CS 598CM: ML for Compilers and Architecture

Instructor: Charith Mendis

ILLINOIS

Brief Announcements

- Recordings and Zoom
- **Reading List:** Live on the website!
- **Paper Selections:** Due on September 7th
- **Paper Reviews:** We will use hotCRP to facilitate review writing. Instructions to come soon!
- **Resources and tutorials:** Will be up by Friday

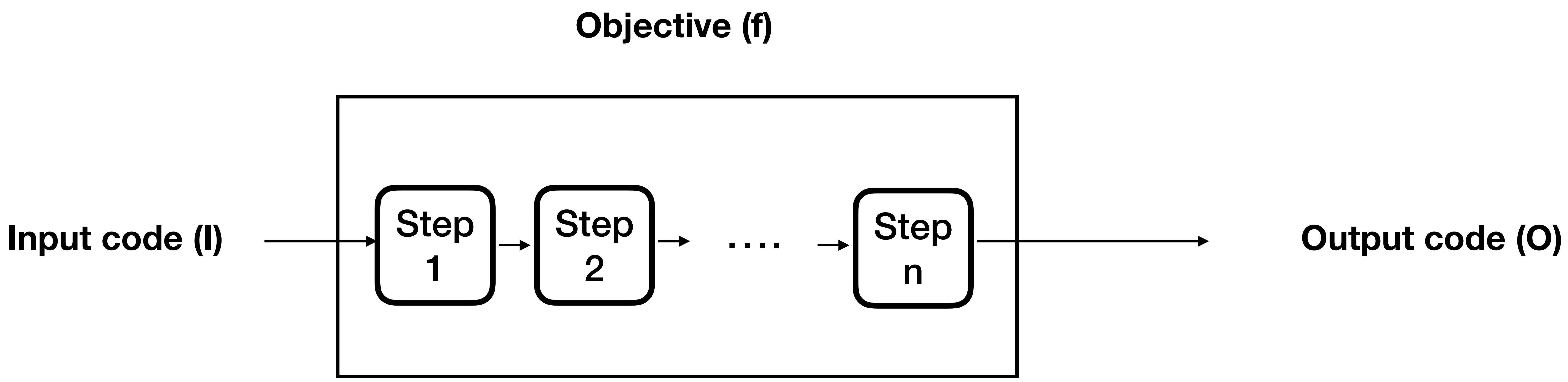
Recap

- Compiler Stages
  - Lexer => Parser => Sema => Optimization => Code Generation
- Two types of compiler optimizations
- Phase ordering problem

