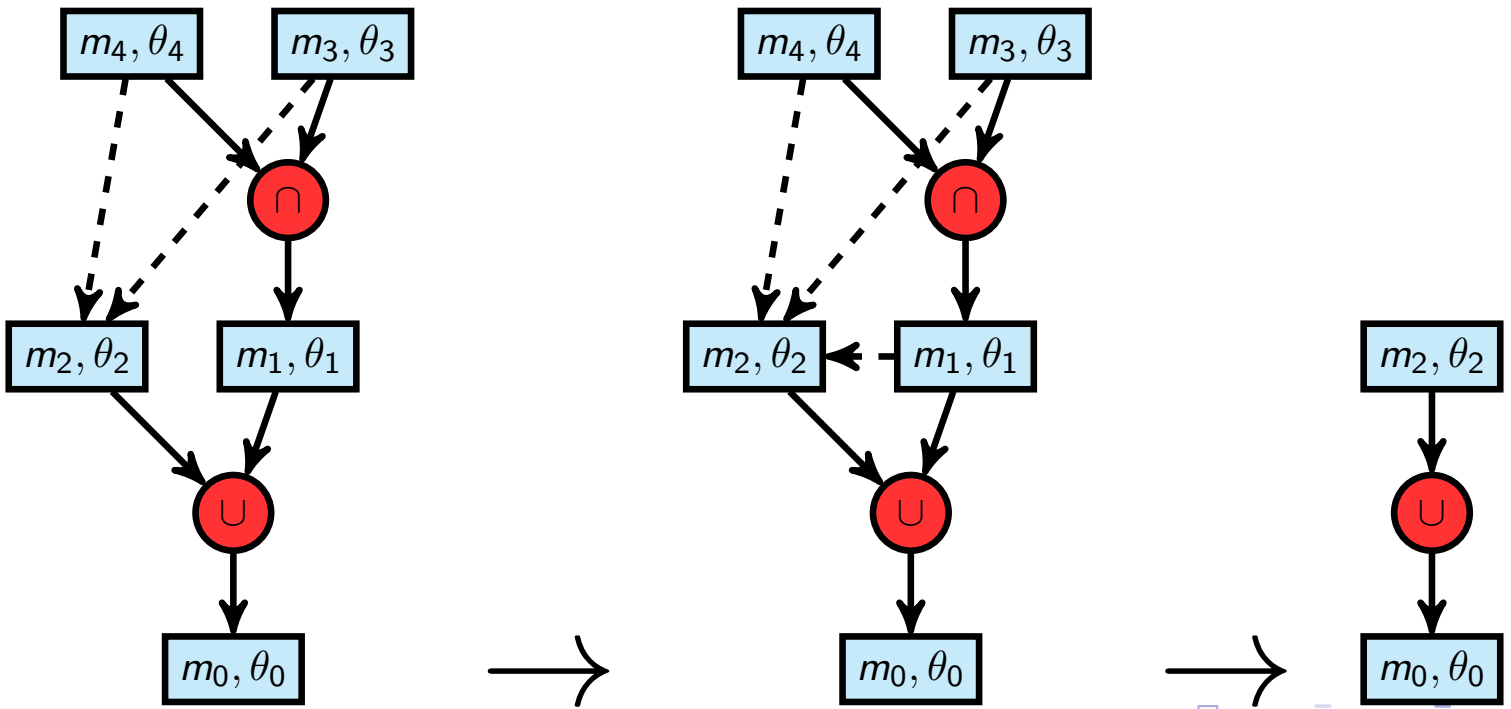




Rewriting

Overview

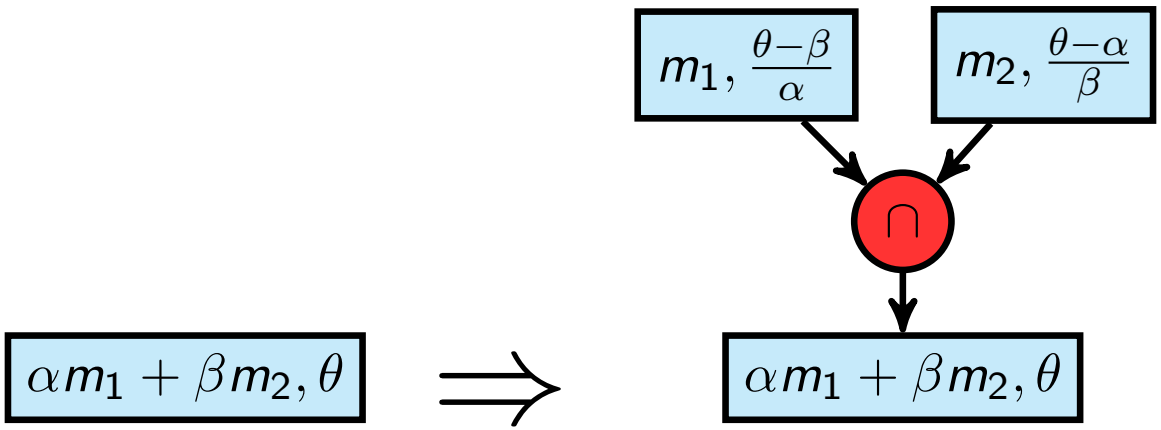
- Fix-point operator
- Three steps
  1. Leaf generation
  2. Dependency detection and propagation
  3. Reduction



Rewriting

Step 1: Leaf generation

- Use equivalence between operators to generate atomic leaves
