# Contribution to the Analysis of the Design-Space of a Distributed Transformation Engine


**Jolan PHILIPPE**

**PhD Defense, speciality: Computer Science**


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|---|---|---|
| Referees: | Jesús SÁNCHEZ CUADRADO | Associate professor, Universidad de Murcia, Spain |
| | Matthias TICHY | Professor, Ulm University, Germany |
| Examiners: | Thomas LEDOUX | Professor, IMT Atlantique, France |
| | Leen LAMBERS | Professor, Brandenburg University of Technology, Germany |
| | Antonio VALLECILLO | Professor, University of Málaga, Spain |
| Ph.D. director: | Gerson SUNYE | Associate professor, University of Nantes, France |
| Ph.D. advisors: | Hélène COULLON | Associate professor, Institut Mines-Telecom Atlantique, France |
| | Massimo TISI | Associate professor, Institut Mines-Telecom Atlantique, France |

lowcomote LS2N

19th December 2022

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

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# Outline

DOCTORAT BRETAGNE LOIRE / MATHSTIC

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

THÈSE DE DOCTORAT DE

L'ÉCOLE NATIONALE SUPÉRIEURE
MINES-TÉLÉCOM ATLANTIQUE BRETAGNE
PAYS-DE-LA-LOIRE - IMT ATLANTIQUE

ÉCOLE DOCTORALE N°601
*Mathématiques et Sciences et Technologies de l'Information et de la Communication*
Spécialité : *Informatique*

Par
**Jolan PHILIPPE**

**Contribution to the Analysis of the Design-Space of a Distributed Transformation Engine**

**Thèse présentée et soutenue à Nantes, le tbd**
**Unité de recherche : Laboratoire des Sciences du Numérique de Nantes**
**Thèse N° : tbd**

**Rapporteurs avant soutenance :**

Jesus SANCHEZ CUADRADO — Associate professos, Universidad de Murcia, Spain
Matthias TICHY — Professor, Brandenburg University of Technology, Germany

**Composition du Jury :**

| | | |
|---|---|---|
| Président : | Thomas LEDOUX | Professor, IMT Atlantique, France |
| Examinateurs : | Leen LAMBERS | Professor, University of Ulm, Germany |
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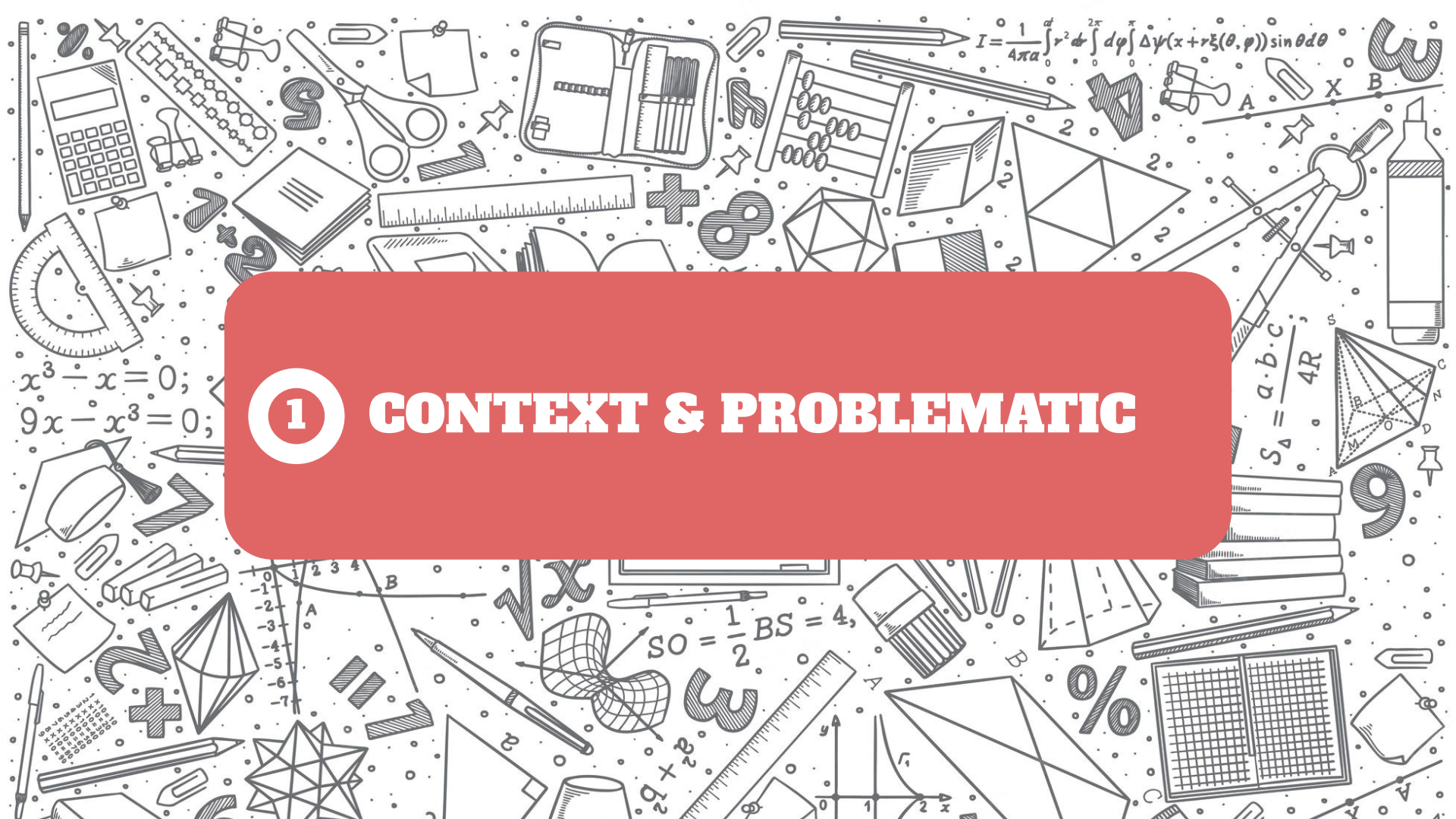
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CONTEXT & PROBLEMATIC

# Context of the thesis

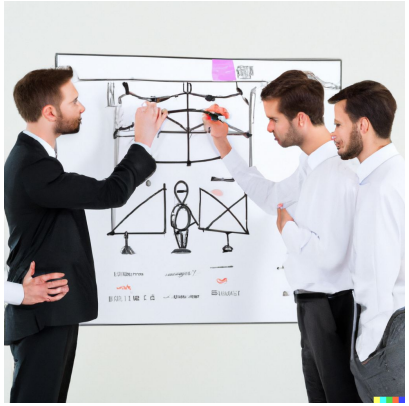
**Lowcomote** is a H2020-ITN project aiming at training 15 PhD students, and build a low-code development platforms based on

- **Model-Driven Engineering**
- **Cloud Computing**
- **Machine Learning**

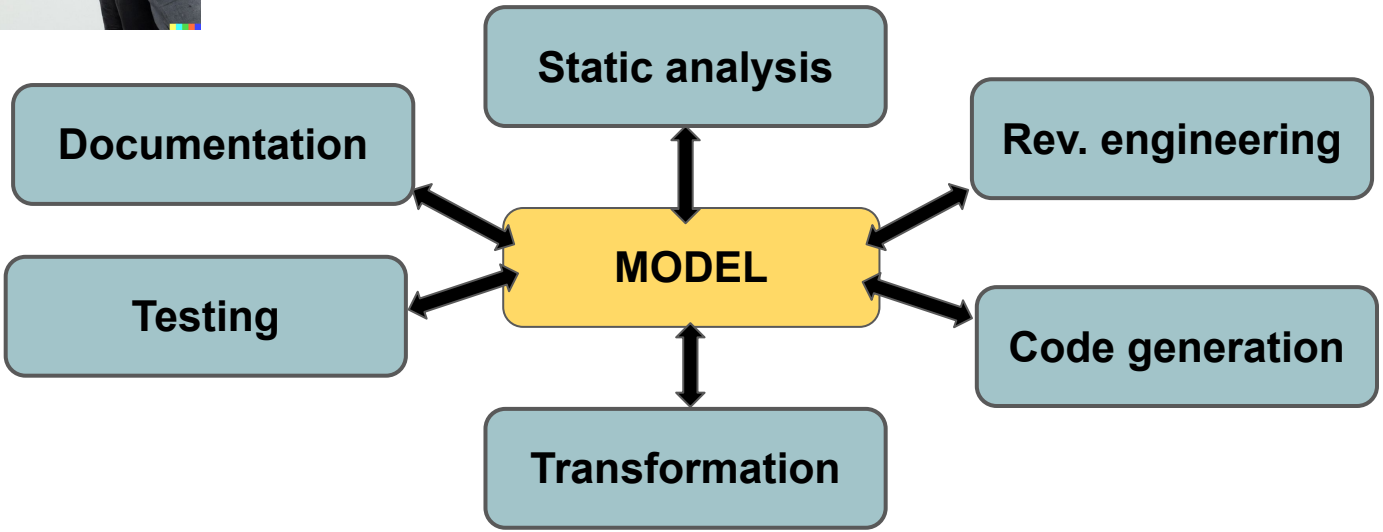
Marie Skłodowska-Curie Actions

**WP5: Scalable Low-Code Artefact Management**

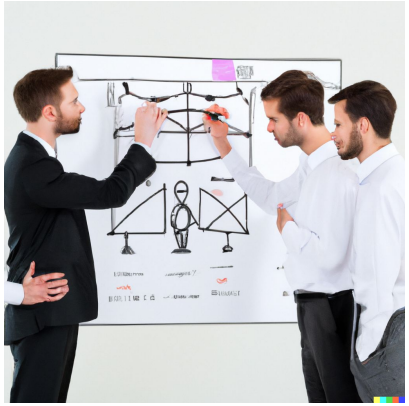
# Model-Driven Engineering



- **Software engineering** approach
- Models as the **central artifact** to represent systems



# Model-Driven Engineering



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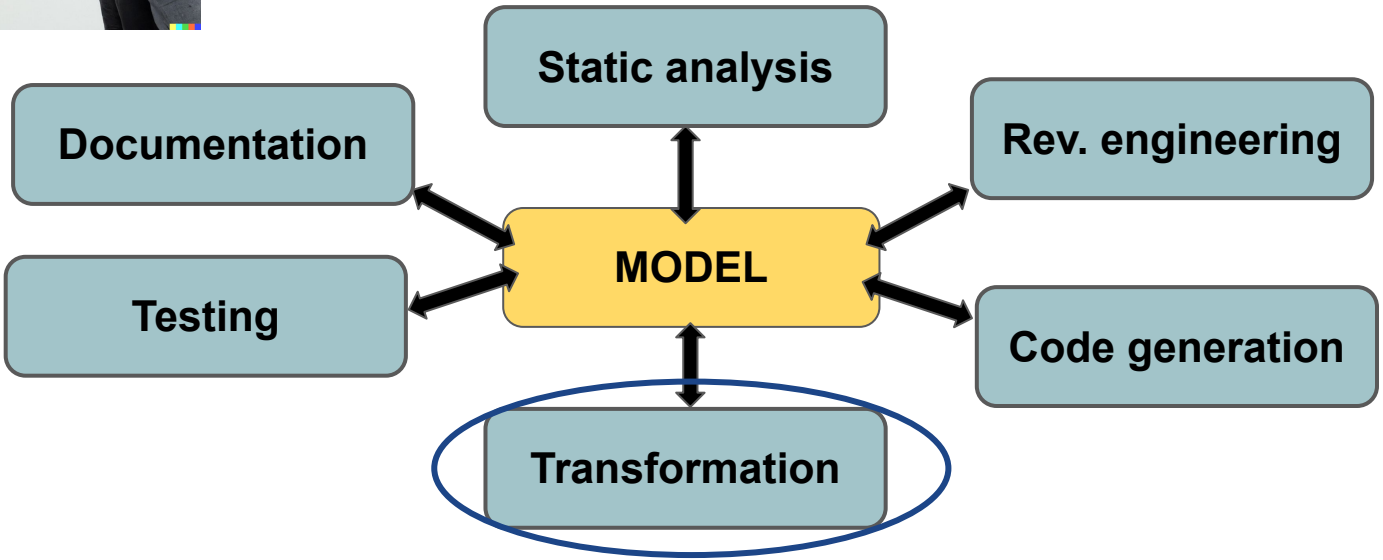

# Model Transformation

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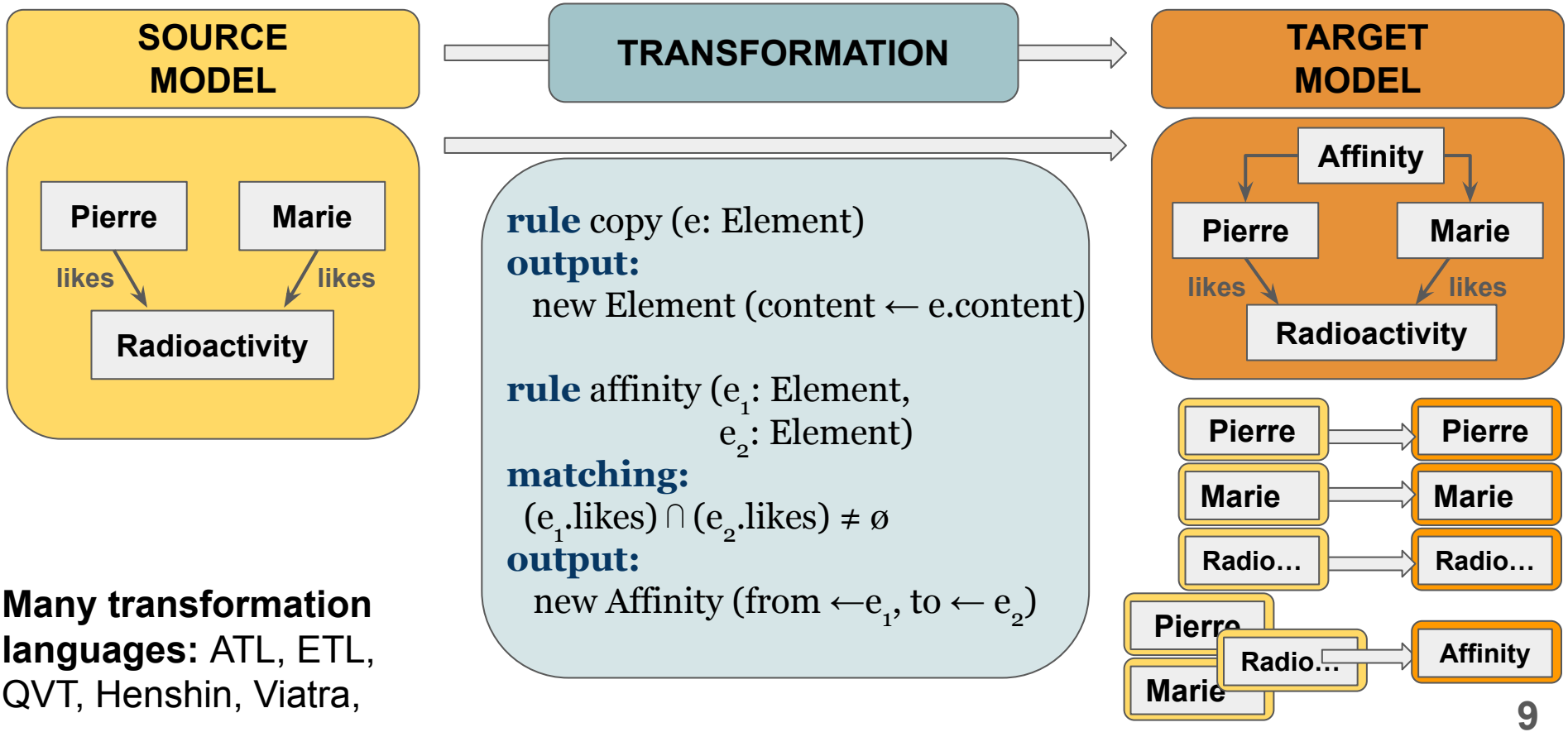
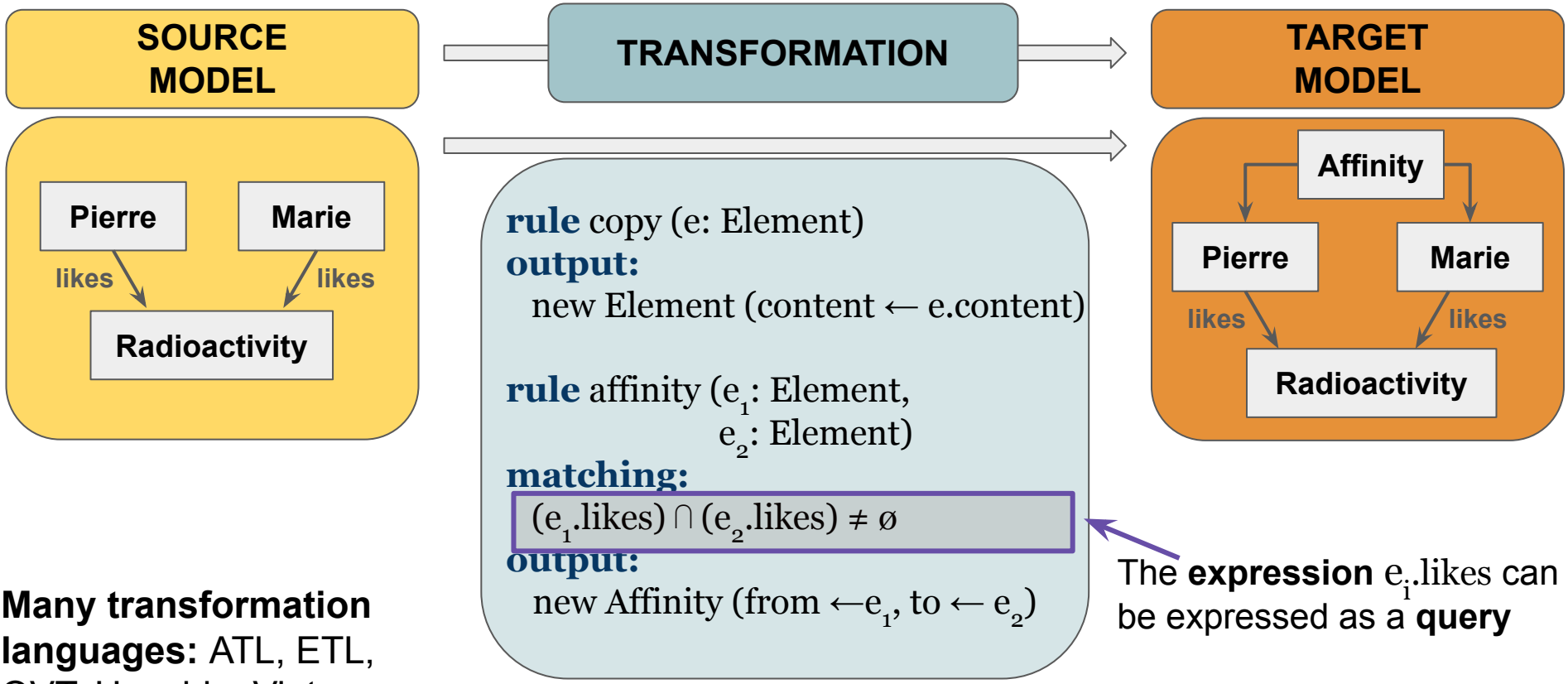