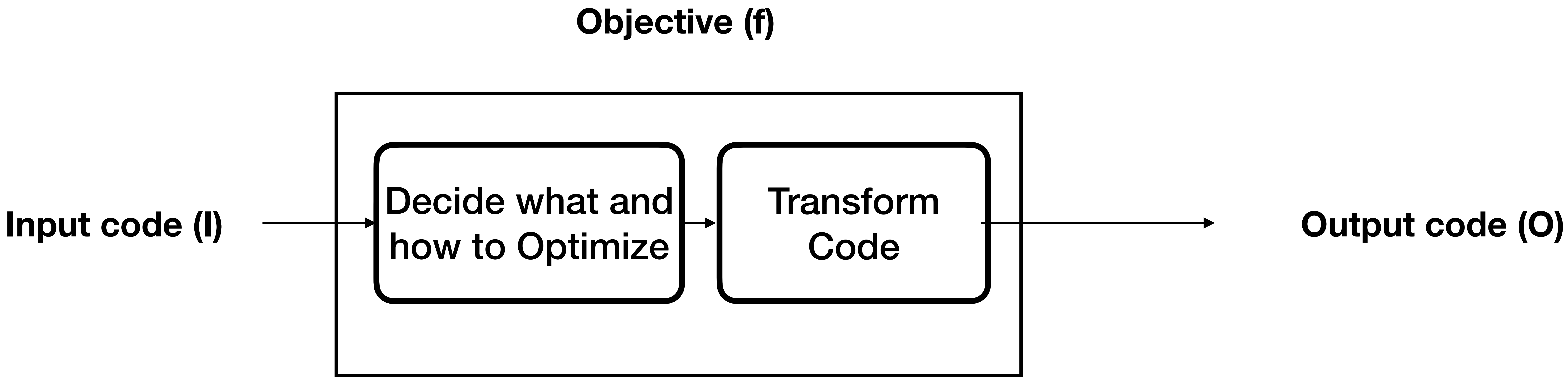
Lecture 3:
Compiler Optimizations

Optimizations + DSLs

Anatomy of an