- Make use of existence of time-efficient algorithms for atomic measures



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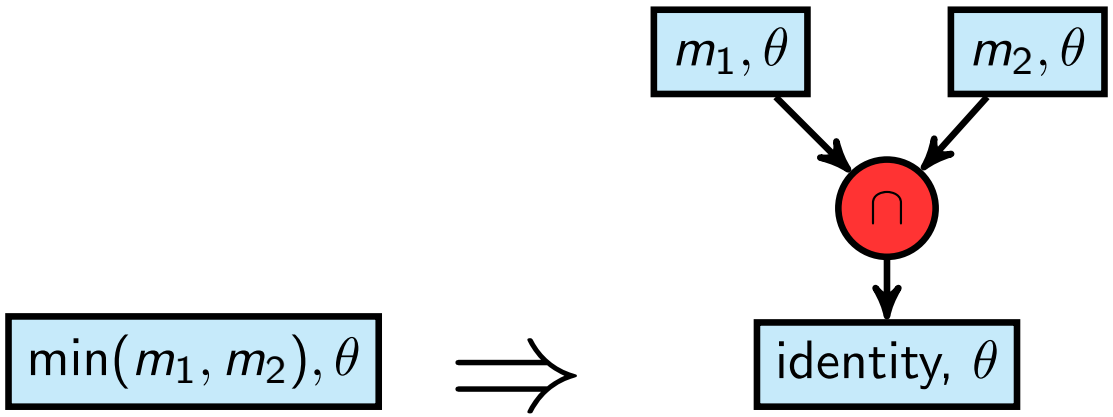

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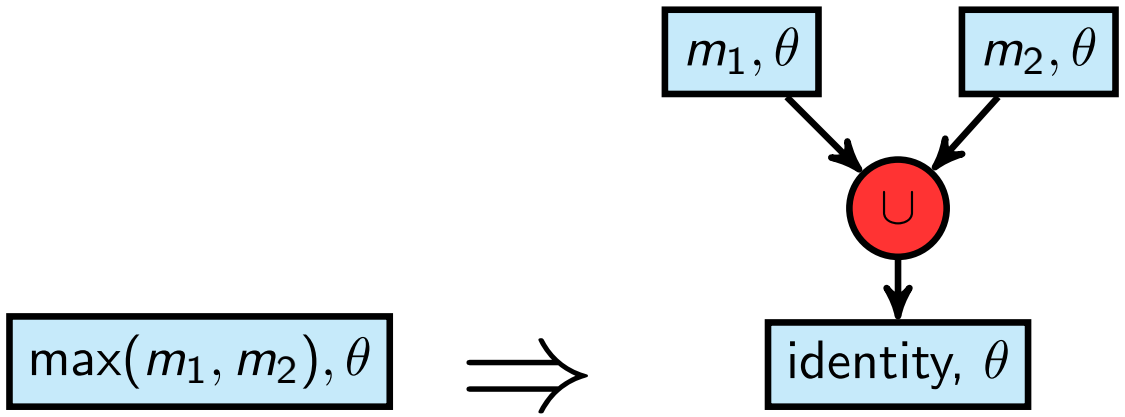