**Many transformation languages:** ATL, ETL, QVT, Henshin, Viatra, …

# Model Transformation

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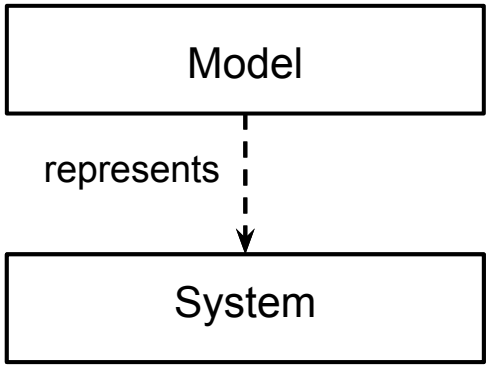
# Use case: A platform for analysing a social network

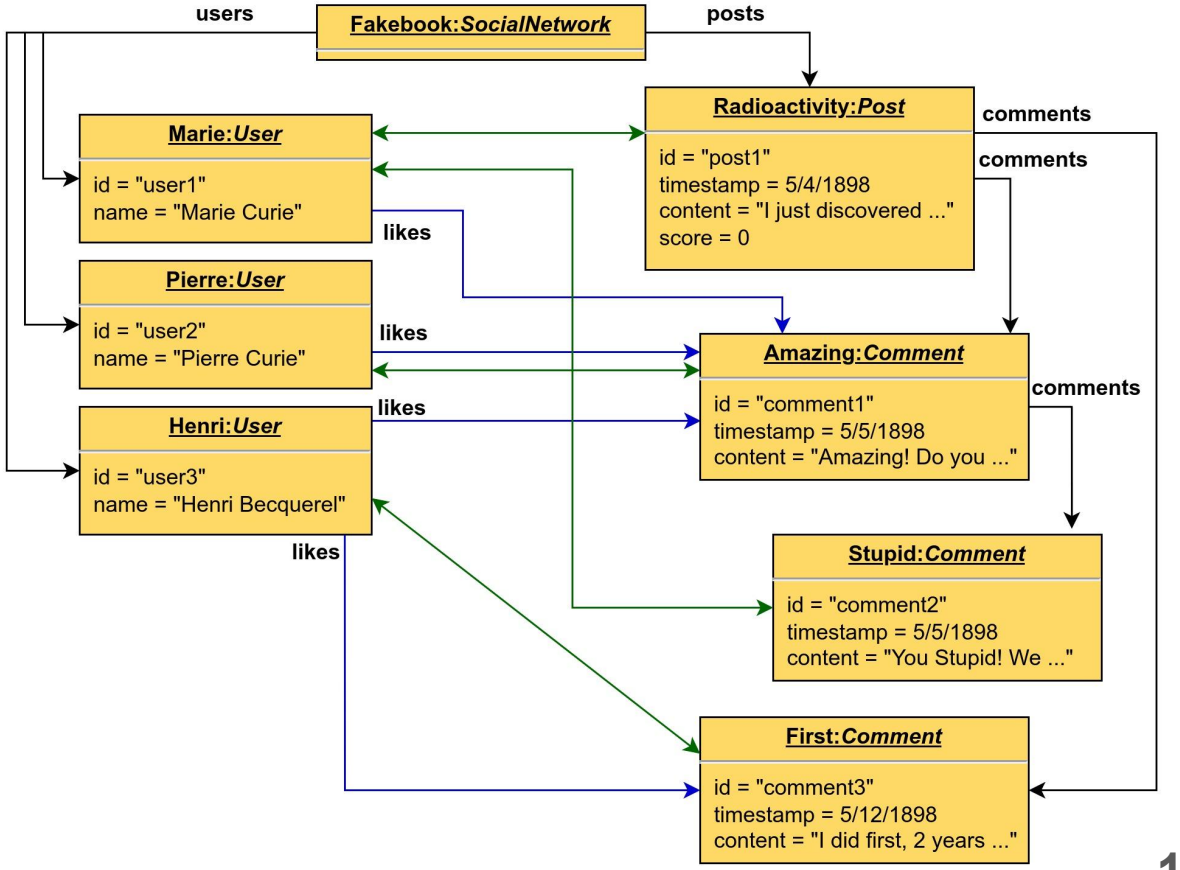


System

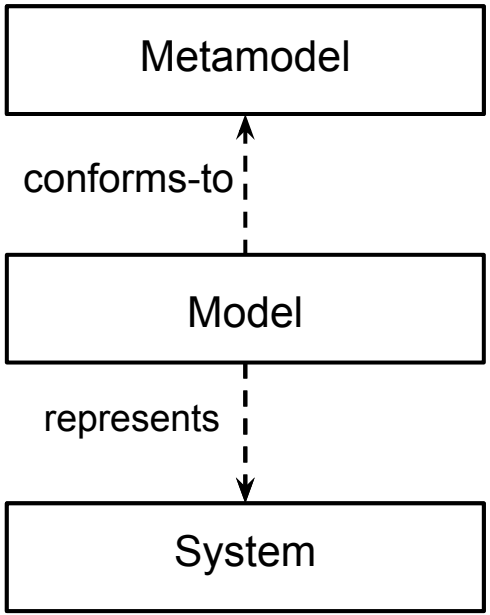
# Use case: A platform for analysing a social network

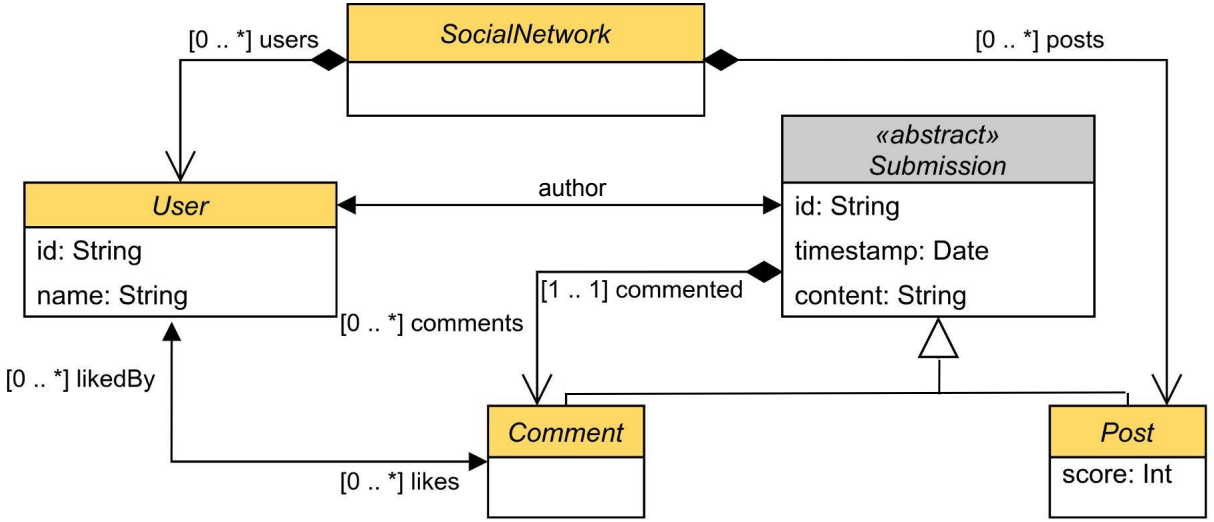




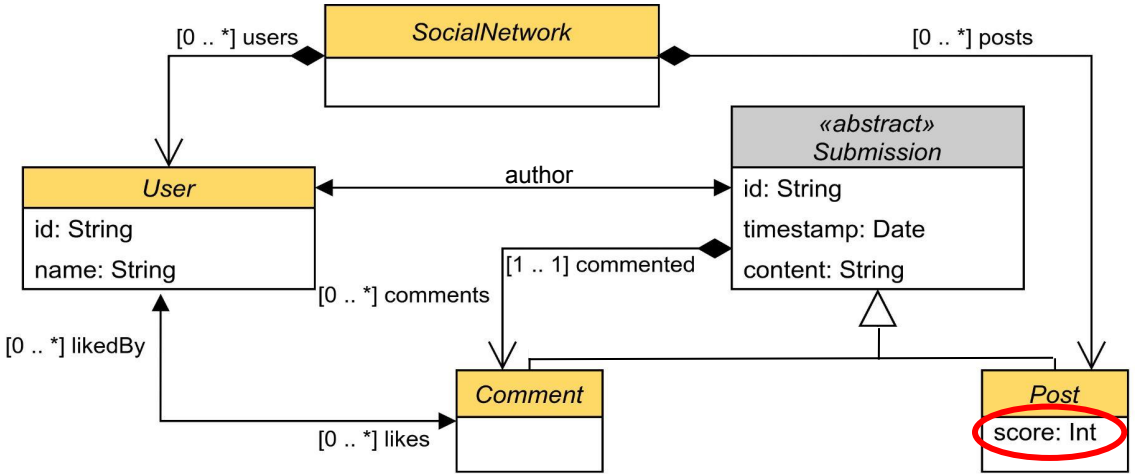
# Use case: A platform for analysing a social network