Optimization Pass



Anatomy of an Optimization Pass



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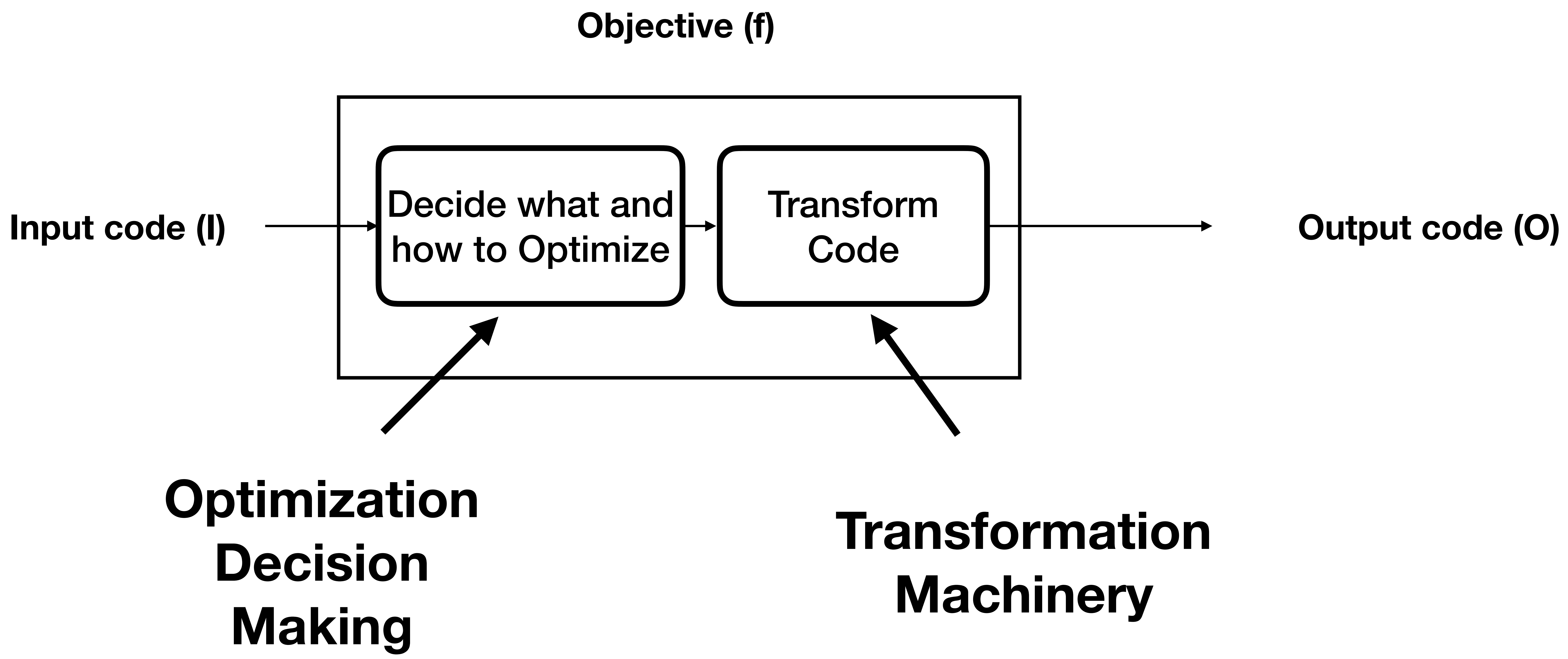
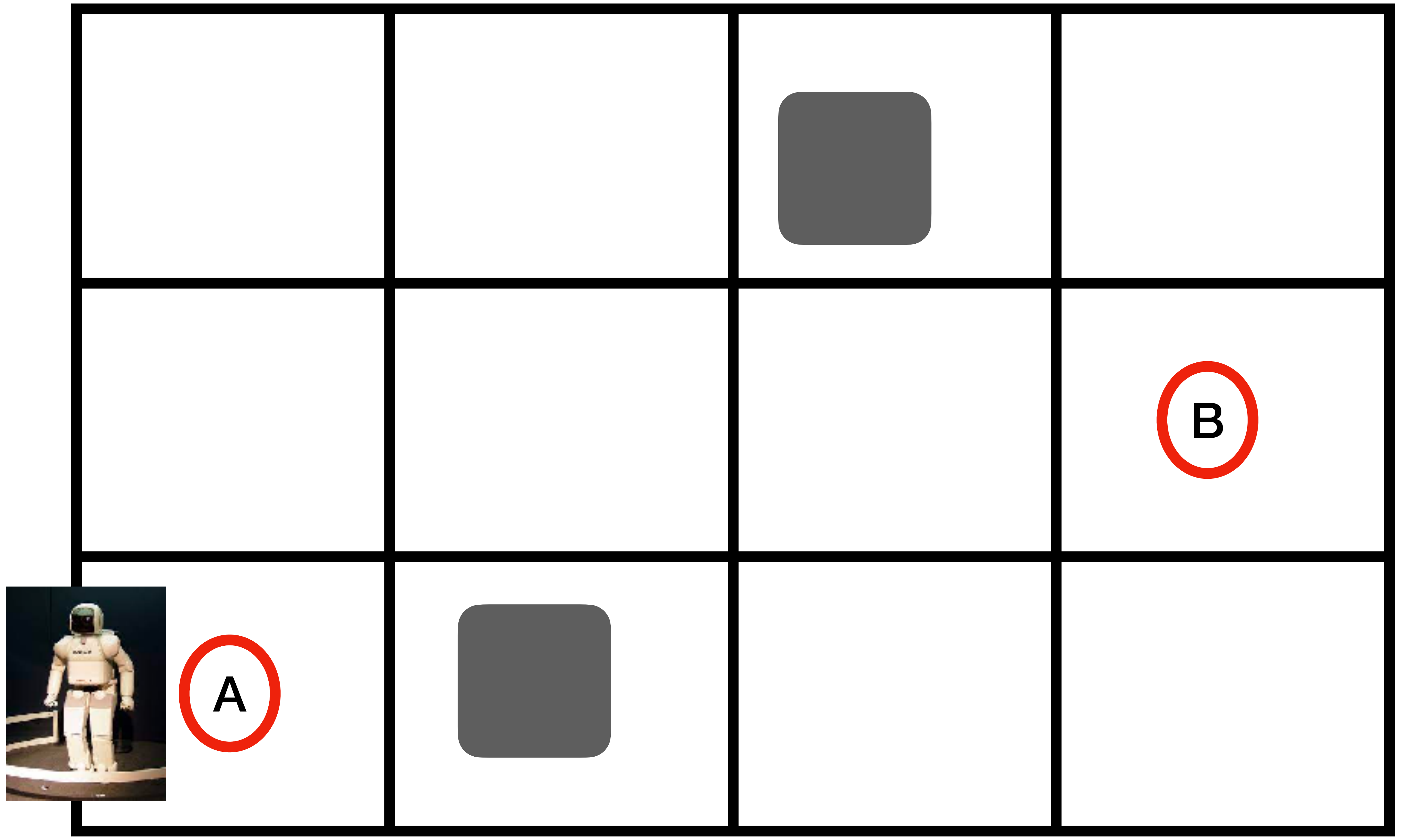
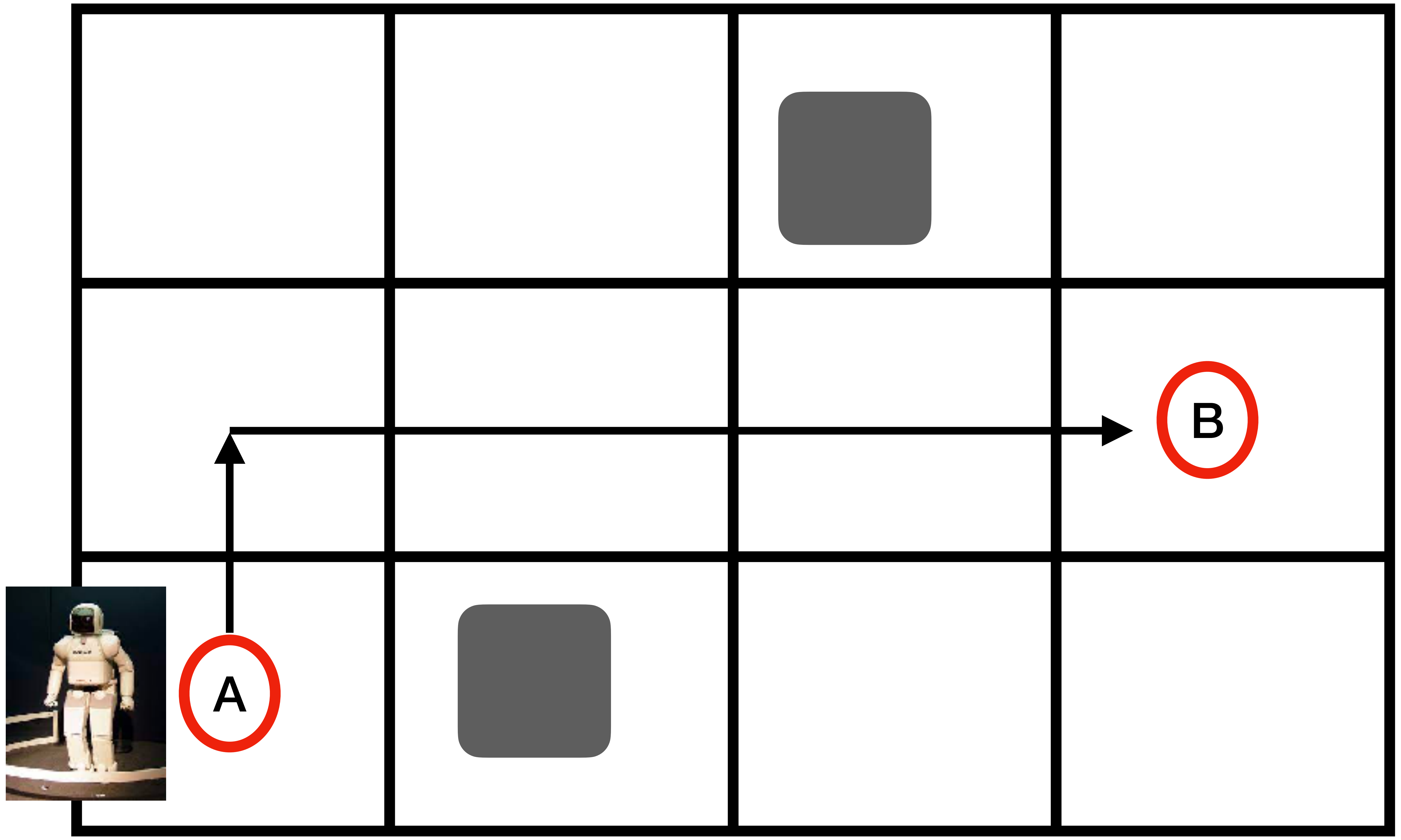