Step 2: **Dependency Detection** and Propagation

- **Idea**: $\mathit{depends}(L_1, L_2) \leftrightarrow \forall S, T : \mathit{result}(L_1) \subseteq \mathit{result}(L_2)$
- Use dependencies between measures, e.g.
  - $\theta_1 \geq \theta_2 \rightarrow \mathit{depends}((m, \theta_1), (m, \theta_2))$
  - $\texttt{jaccard}(x, y) \geq \theta \rightarrow \texttt{overlap}(x, y) \geq \frac{2\theta}{1+\theta}$

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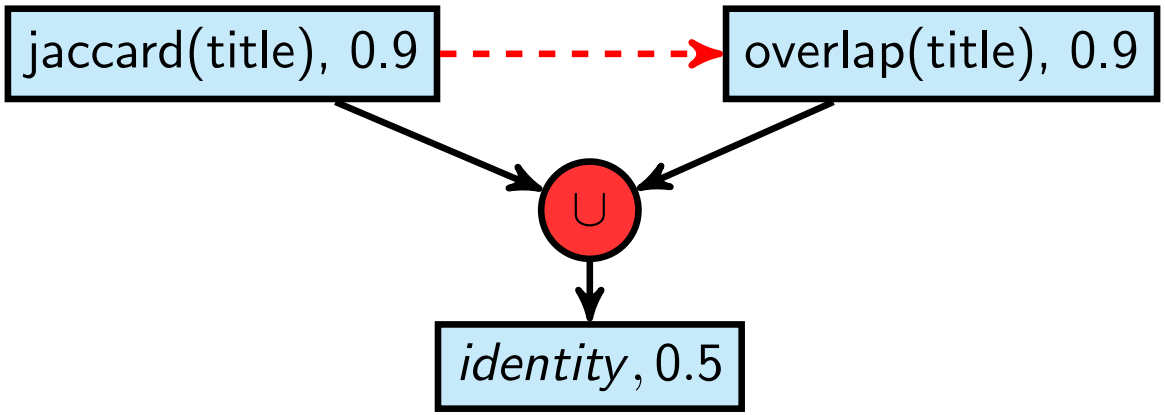

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- **Idea**: Propagate dependencies towards the root
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  - $depends(L_4, L_2) \wedge depends(L_3, L_2) \rightarrow depends(m_1(\cap(L_4, L_3), \theta_1), L_2)$
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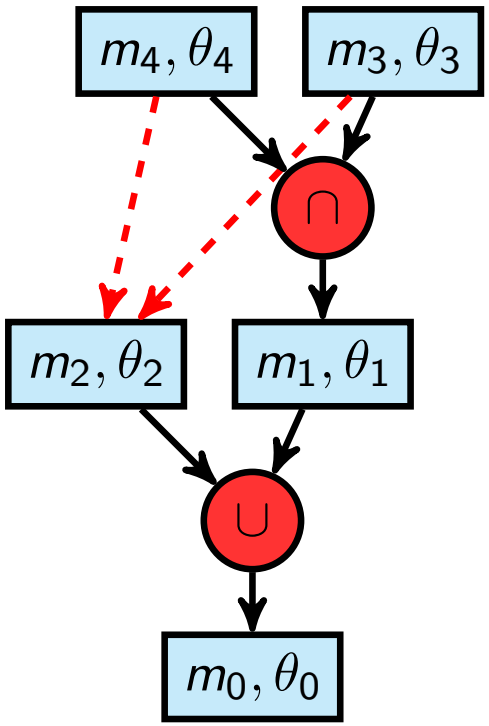