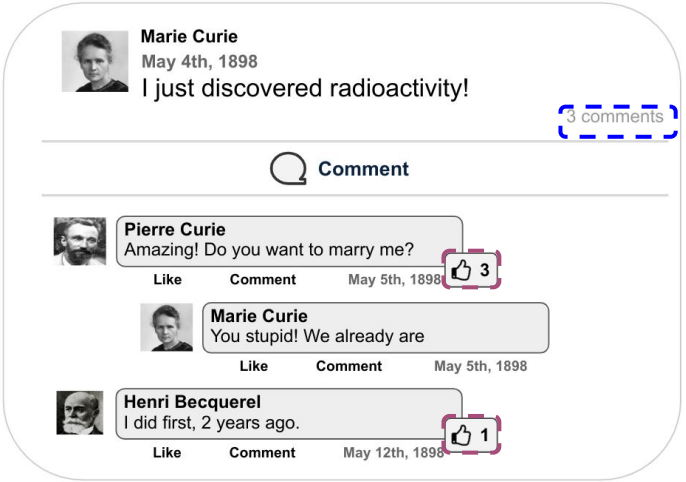


# Example 1: Give an activity score for posts in a social network





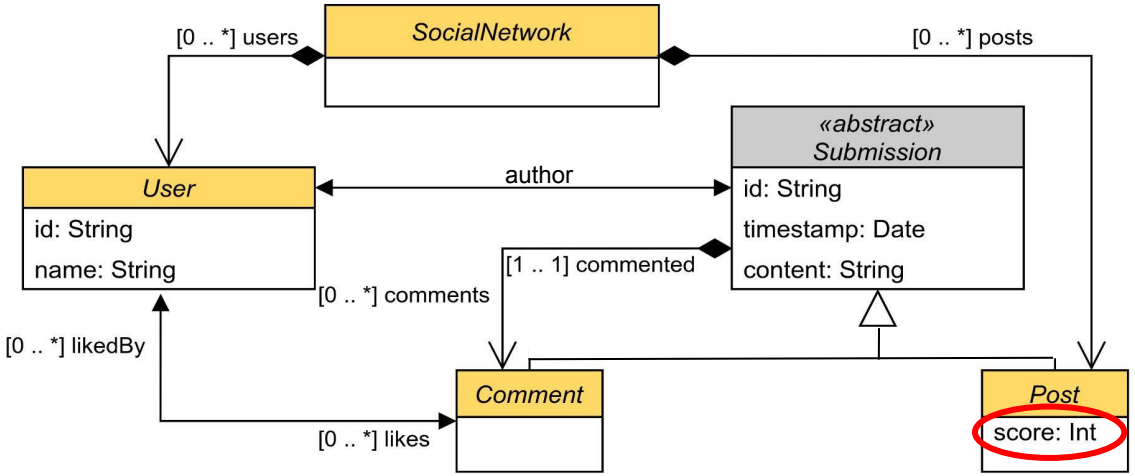



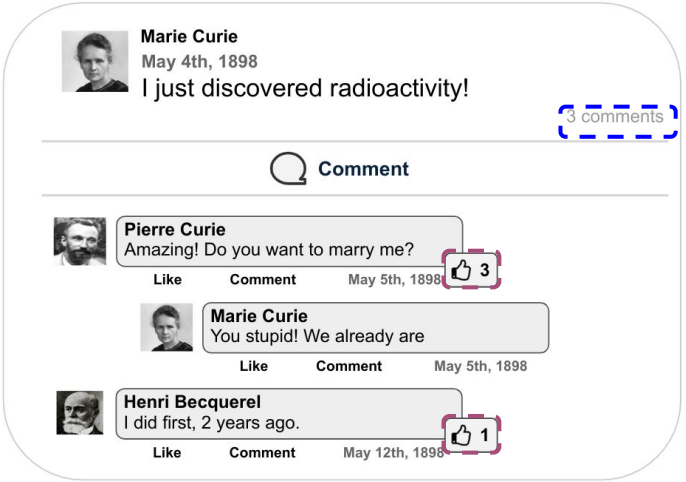

**Example:** score(p: *Post*) ≔ **# comments** × 10 + **# likes**

score(*Radioactivity*) = **3** × 10 + **4** = 34

# Example 1: Give an activity score for posts in a social network





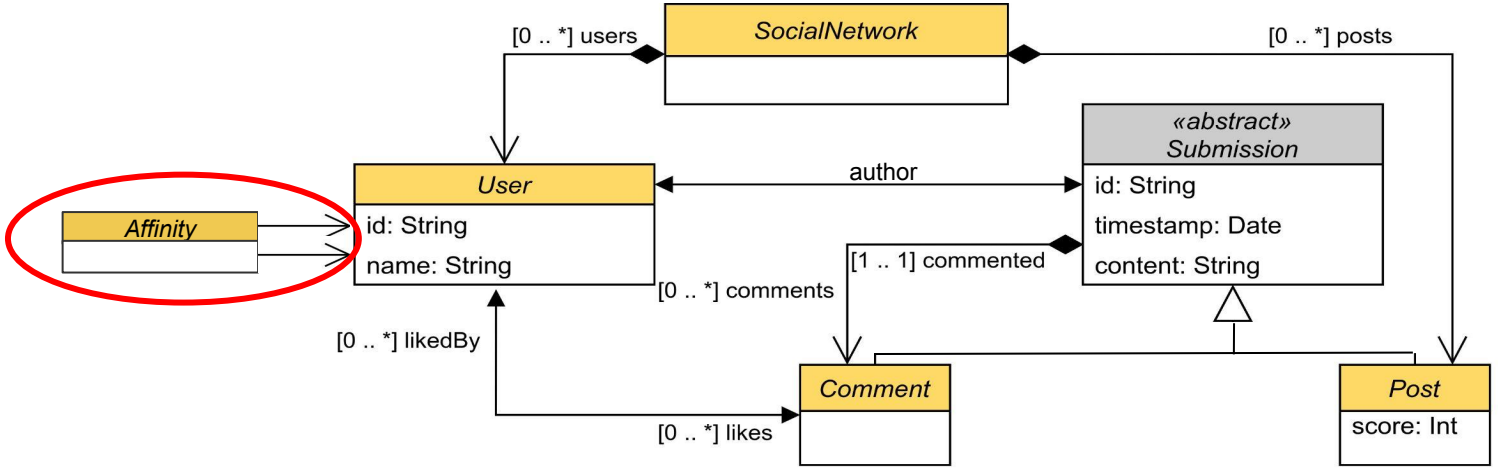

**Example:** score(p: *Post*) ≔ **# comments** × 10 + **# likes**

```
rule Post2ScoredPost (p:Post)
output:
  new Post (id ← p.id,
            timestamp ← p.timestamp
            content ← p.content,
            score ← score(p))
```

**score** as a **query**

# Example 2: Look for user affinities in a social network





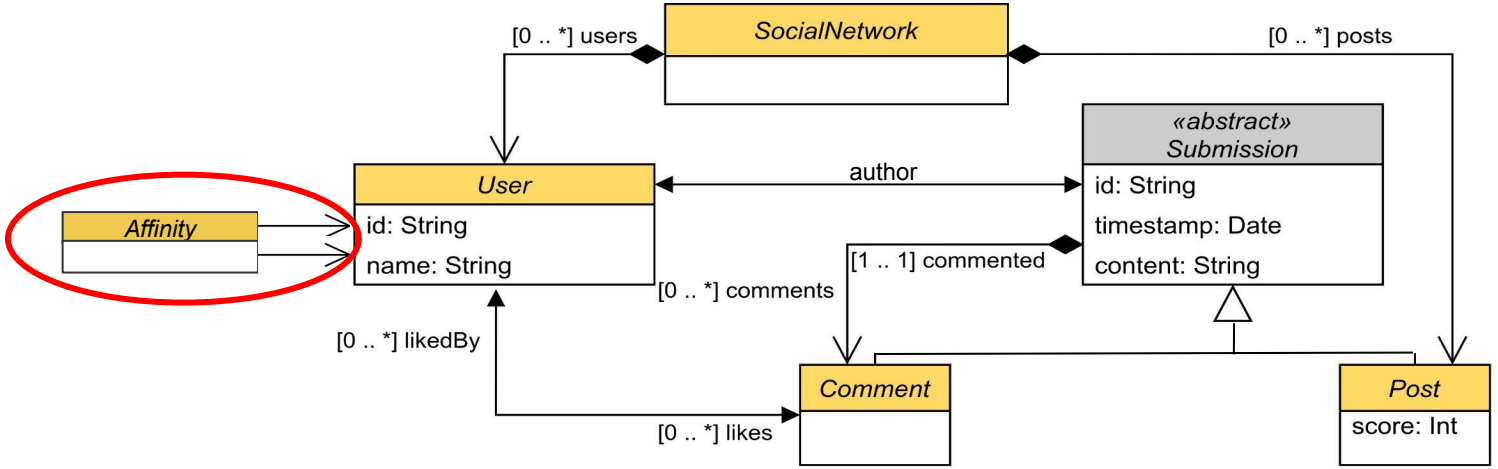

**Example:** Comment at least 3 same posts

**Pierre Curie**

**Marie Curie**

# Example 2: Look for user affinities in a social network



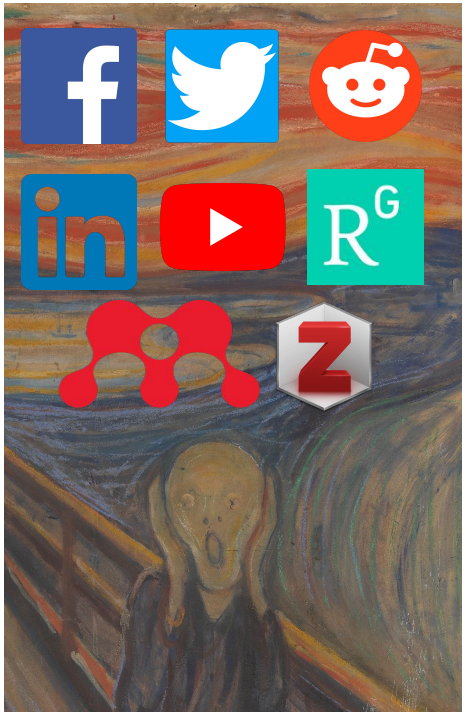



**Example:** Comment at least 3 same posts

**rule** FindAffinity ($u_1$:User, $u_2$:User)
**matching:**
$commentedPosts(u_1) \cap commentedPosts(u_2) \geqslant 3$
**output:**
new Affinity($user_1 \leftarrow u_1$, $user_2 \leftarrow u_2$)

# Model management for Very Large Models (VMLs)[1]



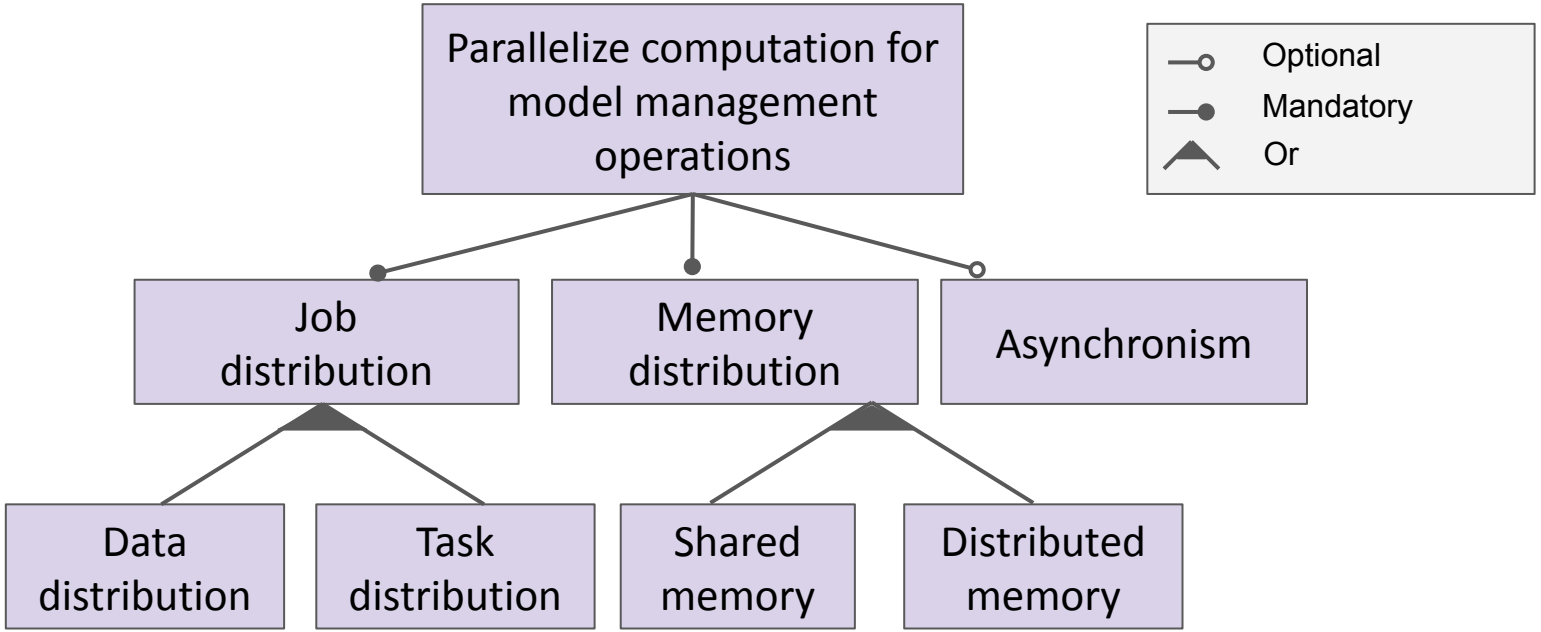


- Computational complexity
  - Size of the model
  - Storage and memory constraints
- Scalability with increasing resources
- Implicit optimization

➢ Two main approaches
  - Avoid computation
  - Parallelize computation

[1] Dimitrios S. Kolovos, Louis M. Rose, Nicholas Drivalos Matragkas, Richard F. Paige, Esther Guerra, Jesús Sánchez Cuadrado, Juan de Lara, István Ráth, Dániel Varró, Massimo Tisi, Jordi Cabot. **A research roadmap towards achieving scalability in model driven engineering.** *BigMDE@STAF 2013*

# Scalability of model management for VLMs



# Parallelization in model transformation

| | Model query | Model transfo. | Pattern match. | Optimization | Shared mem. | Distrib. mem. | Task-parallel | Data-parallel | Asynchronism |
|---|---|---|---|---|---|---|---|---|---|
| Amine Benelallam et al. «**Efficient model partitioning for distributed model** …» SLE 2016 | | X | | X | | X | | X | |
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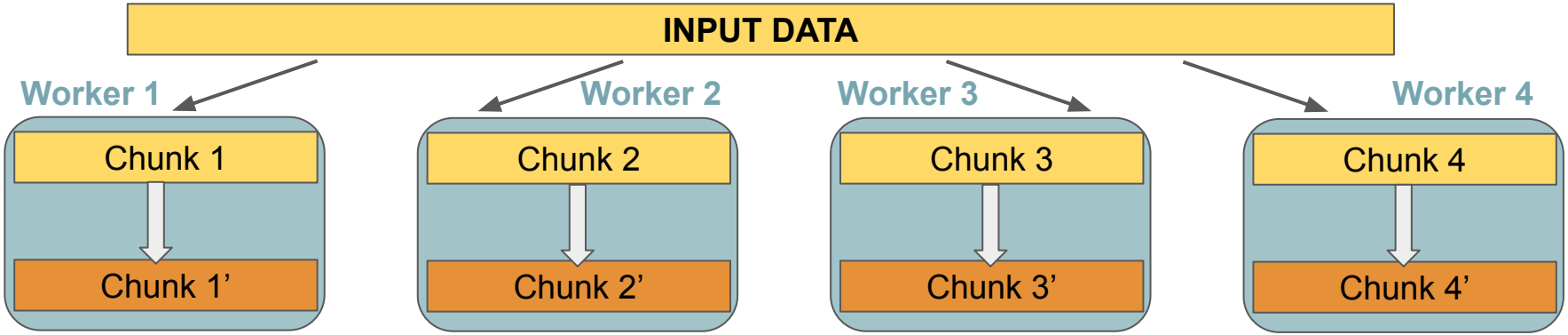
# Data-parallelism as a strategy



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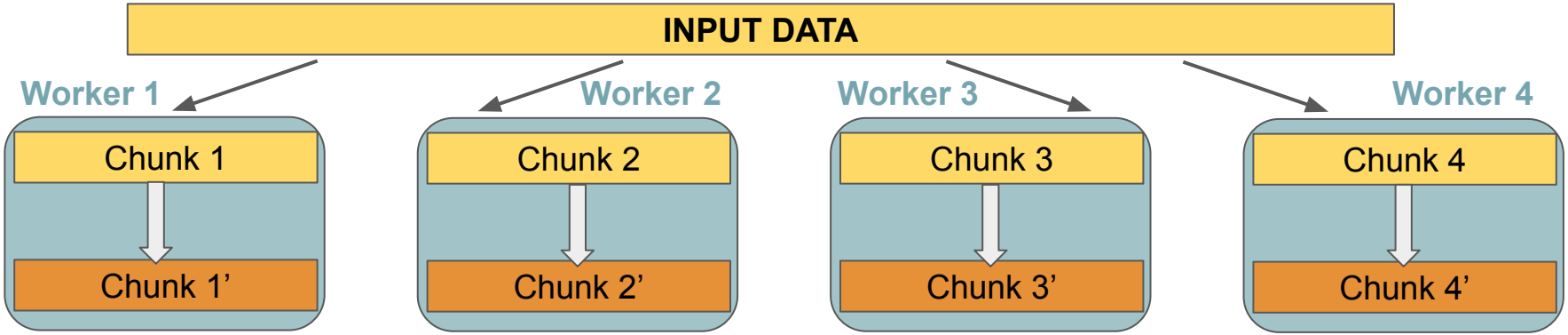
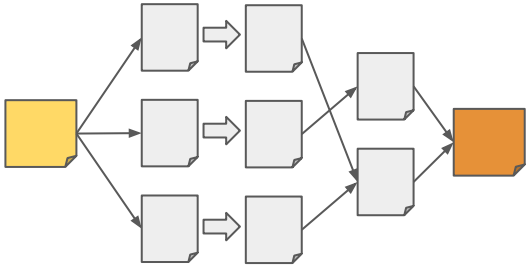
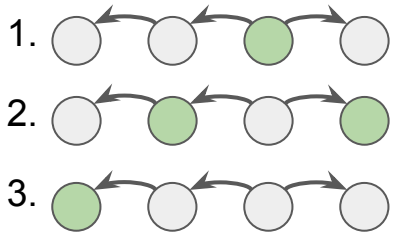
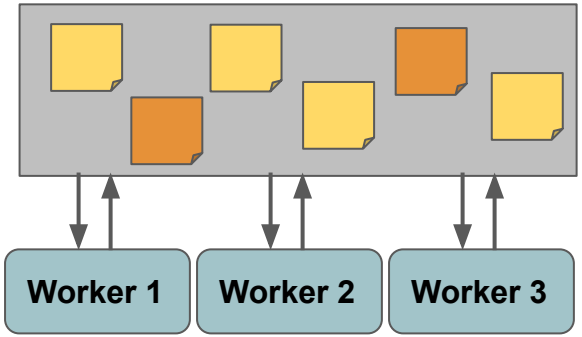


**MapReduce**




**Pregel (vertex-centric)**




**Blackboard**

# Parallel / Distributed in model transformation

- Large number of distributed engines
  - Designed with **≠ purposes**
  - Following **≠ design choices**
  - Implemented on **≠ languages** for **≠ infrastructures**

⇒ What are the optimal design choices for a given case?