Robot Analogy



Task: Move from A to B cheaply

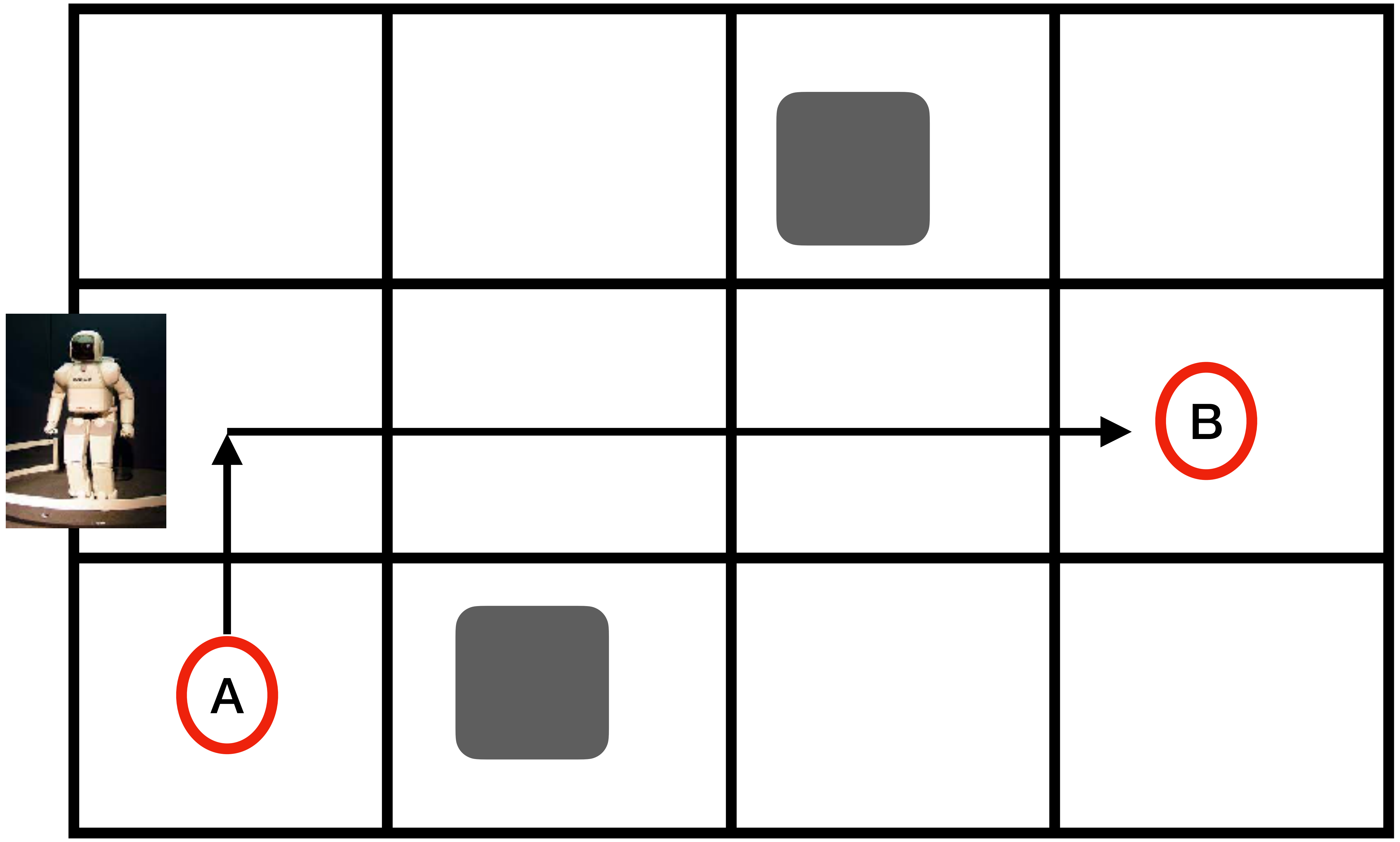
Robot Analogy



Task: Move from A to B cheaply

1. Plan