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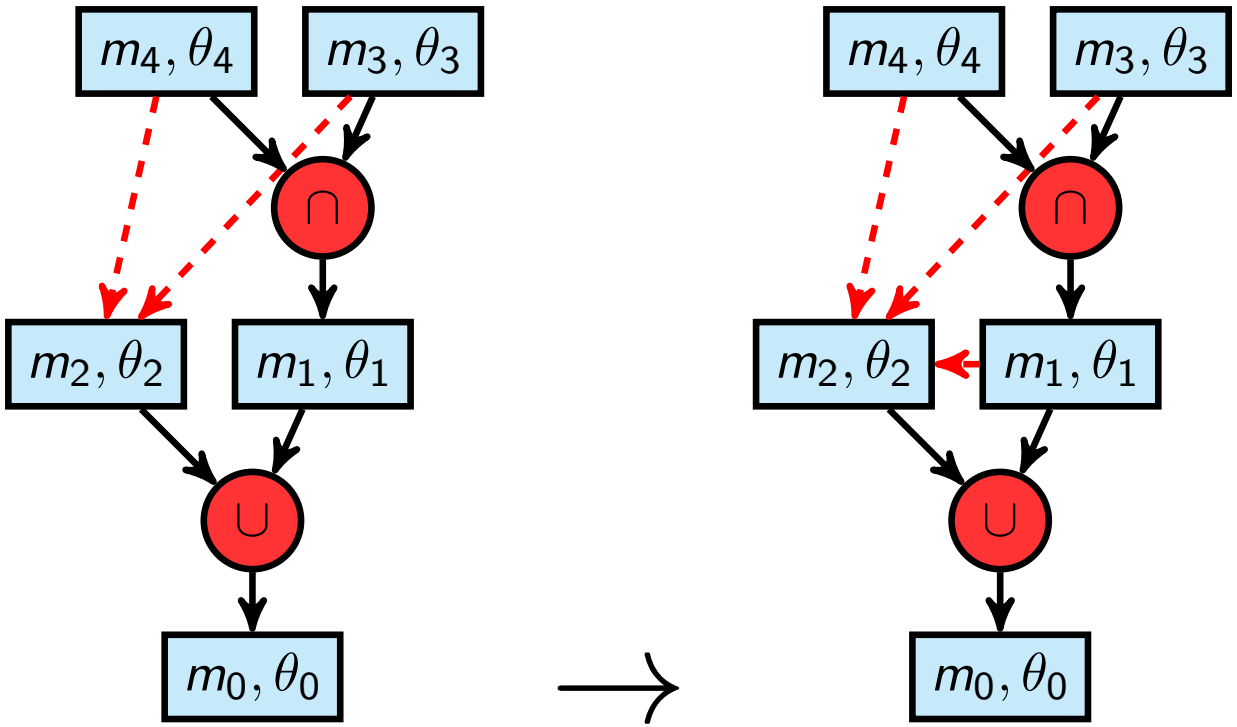

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Step 3: Reduction

- **Idea**: Remove unnecessary specs
- Use set theory, e.g.,
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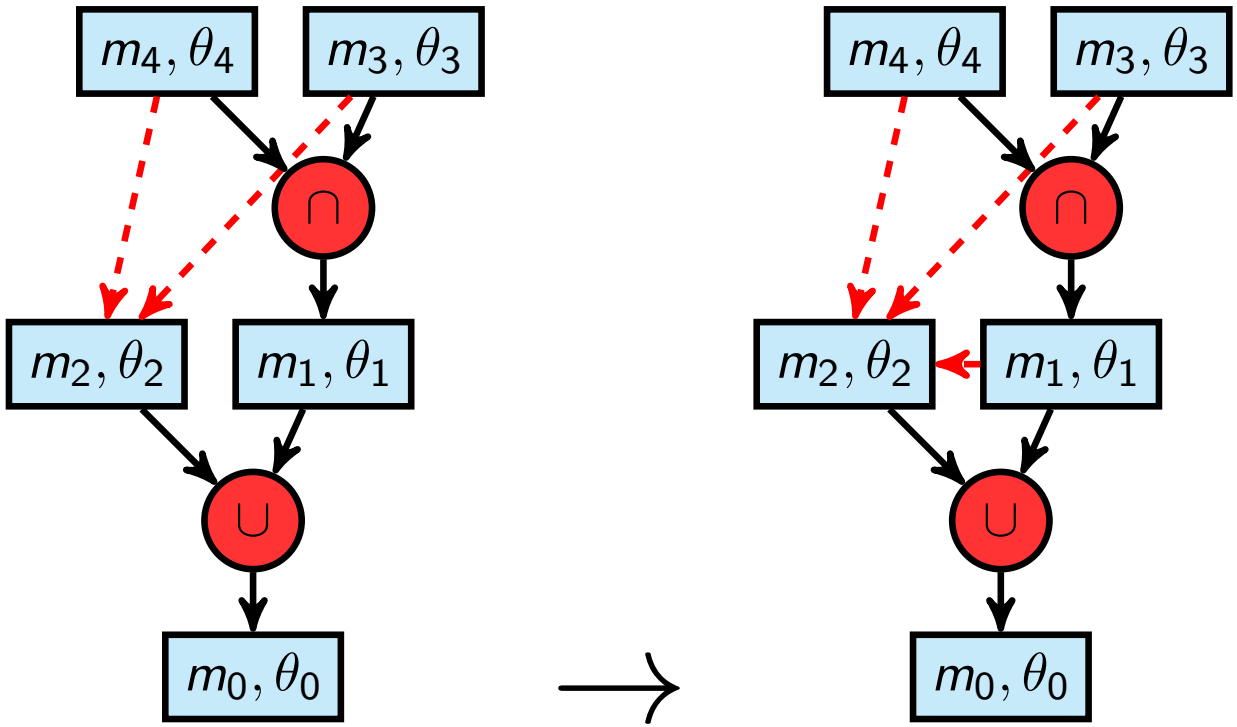