# Related work

- Automatic adapted strategy
  - Pattern matching (**Bergman et al.**)
- Classification of features of MDE solution
  - For languages (**Tamura et al., M Rose et al.**)
  - Transformation approaches (**Czarnecki et al., Kahani et al.**)
  - Performance oriented (**Groner et al.**)
  - Specific topic: bi-directionality (**Hidaka et al.**)

# Optimization in model transformation

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# Problem: A configuration issue

- What solution to use?
- How to optimally configure a solution?

**Problem 1:**
**Many solutions for executing rules distributively**

**Problem 2:**
**Many solutions for executing queries distributively**

**Problem 3:**
**Lack of unified proposition for comparing design choices**

➢ **Goal:** Getting an insight of how design choices impact scalability of a distributed transformation

# Contribution of the thesis

**Problem 1:**
**Many solutions for executing rules distributively**

Evaluation of distributed design choices for **rule execution**

- Building a new distributed transformation engine: SparkTE

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**Many solutions for executing rules distributively**

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Evaluation of distributed design choices for **query execution**

- Analysing different distributed execution strategies for a query

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**Problem 1:**
**Many solutions for executing rules distributively**

Evaluation of distributed design choices for **rule execution**

- Building a new distributed transformation engine: SparkTE

**Problem 2:**
**Many solutions for executing queries distributively**

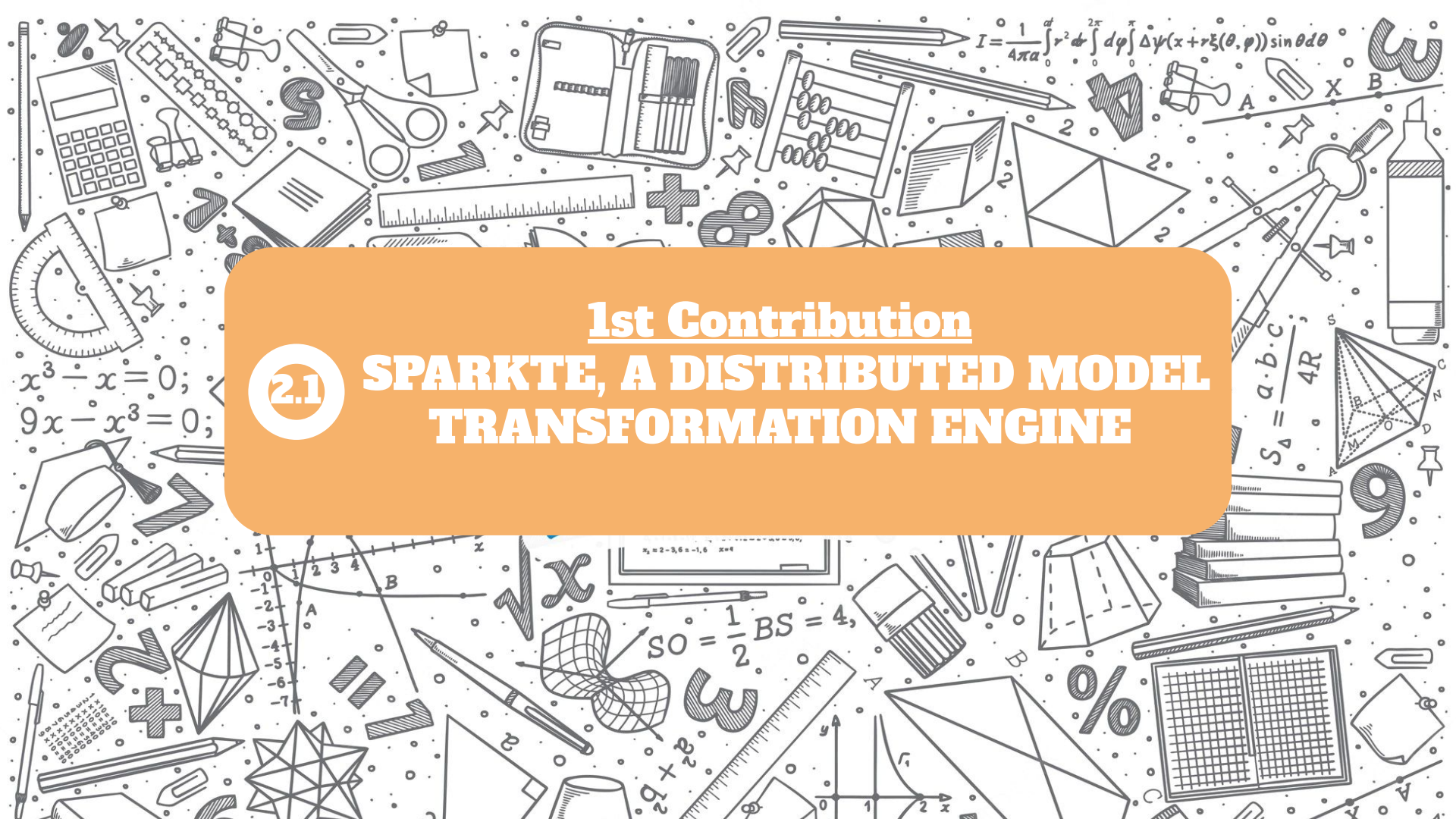
Evaluation of distributed design choices for **query execution**

- Analysing different distributed execution strategies for a query

**Problem 3:**
**Lack of unified proposition for comparing design choices**

Make possible configurable distributed transformation

- Modeling the design space
- Making the configurable engine: Configurable SparkTE



# 1st Contribution

## 2.1 SPARKTE, A DISTRIBUTED MODEL TRANSFORMATION ENGINE

# Problematic and proposal

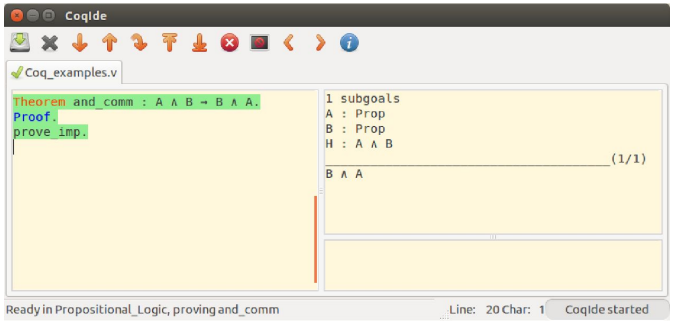
**Many solutions for executing rules distributively**

➢ Evaluation of distributed design choices for **rule execution**

- An engine with design choices for rule execution: SparkTE
- Prove design choices have no impact on the result
- Evaluate the scalability of a such engine

# CoqTL for reasoning

Coq




- Designed for specifying semantics
- A proof assistant based on **Hoare logic**
- Extraction mechanism (to ML lang)

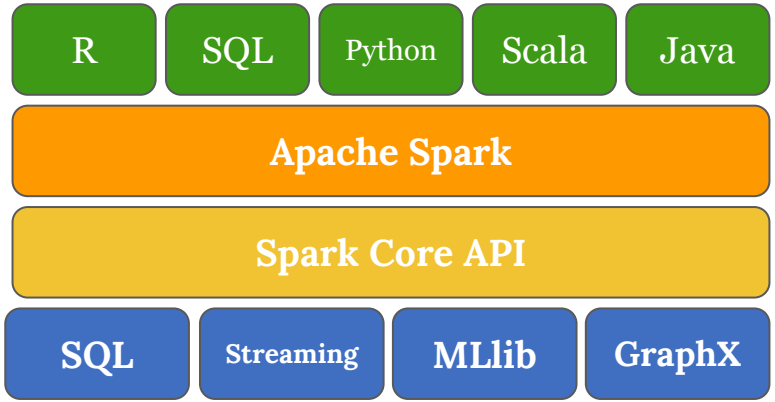
- **DSL** for rule-based model transformation
- Made for **reasoning on transformations**
- Can **reason on the semantic** of the transformation

atlanmod/**coqtl**

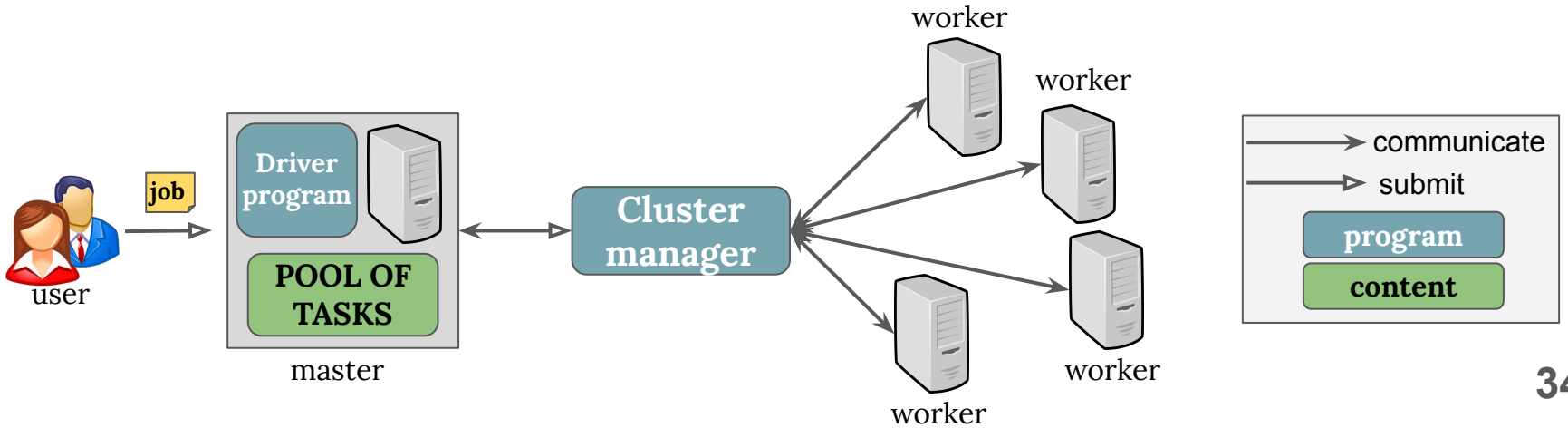
CoqTL allows users to write model transformations and prove engine/transformation correctness in Coq

4 Contributors · 12 Issues · 10 Stars · 14 Forks

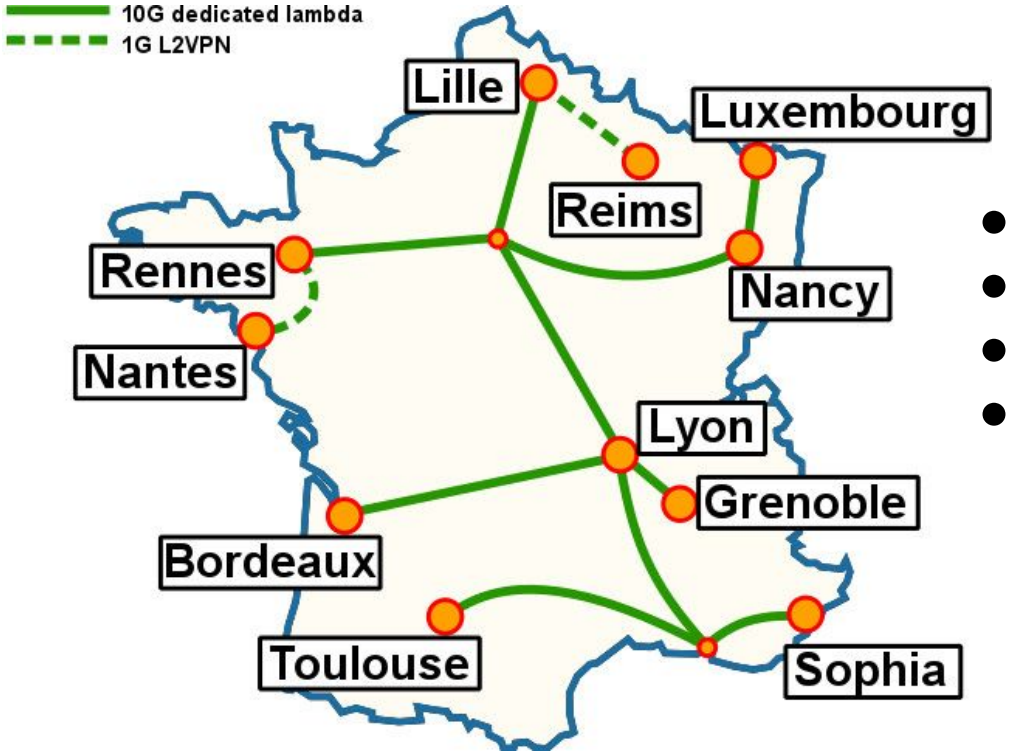
# Spark as a target




- Popular distributed computing for **large-scale data** processing
- Support for **many paradigms**
  - MapReduce, vertex-based (Pregel), …
- **Open-source**



# Spark on Grid'5000

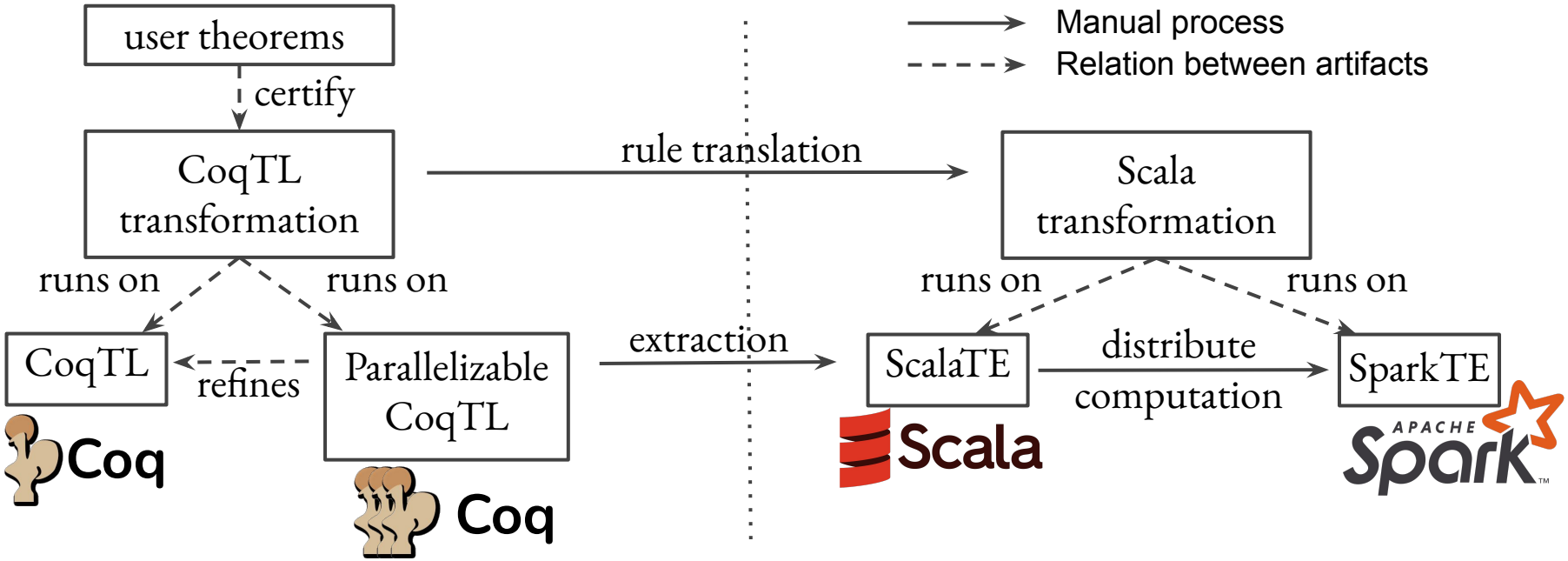



- French cluster for experimentation
- Library for benchmarking
- Support for distributed computing
- More than 15,000 cores; 800 nodes