Robot Analogy

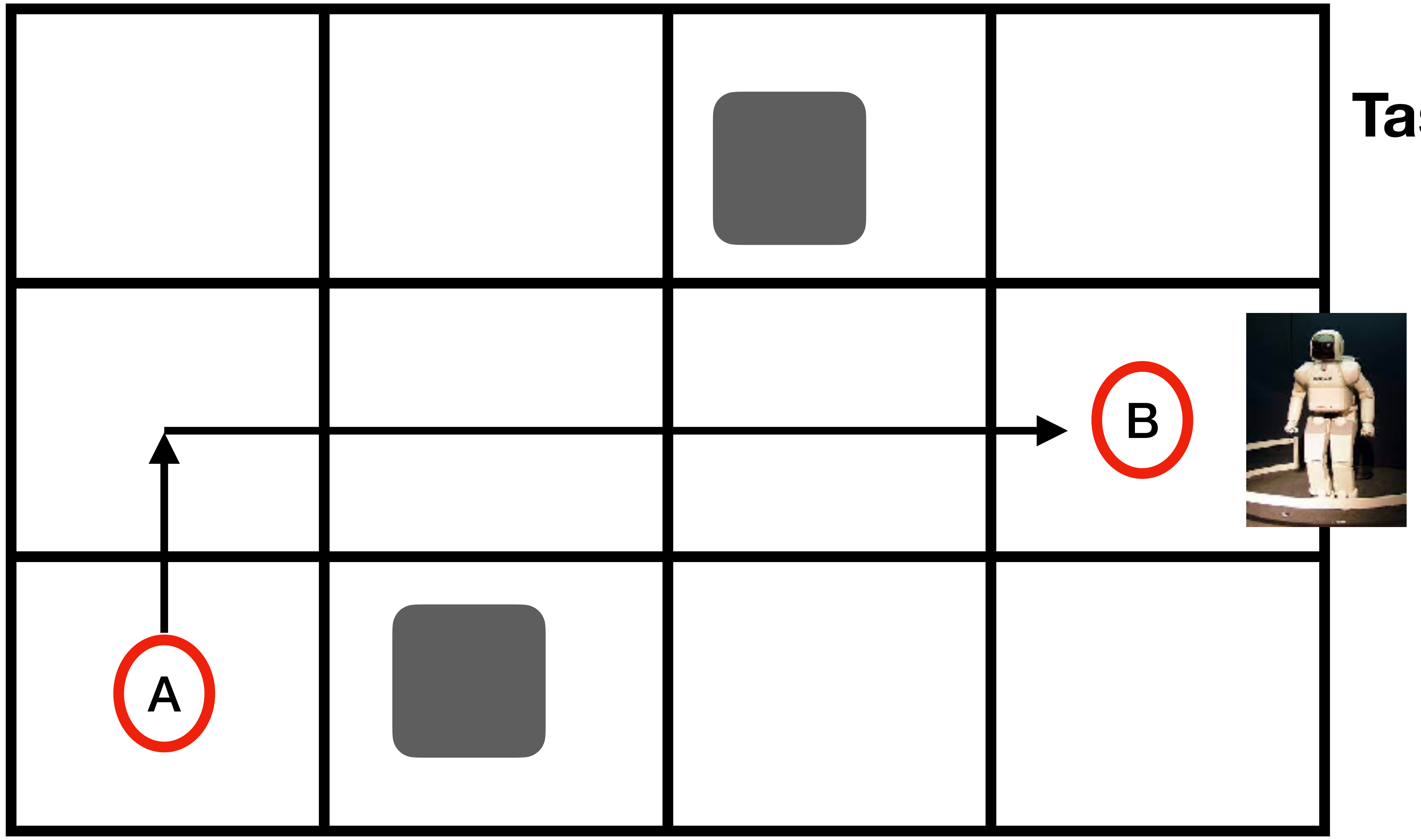


Task: Move from A to B cheaply

1. Plan

2. Execute

Robot Analogy