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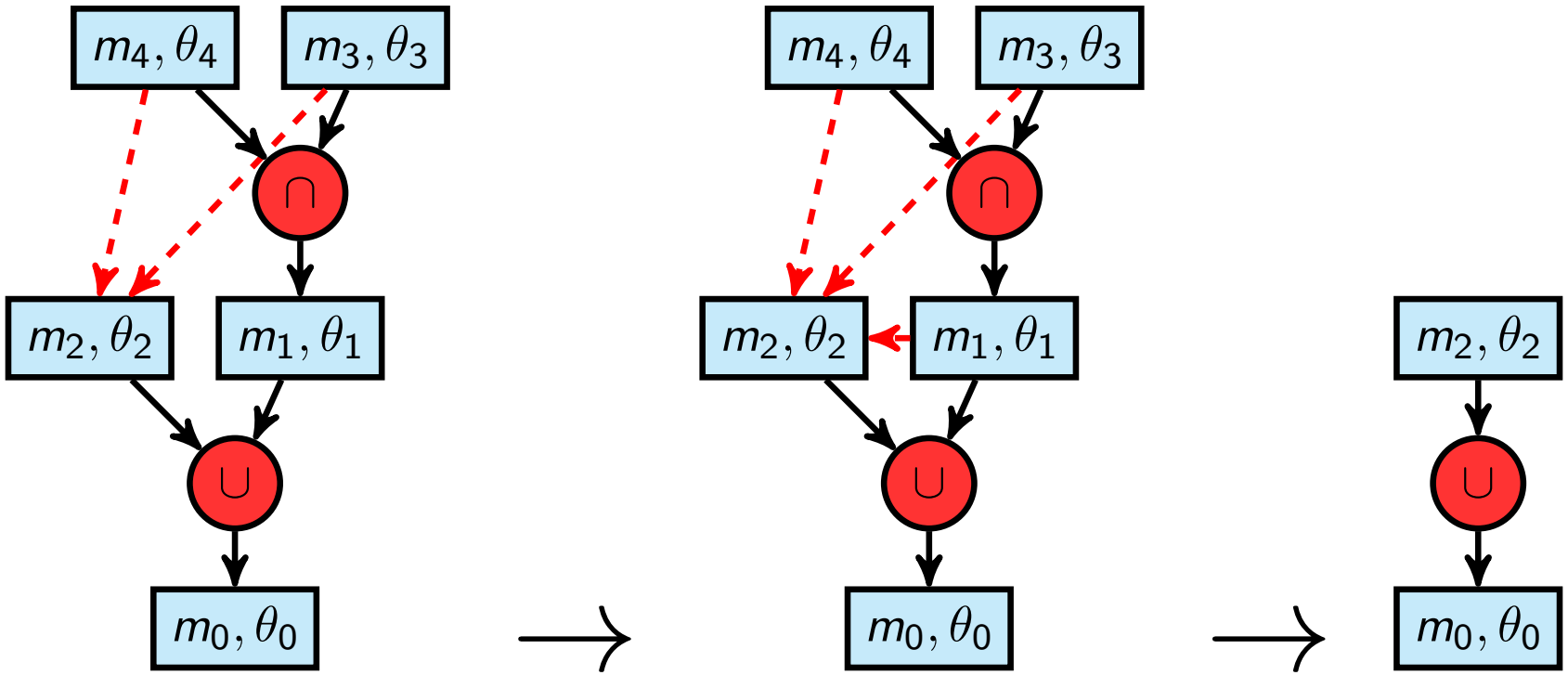