Grid'5000

# Engine based on a formal semantic: from CoqTL to SparkTE





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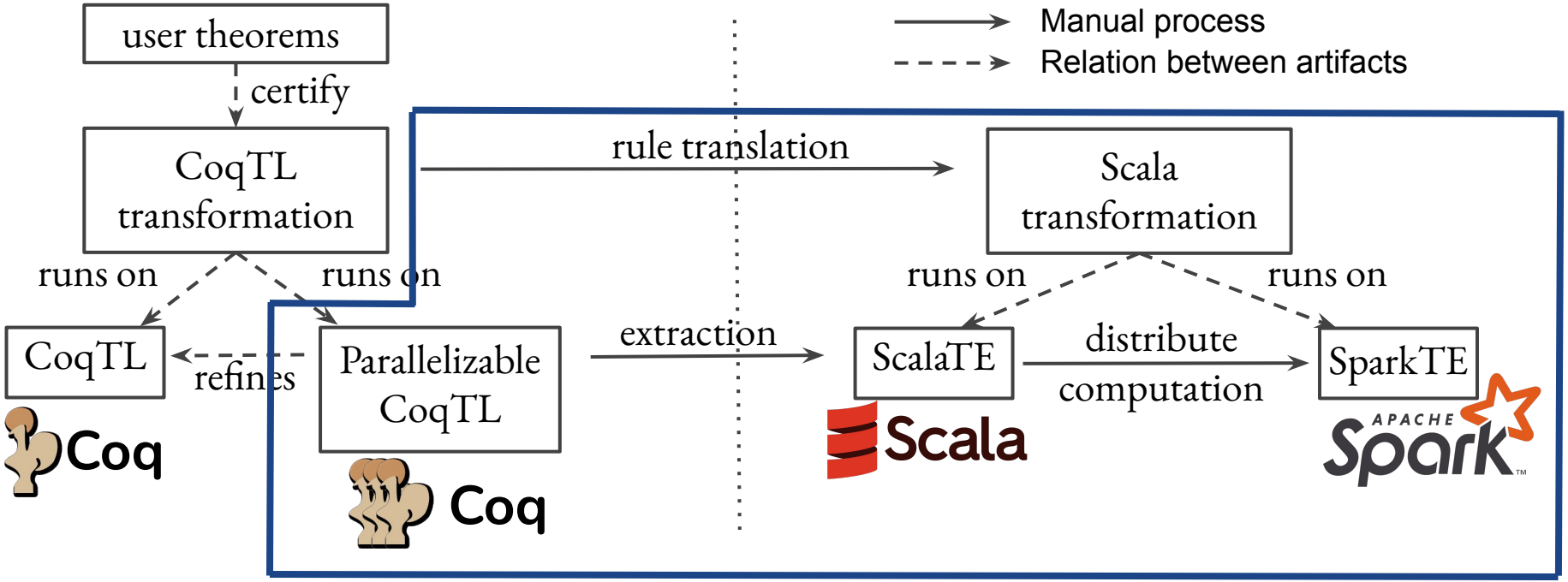
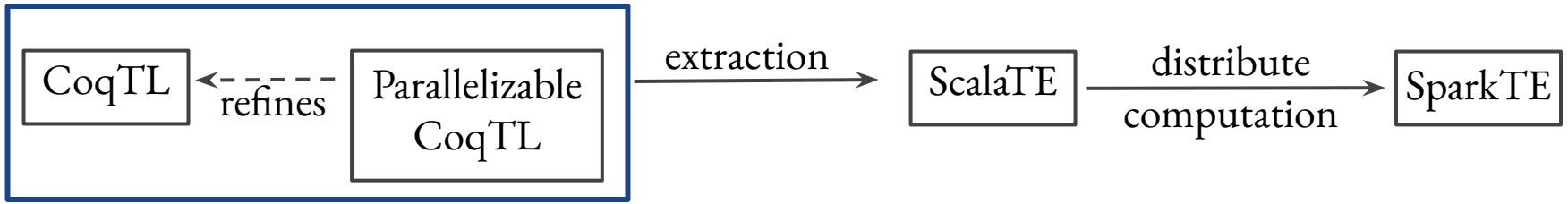


# Contribution: Parallelizable CoqTL as a CoqTL refinement

- **Increase parallelization**
  1. Two distinct phases: **instantiate** & **apply**
     - Define map-reduce phases
  2. Iterate on rules instead of src patterns
     - Avoid unnecessary computations
  3. Iterate on trace links instead of src patterns
     - Reuse of intermediate results

- **Formal proof** of equivalence with CoqTL



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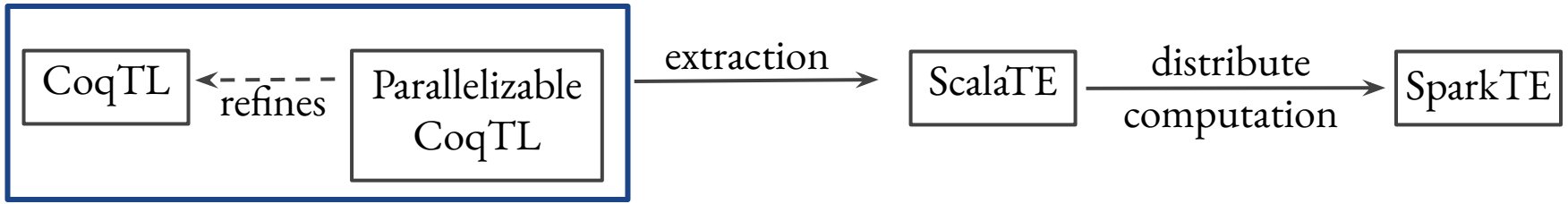
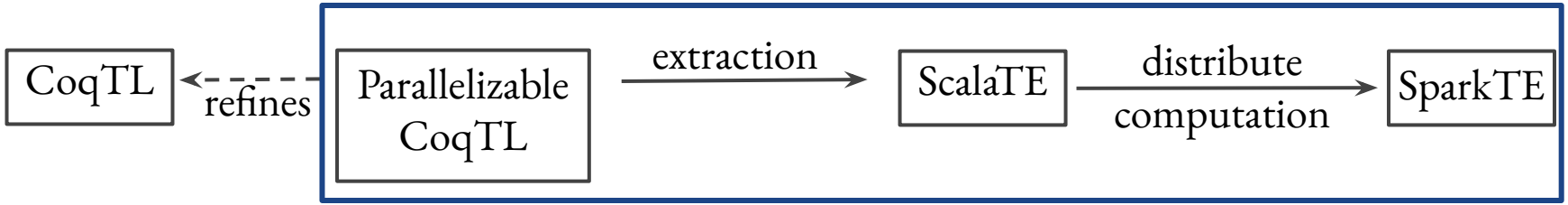
| | Spec. size (LoC) | Cert. size (LoC) | Proof effort (man-days) |
|---|---|---|---|
| 1. | 69 | 484 | 10 |
| 2. | 42 | 487 | 7 |
| 3. | 69 | 520 | 4 |

- **Formal proof** of equivalence with CoqTL



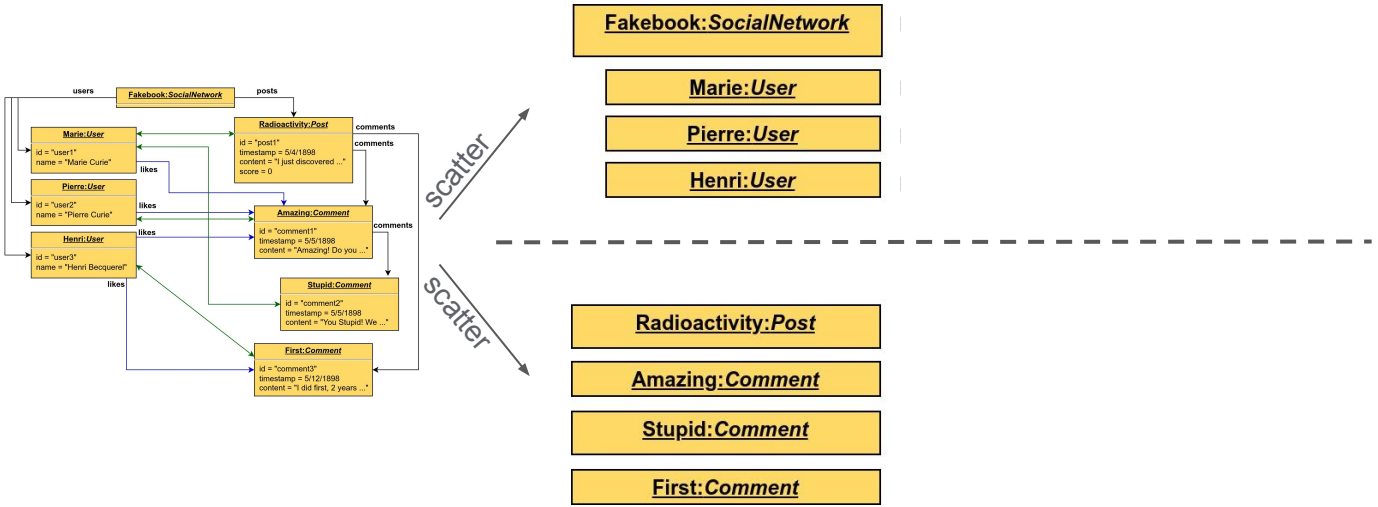
# Contribution: Build executable and distributed transformation engine


1. **Produce** executable and maintainable **code**
   - Object-oriented approach
   - Pure Scala functions (correctness)
2. **Distribute the computation**
   - Distribute data-structures
   - Explicit communication operations
     - Take advantage of scatter/gather operations
     - Broadcast global knowledge



# Instantiate phase: Create output elements






**Data-distributed** strategy: (*Map-Reduce* phase)

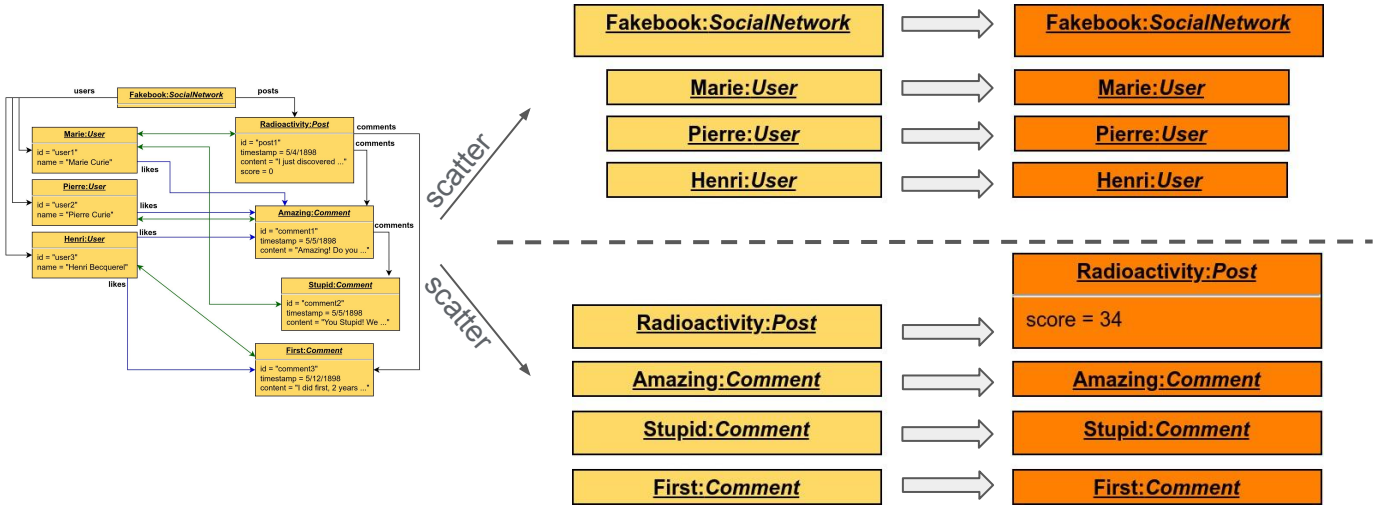
- Input **elements** are **distributed**
- Input **model** is **broadcasted**

As output:

- Instantiated **output model elements**
- **Trace-links** (mapping input-output)

# Instantiate phase: Create output elements



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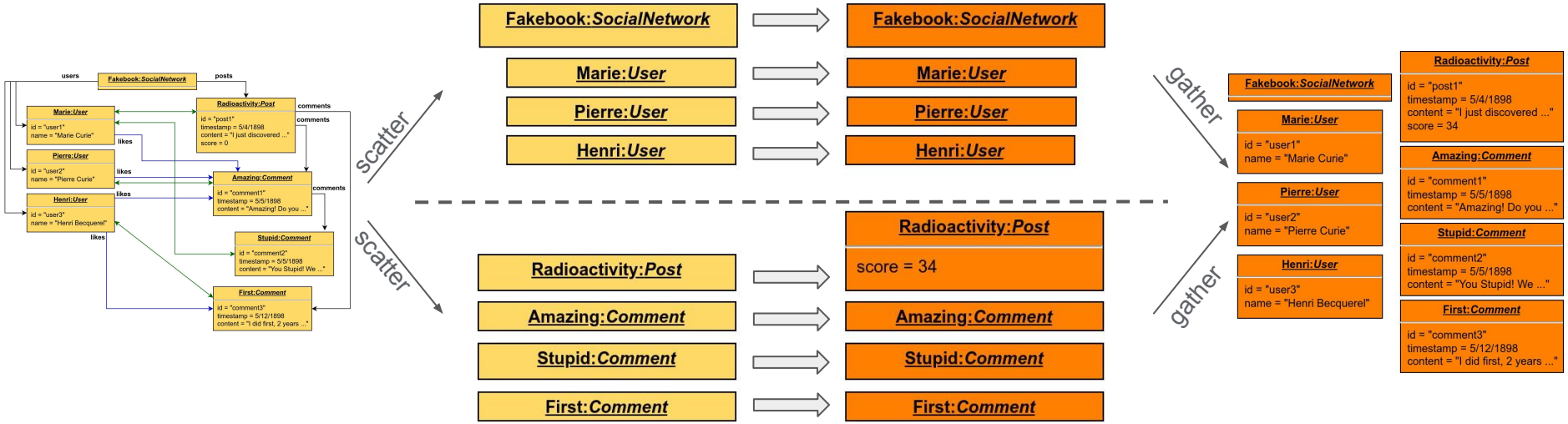