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1. Plan

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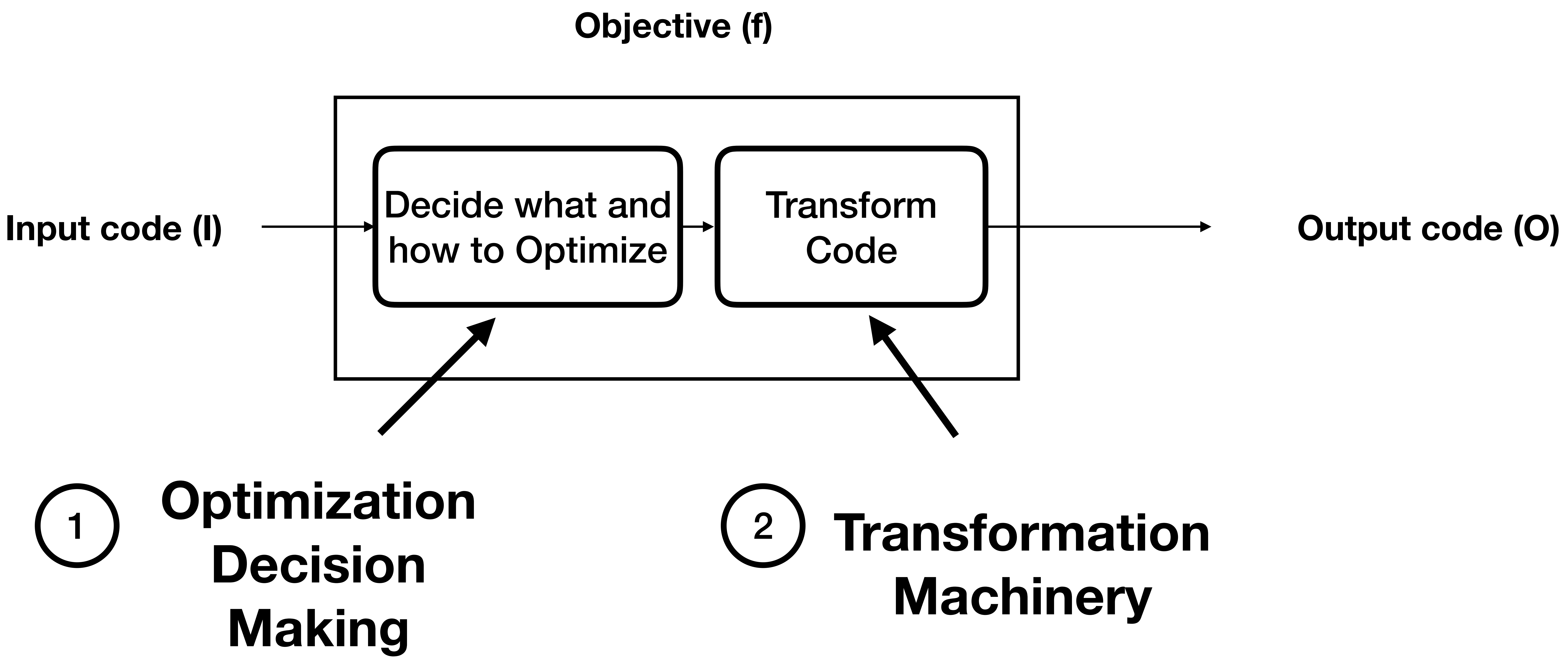