Approach

HELIOS Planner

- **Goal**: Derive equivalent and complete from rewritten specification
- **Required**:
  1. Plan evaluation to detect good plans
  2. Heuristic to reduce number of plans to evaluate
- **Important**:
  1. No a-priori statistics on S and T

Plan Evaluation

Evaluation Functions

- **Runtime**: How long will the plan need?
- **Selectivity**: How many results will the plan generate?

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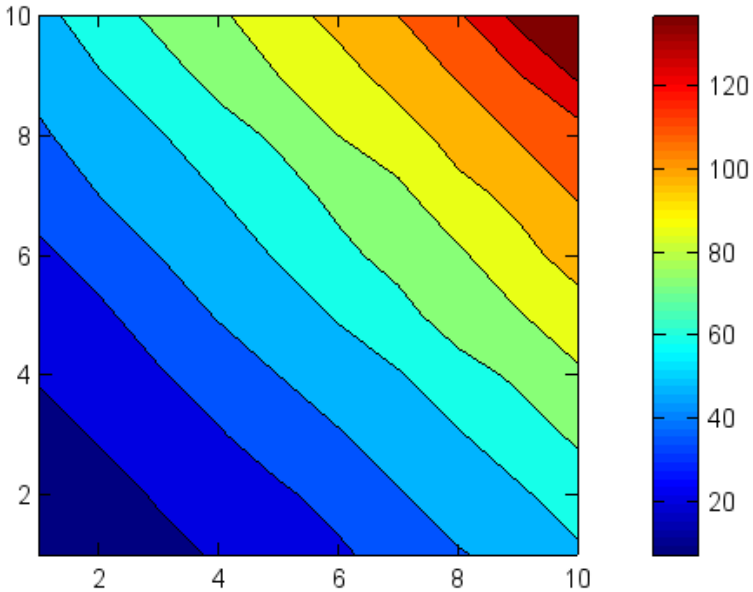
- **Runtime**: How long will the plan need?
- **Selectivity**: How many results will the plan generate?

- **A-priori Runtime Evaluation**
  1. Measure runtime on samples
  2. Compute perfect numerical solution to linear regression
  3. Derive runtime characteristic for each measure
  4. $\gamma(L) = \sum_{L' \subseteq L} \gamma(L') + \gamma(root(L))$

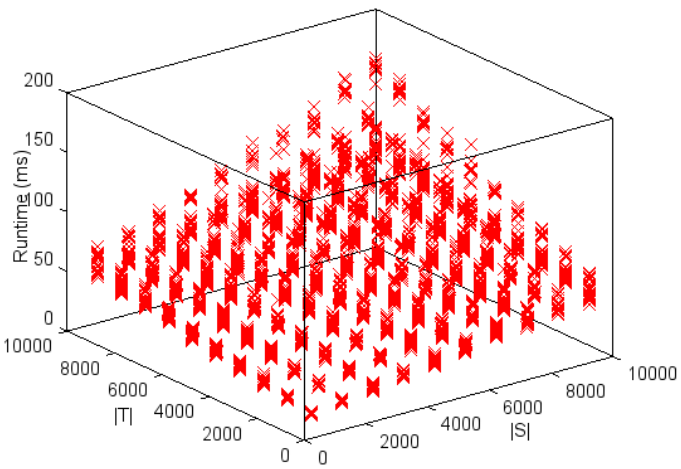


Plan Evaluation

Evaluation Functions

- **Runtime**: How long will the plan need?
- **Selectivity**: How many results will the plan generate?