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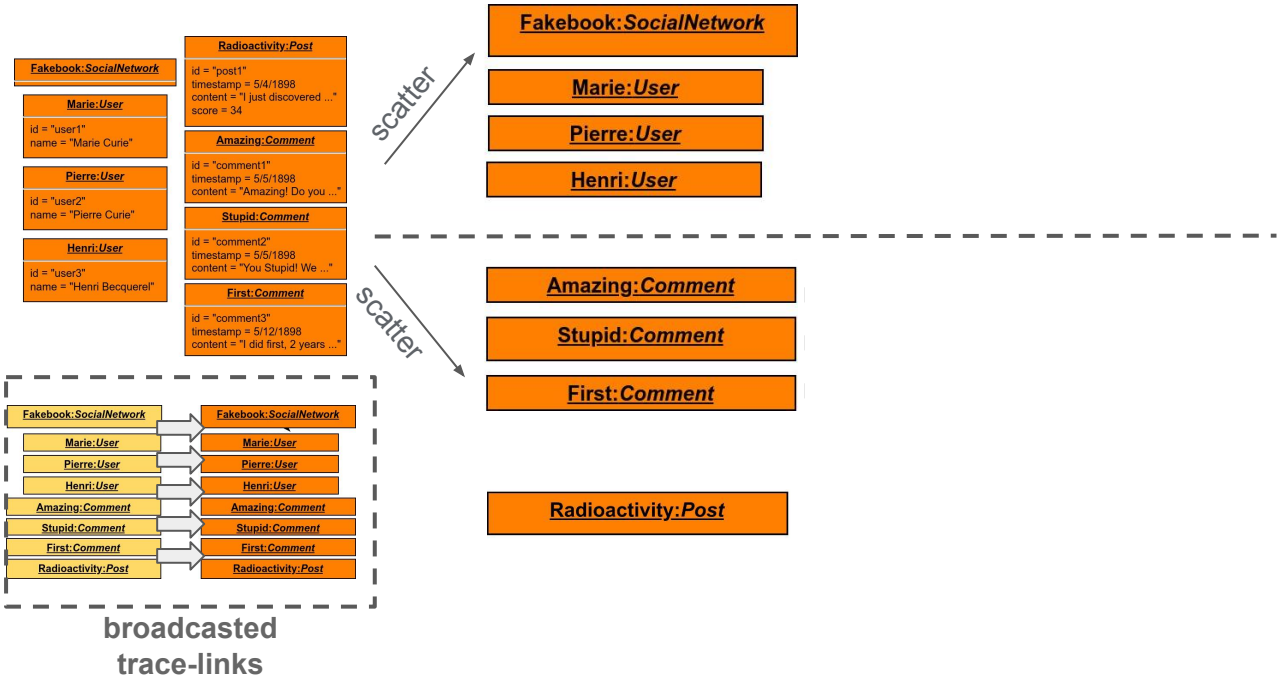
# Apply phase: Create output links



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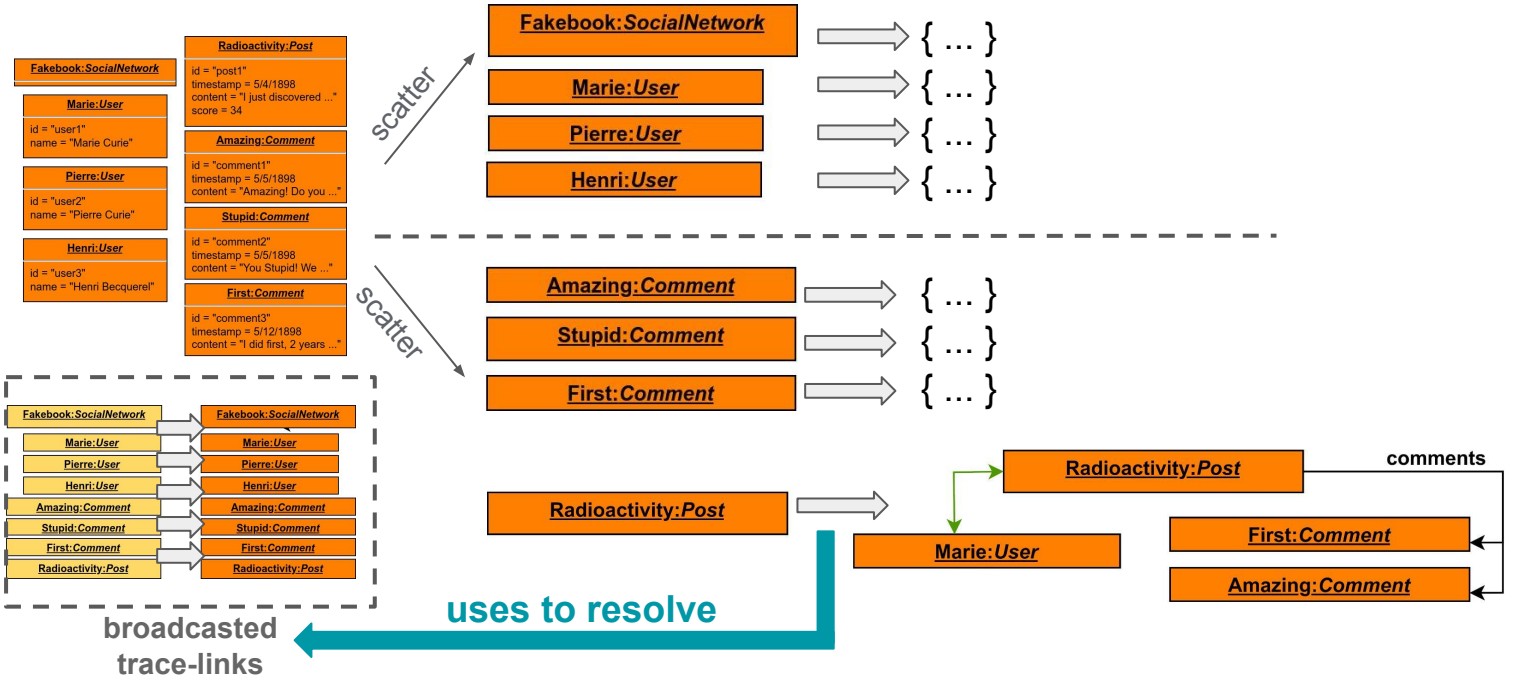


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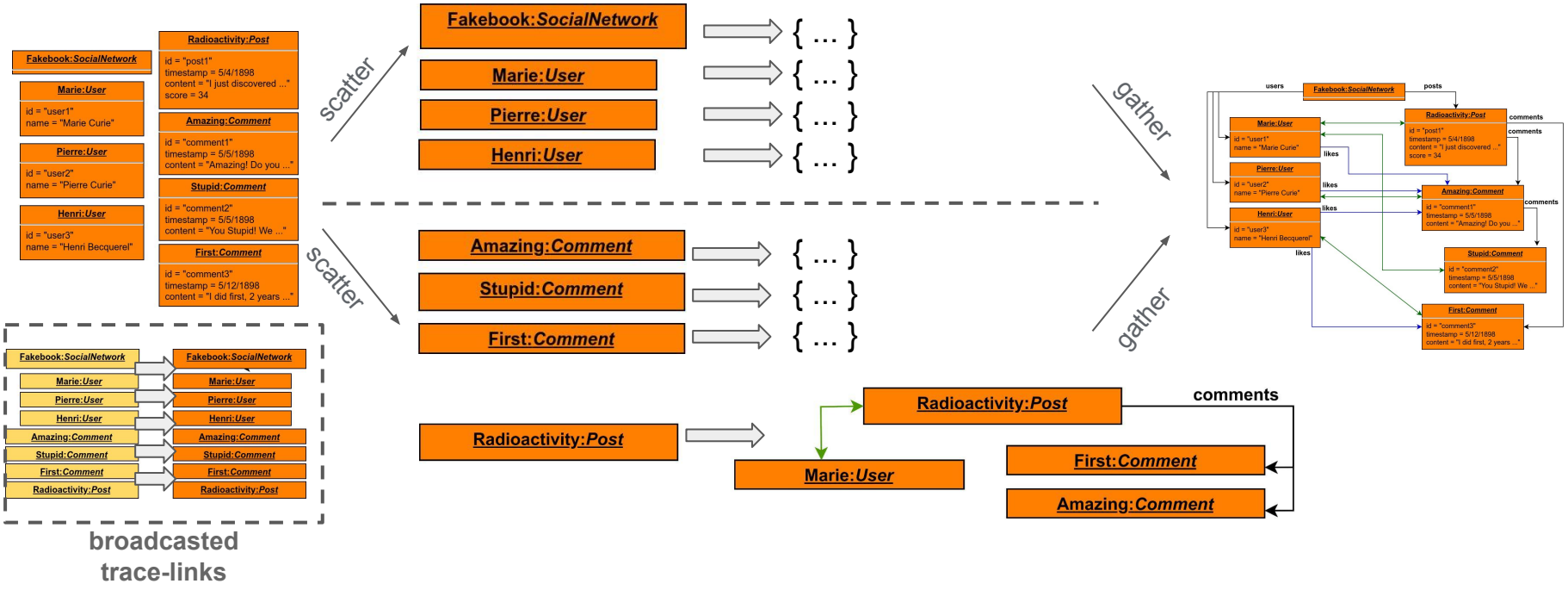



**Data-distributed** strategy: (*Map-Reduce* phase)

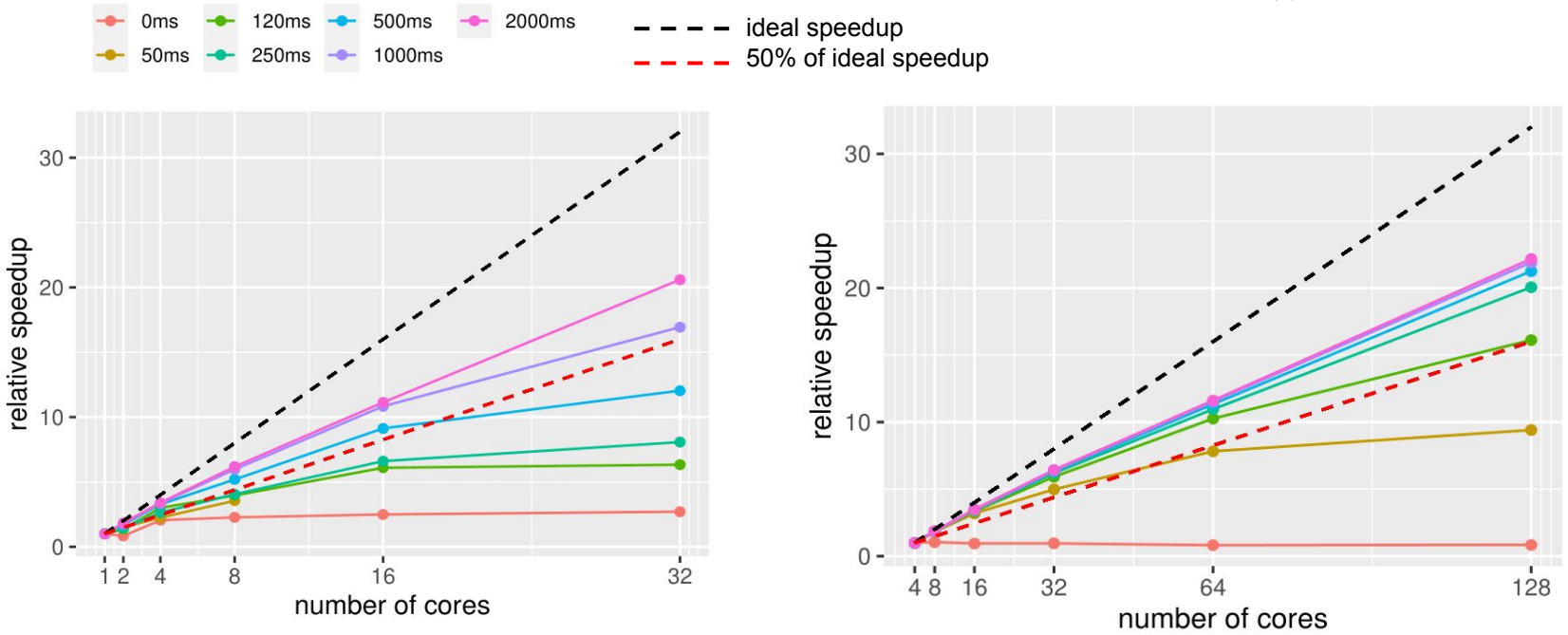
- Output **elements** are **distributed**
- Trace-links are **broadcasted**

# Vertical scalability of model transformation on Spark



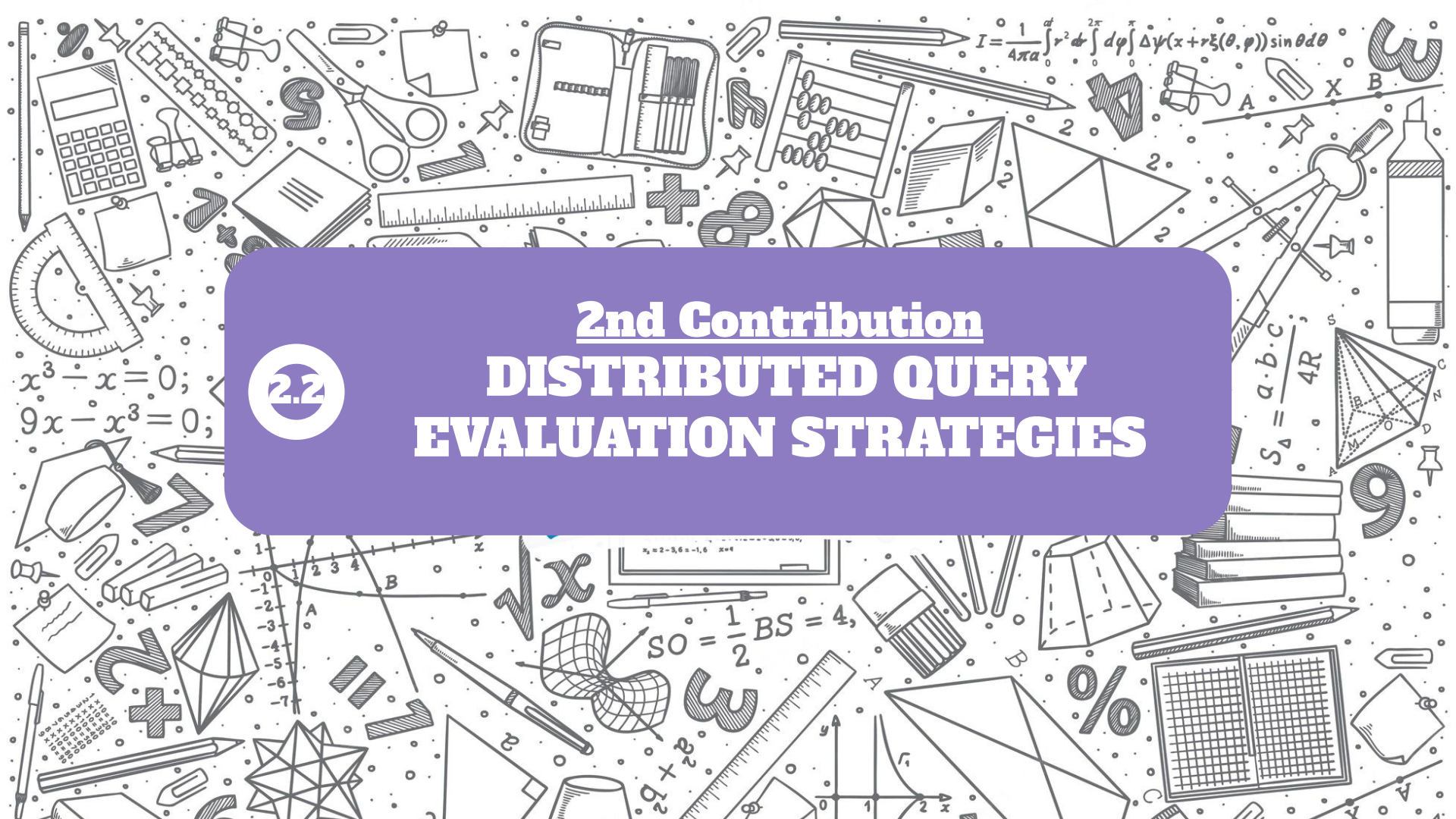
- Simulate a uniform amount of computation on nodes
  - fixed time for each task

Grid'5000




Model of 150 elements and 290 links, on 4 machines

Model of 600 elements and 1060 links, 8 machines


2.2
2nd Contribution
DISTRIBUTED QUERY EVALUATION STRATEGIES

# Problematic and proposal

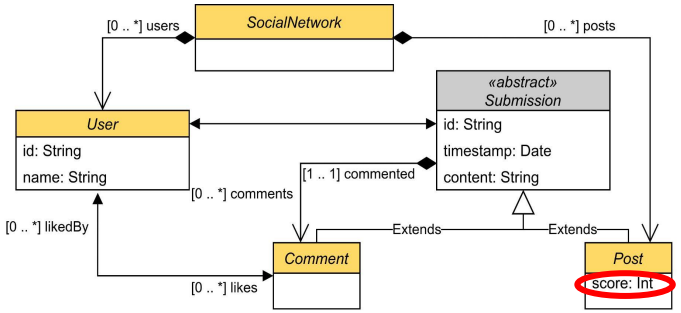
**Many solutions for executing queries distributively**