- **Selectivity**
  - Similar approach
  - Derive probability of pair in input also being in output
  - Assume independence of sub-specifications, e.g.
    - $s(\cap(L_1, L_2)) = s(L_1)s(L_2)$
    - $s(\cup(L_1, L_2)) = 1 - (1 - s(L_1))(1 - s(L_2))$



Plan Optimization

Approach

- If L is atomic, return L
- For $L = m(op(L_1, L_2), \theta)$
  1. Compute plans for L_1 and L_2
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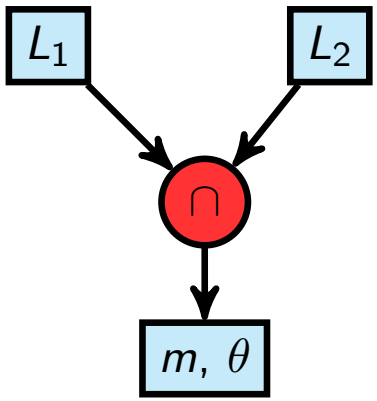

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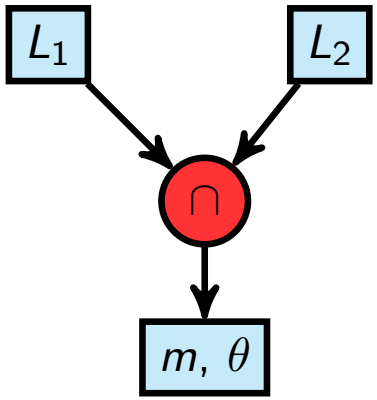

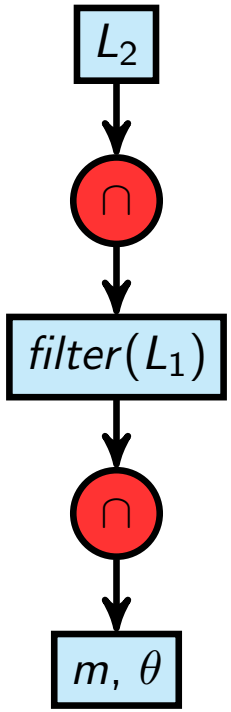

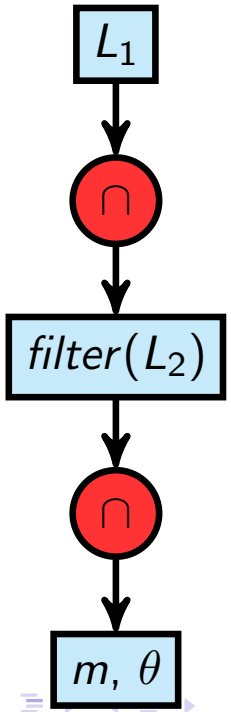

Experimental Setup

- Implemented in LIMES
- Comparison with canonical LIMES planner
  - Optimized algorithms
  - Time-efficient
- Two types of datasets
  - Manually generated
    - Domain experts
    - 17 specifications
    - 18 datasets
    - Size between 1 and 3
  - Automatically generated
    - EAGLE algorithm
    - 2180 specifications
    - 6 datasets
    - Size between 1 and 11

Runtime on Expert Specifications

Source - Target	$\|S\| \times \|T\|$	*LIMES* (ms)	*RW* (ms)	*HP* (ms)	HELIOS (ms)	Gain (ms)
Stad - Rmon	341.9×10^3	25	23	15	**14**	11
EVT - DF (E)	531.0×10^3	**893**	906	909	905	-12
Climb - Rail	1.9×10^6	41	**40**	**40**	**40**	1
DBLP - DataSW	92.2×10^6	59	59	58	**54**	5
EVT - DF (P)	148.4×10^6	2,477	2,482	2,503	**2,434**	43
EVT - DBLP	161.0×10^6	9,654	**9,575**	9,613	9,612	42