➢ Evaluation of distributed design choices for **query execution**

- Take a query whose evaluation is dependant from input model
- Implement with several design choices
- Evaluate them and try to correlate with input

# Several design choices for running a query

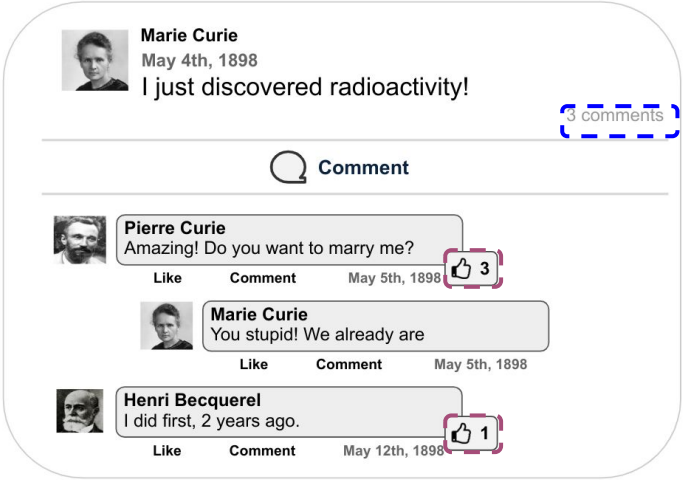
- Query:
  What is the score for a post in a social network?
- A score function
  **score**(p: *Post*) := **# comments** × 10 + **# likes**




```
score(p: Post) :=   comments(p).size() * 10
                          + likes(p).size()

comments(s: Submission) :=  [s.comments].
      union(c: s.comments.flatMap(
                  λc.comments(c))

likes(p: Post) := comments(p).map(λc.likes)
```