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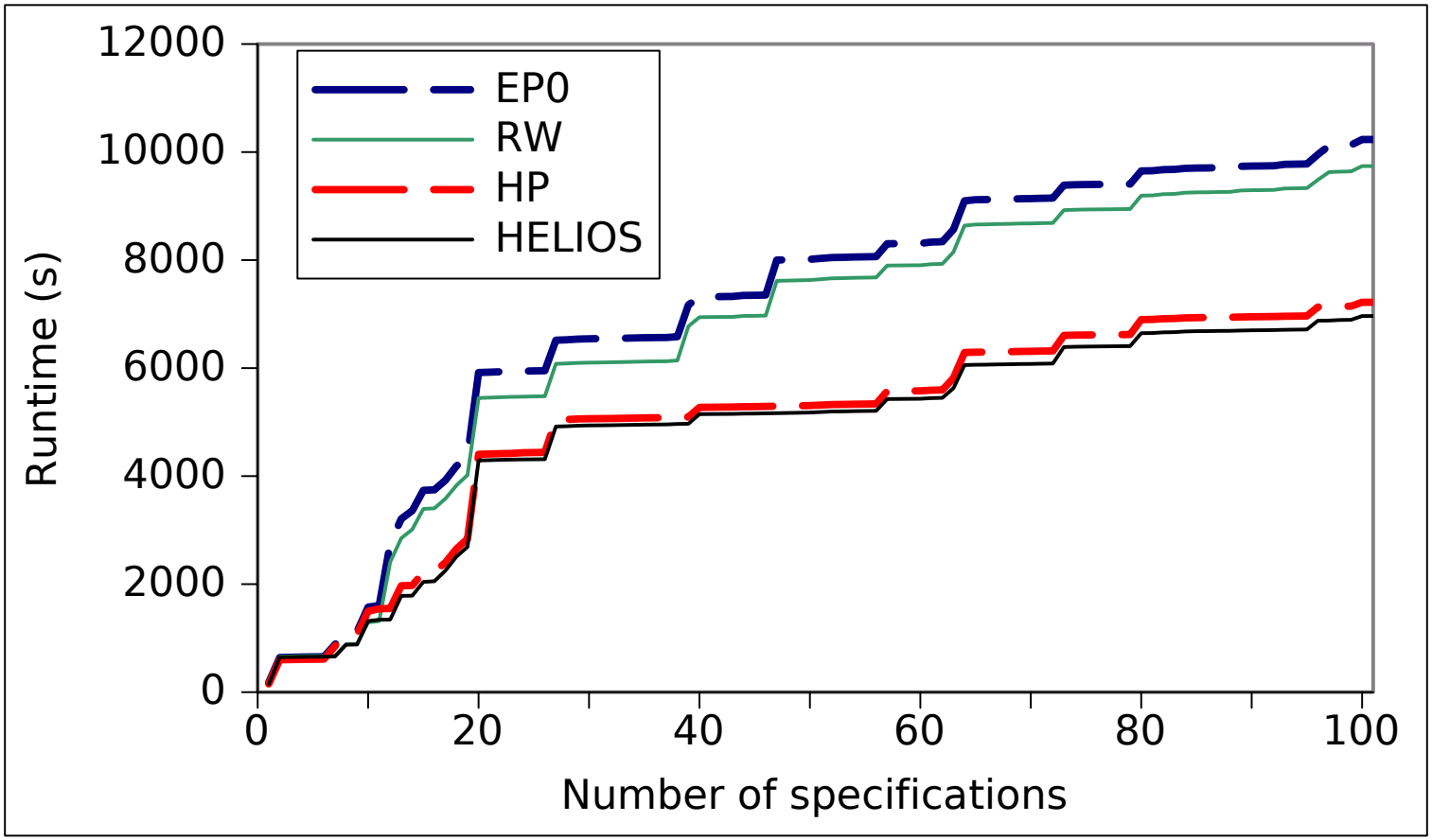
Climb - DBP	312.4×10^3	**55**	**55**	**55**	**55**	0
DBP - LGD (E)	34.1×10^6	2,259	2,133	**1,206**	1,209	1,050
Climb - LGD	215.0×10^6	24,249	24,835	**3,497**	3,521	20,728
DBP - LGD (A)	383.8×10^6	52,663	59,635	1,066	**1,064**	51,599
LGD - LGD	509.3×10^9	46,604	38,560	32,831	**22,497**	24,107

- Runtime on specifications of size 1 not worse
- Significantly better (up to 49.5 times) on specifications of size 3
- HELIOS better than RW or HP alone in most cases

Runtime on LGD



- Significantly outperform the canonical planner
- Effect of rewriting can be clearly seen
- Planner leads to highest gain

Conclusion and Future Work

- Presented HELIOS
- Rule-based rewriting
- Divide-and-conquer approach to planning
- Not yet explored
  - Search-based approaches
  - Backtracking
  - Dynamic planning

That's all Folks!

Thank you!
Questions?

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