# Several design choices (implementation)

```
score(p: Post) :=
  comments(p).size() * 10
      + likes(p).size()

comments(s: Submission) :=
  [s.comments].union(
      c: s.comments.flatMap(
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likes(p: Post) :=
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```

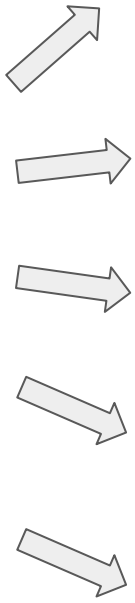

- Design-choices for running the query:
  1. **Scala-OCL**
     - No distribution (sequential)
  2. **Spark-OCL** (Spark core API)
     - Delegate distribution to Spark
  3. **MapReduce** (Spark core API)
     - More control of parallelism
  4. **Pregel** from (GraphX)
     - Iterative process
  5. Hybrid approaches
     - **Spark-OCL + Pregel**
     - **MapReduce + Pregel**

# Experiments

- Proposed models from TTC
- Calculate score value
- Cannot really extract relevant metrics about topology

| | Dataset | | | | Speed-up (compared to Sequential Scala-OCL) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | # users | # posts | # comments | # likes | Scala-OCL | Spark-OCL | Pregel | MapReduce | Spark-OCL + Pregel | MapReduce + Pregel |
| 1 | 889 | 1064 | 118 | 24 | **1x** | 0.39x | 0.36x | 0.46x | 0.44x | 0.46x |
| 2 | 1845 | 2315 | 190 | 66 | **1x** | 0.51x | 0.68x | **0.85x** | 0.66x | 0.71x |
| 3 | 2270 | 5056 | 204 | 129 | **1x** | 0.27x | 0.35x | 2.34x | 0.15x | **2.96x** |
| 4 | 5518 | 9220 | 394 | 572 | **1x** | 4.25x | **5.21x** | 4.17x | 4.68x | 4.03x |
| 5 | 10929 | 18872 | 595 | 1598 | **1x** | **4.68x** | 2.83x | 2.39x | 1.97x | 3.91x |
| 6 | 18083 | 39212 | 781 | 4770 | **1x** | 4.07x | 4.12x | 4.58x | **5.17x** | 3.27x |

# Experiments: Correlation input vs. results



| Correlation matrix: *input model* vs. *speed-ups* | | | | | |
|---|---|---|---|---|---|
| **Size** | **Spark- OCL** | **Pregel** | **MapReduce** | **Spark-OCL + Pregel** | **MapReduce + Pregel** |
| **# users** | 0.78 | 0.67 | 0.74 | 0.76 | 0.39 |
| **# posts** | 0.71 | 0.62 | 0.75 | 0.75 | 0.32 |
| **# comments** | **0.86** | **0.74** | **0.78** | **0.79** | **0.51** |
| **# likes** | 0.62 | 0.57 | 0.7 | 0.73 | 0.19 |

# Experiments: Correlation input vs. results

**Correlation matrix: *input model* vs. *speed-ups***

| Size | Spark- OCL | Pregel | MapReduce | Spark-OCL + Pregel | MapReduce + Pregel |
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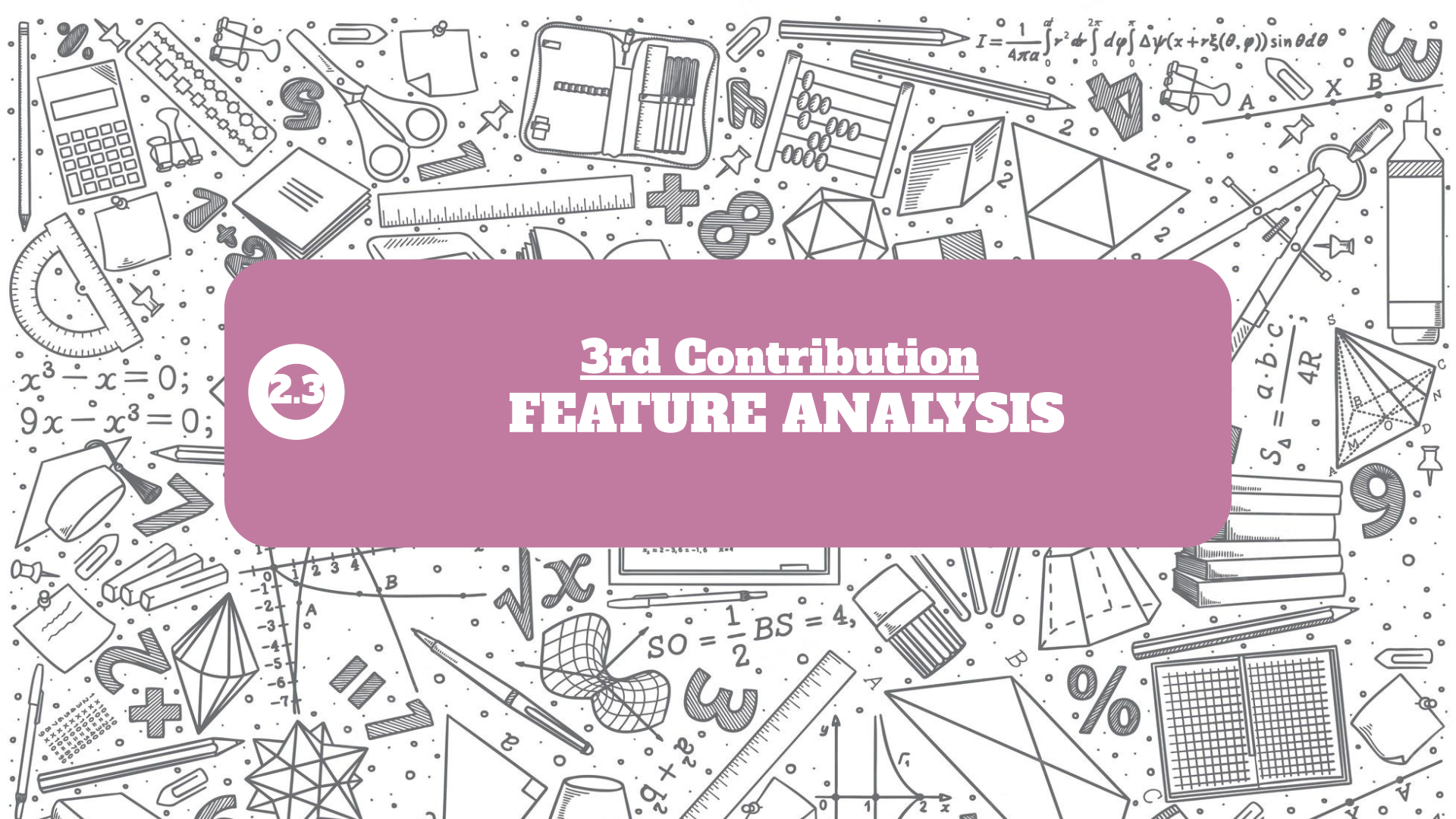
| # likes | 0.62 | 0.57 | 0.7 | 0.73 | 0.19 |

**Correlation matrix: *ratio in input model* vs *speed-ups***

| | Spark-OCL | Pregel | MapReduce | Spark-OCL + Pregel | MapReduce + Pregel |
|---|---|---|---|---|---|
| ratio: #users / #likes | -0.85 | -0.79 | **-0.89** | -0.75 | -0.82 |
| ratio: #posts / #likes | **-0.96** | **-0.88** | -0.82 | **-0.85** | -0.66 |
| ratio: #comments / #likes | -0.8 | -0.74 | -0.86 | -0.69 | **-0.83** |


2.3
3rd Contribution
FEATURE ANALYSIS

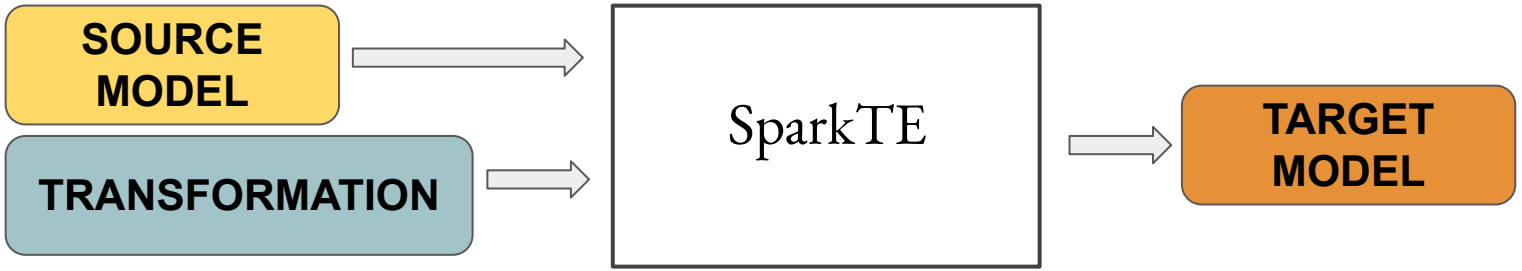
# Problematic and proposal

**Lack of unified proposition for comparing design choices**

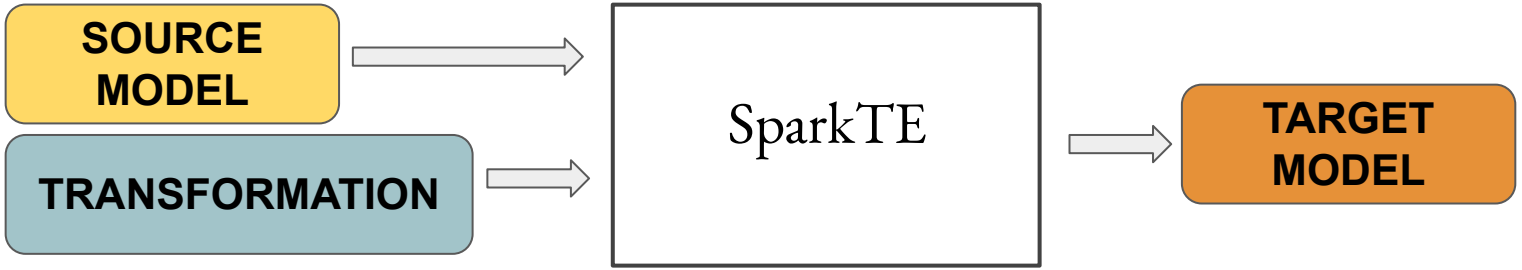
➢ Make possible configurable distributed transformation

- Formalized past contributions and additional design choices
- Design a configurable engine
- Evaluate them and analyse impact

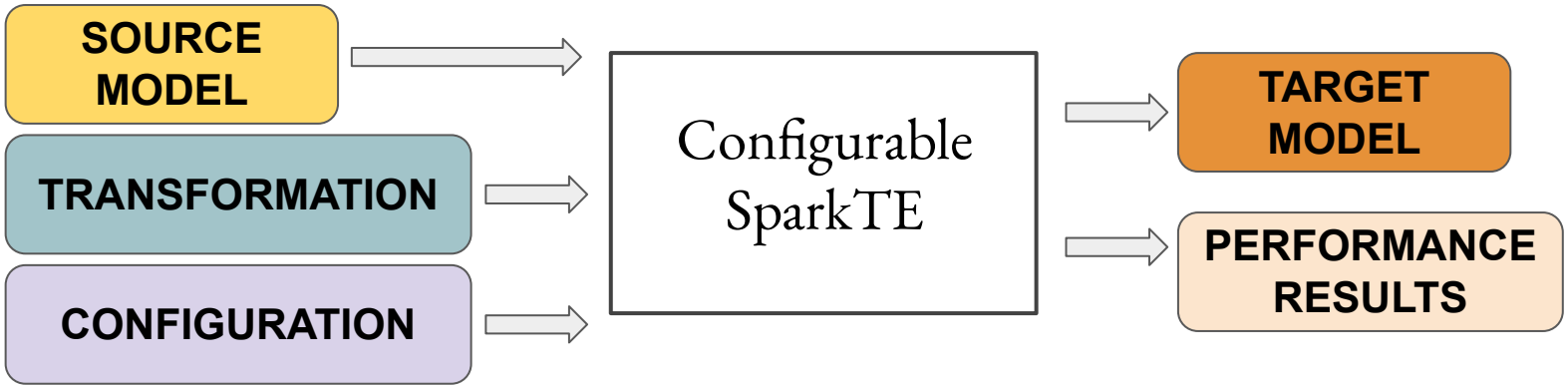
# Configurable engine



# Configurable engine

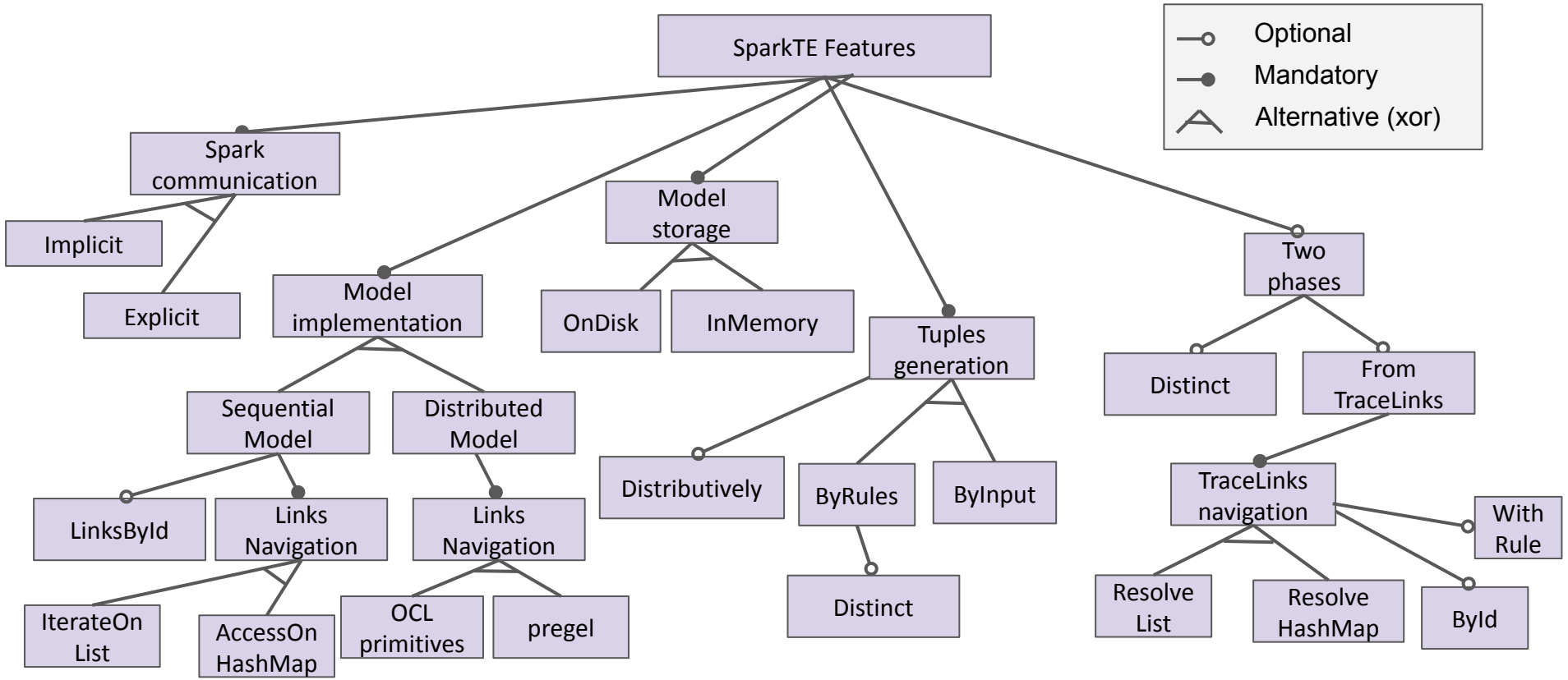



- Take **as input** a configuration conforms to the feature model
- Produce **as output** performance results (computation time)

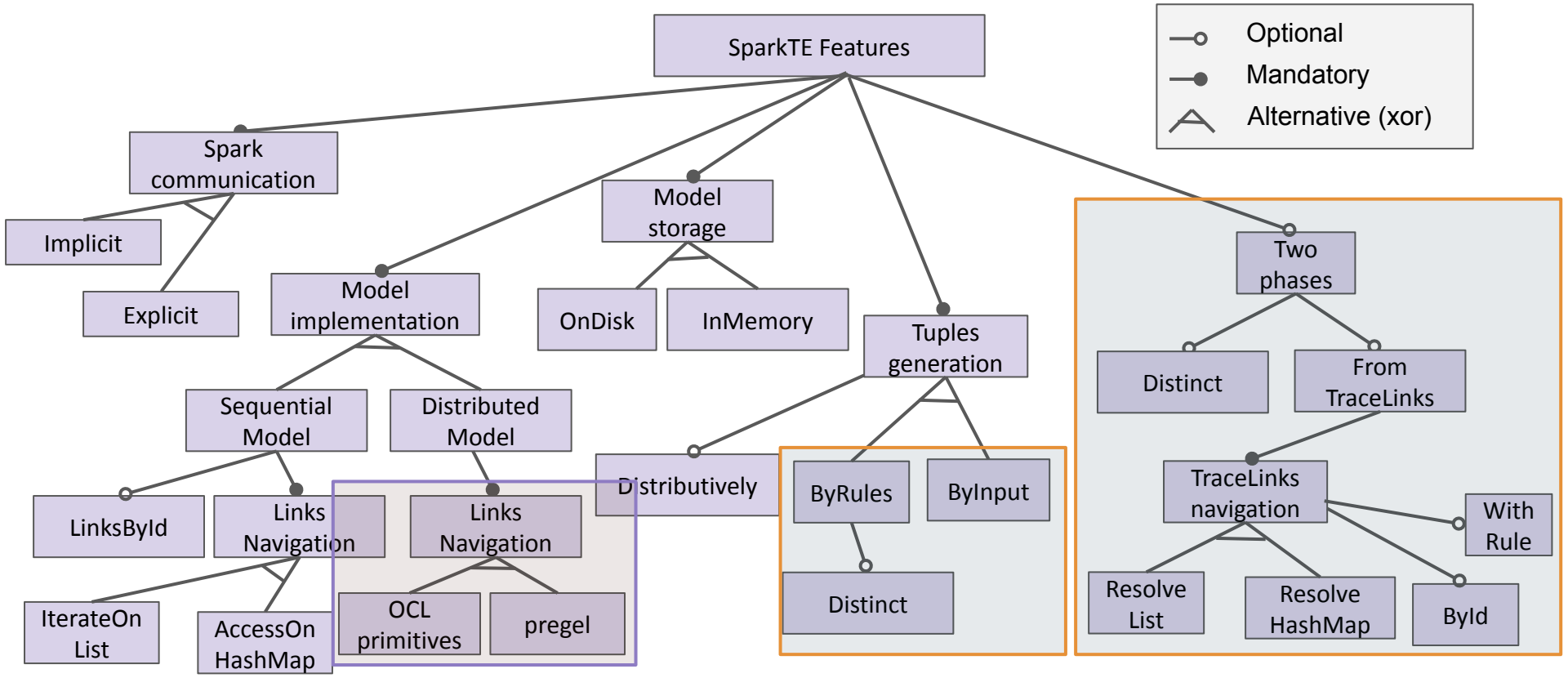


# SparkTE feature diagram





# SparkTE feature diagram

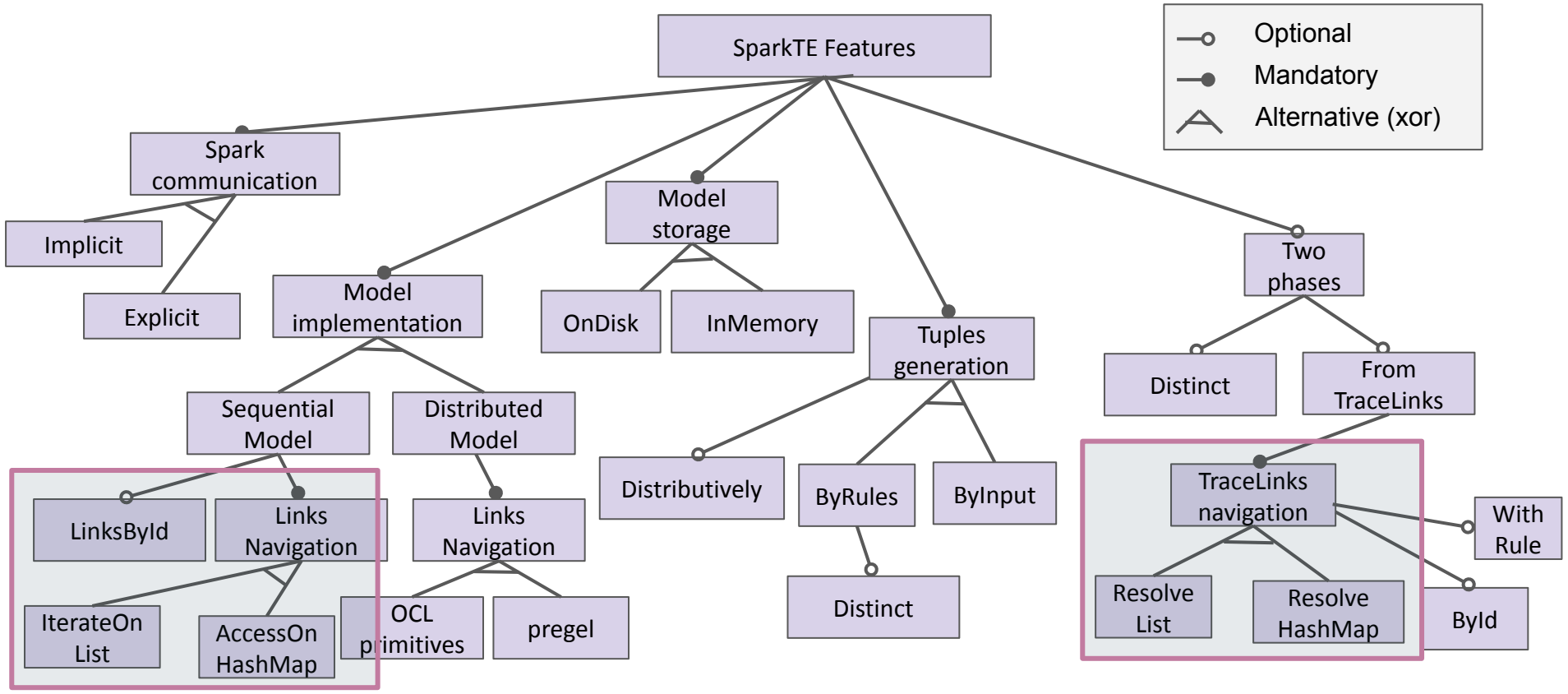



**Distributed query strategies**

**Optimization from** Parallelizable CoqTL

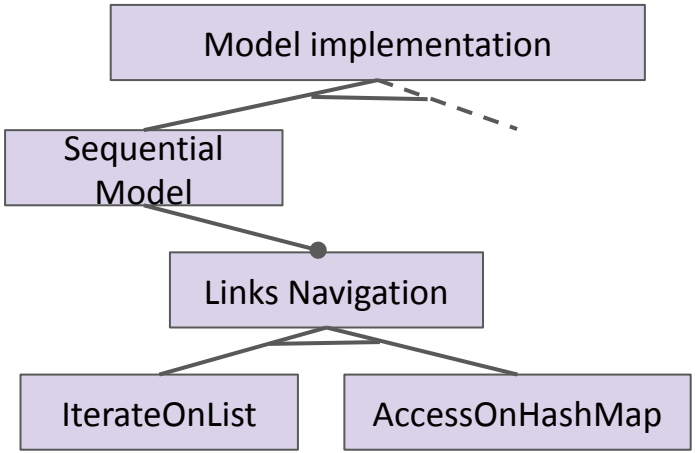
# SparkTE feature diagram





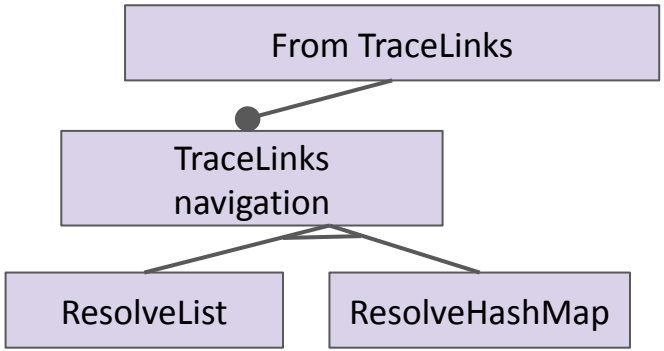
# Feature 1: Link navigation strategy in sequential model






- IterateOnList :
  - Navigation by iteration
  - Simple to set-up
- AccessOnHashMap :
  - Additional computation in model loading
  - Increase memory usage
  - Direct access on links from elements

# Feature 2: Trace-Links structure and resolution in apply phase




- ResolveList :
  - Resolution by iteration
  - Naturally gathered by master node
- ResolveHashMap :
  - Additional computation in instantiate phase
  - Increase memory usage
  - Fastest resolution

# Using configurable engine to find features synergie



Execution of **Identity** transformation on a model of 100k elements and 250k links (4 cores)

| Configuration 1: Links navigation | Configuration 2: TraceLinks navigation | Computation time (sec) | Instantiate phase (sec) | Apply phase (sec) |
|---|---|---|---|---|
| IterateOnList | ResolveList | 1636 sec | 3 sec | 1633 sec |
| IterateOnList | ResolveHashMap | 1584 sec | 3 sec | 1581 sec |
| AccessOnHashMap | ResolveList | 233 sec | 6 sec | 227 sec |
| AccessOnHashMap | ResolveHashMap | 12 sec | 6 sec | 6 sec |

- **TraceLinks navigation**'s impact
  - on the **whole** computation is **negligible**
  - is **important** when **Links navigation** is processed by AccessOnHashMap
- **Links navigation**'s impact
  - decreases the **whole** computation time
  - increases the computation time of the instantiate phase

# Design-space exploration for the Find affinity case



| Feature label | Parallelizable CoqTL design choices (C1) | Optimal design choices (C2) |
|---|---|---|
| Model implementation | Sequential Model | Sequential Model |
| ○ linksById | false | false |
| ● **Link Navigation** | **IterateOnList** | **ResolveHashMap** |
| Model storage | InMemory | InMemory |
| Spark communication | **Implicit** | **Explicit** |
| **Tuples generation** | **ByRules** | **ByInput** |
| ○ Distributively | false | false |
| ○ **Distinct** | **false** | **true** |
| TraceLinks Navigation | ResolveList | ResolveList |
| ○ byId | false | false |
| ○ **withRule** | **false** | **true** |
| ○ **Distinct** | **false** | **true** |

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| ○ **Distinct** | **false** | **true** |
| TraceLinks Navigation | ResolveList | ResolveList |
| ○ byId | false | false |
| ○ **withRule** | **false** | **true** |
| ○ **Distinct** | **false** | **true** |

| #elements | #links | C1 computation time | C2 computation time |
|---|---|---|---|
| 1000 | 3000 | 9.799 sec | 4.978 sec |
| 2500 | 7300 | 81.047 sec | 7.803 sec |
| 5000 | 15000 | 882.708 sec | 19.127 sec |
| 7500 | 22000 | > 2h | 36.928 sec |
| 10000 | 45000 | Timeout error | 65.198 sec |

- The feature model is useful for comparing implementations
- Gives useful insights about the engine
- Highlighted correlation between features

# CONCLUSION

# Contribution of the thesis

**Problem 1:**
**Many solutions for executing rules distributively**

Built a **distributed solution** from a **specification**

- Re-designed specification to make it distributable
- Made a proof of equivalence for optimizations
- Shown our solution is scalable

**Problem 2:**
**Many solutions for executing queries distributively**

**Evaluated** distributed execution **strategies for a query**

- Implemented three design-choices
- Proposed hybrid solution
- Performance variation depending on the strategy

**Problem 3:**
**Need an unified proposition for comparing design choices**

**Formalized features** in our distributed solution

- Shown the synergies between them
- Shown the impact on performance

# Publications

- Jolan Philippe, Hélène Coullon, Massimo Tisi, Gerson Sunyé. **Towards Transparent Combination of Model Management Execution Strategies for Low-Code Development Platforms.** *23rd ACM/IEEE International Conference on Model Driven Engineering Languages and Systems (MODELS): Companion Proceedings*, Oct 2020, Montreal (Virtually), Canada. 10.1145/3417990.3420206. Hal-02952952

- Jolan Philippe, Massimo Tisi, Hélène Coullon, Gerson Sunyé. **Executing Certified Model Transformations on Apache Spark.** *14th ACM SIGPLAN International Conference on Software Language Engineering (SLE)*, Oct 2021, Chicago IL, United States. 10.1145/3486608.3486901. Hal-03343942

- Ongoing: Jolan Philippe, Massimo Tisi, Gerson Sunyé. **Analysis of the Design-Space of a Distributed Transformation Engine.** *Software and Systems Modeling (SoSyM)*

- *Several public Lowcomote deliverables*
  - **Concepts for Multi-paradigm distributed transformation**
  - **Scalable low-code artefact persistence and query**
  - **Multi-paradigm distributed transformation engine**

# Future work

- **Automated design-space exploration for a given scenario**
  - A model of the input (e.g., topological metrics)
  - A model of the platform **(Spark and ≠)**
  - Constraints and requirements

- **Other parameters to optimize (≠ CPU time)**
  - Network bandwidth
  - Memory consumption
  - Energy consumption/production

+ **Other execution strategies (≠ data-dist)**
  - Take advantage of Spark for task-distribution
  - Combine incrementality and laziness to distribution

# Contribution to the Analysis of the Design-Space of a Distributed Transformation Engine

**Jolan PHILIPPE**

**PhD Defense, speciality: Computer Science**