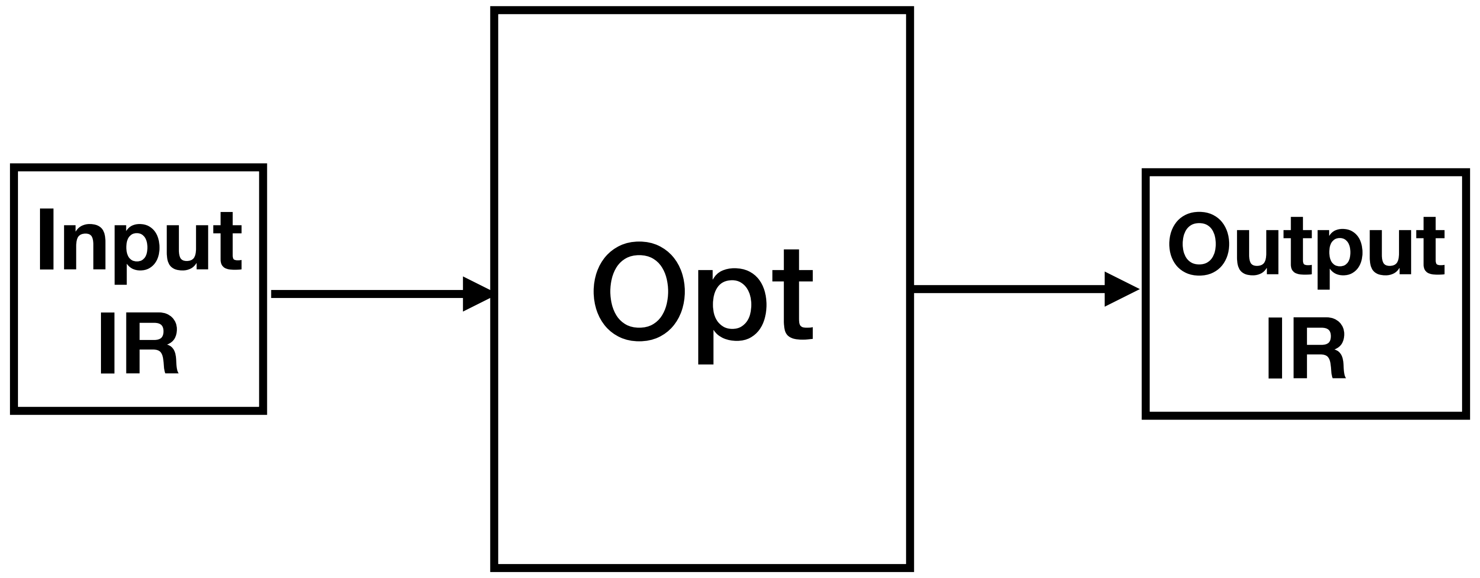
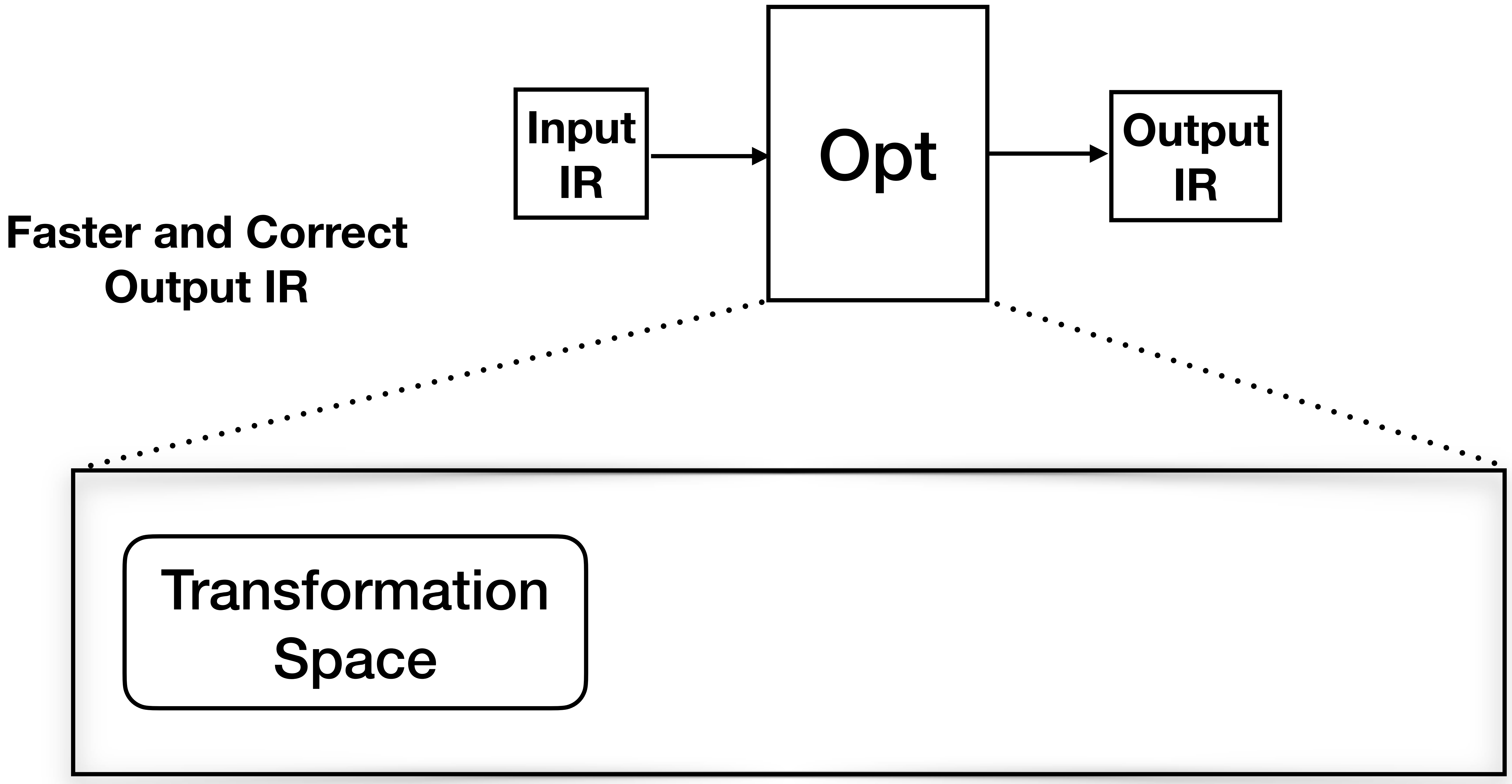


Optimization Decision Making

Faster and Correct
Output IR

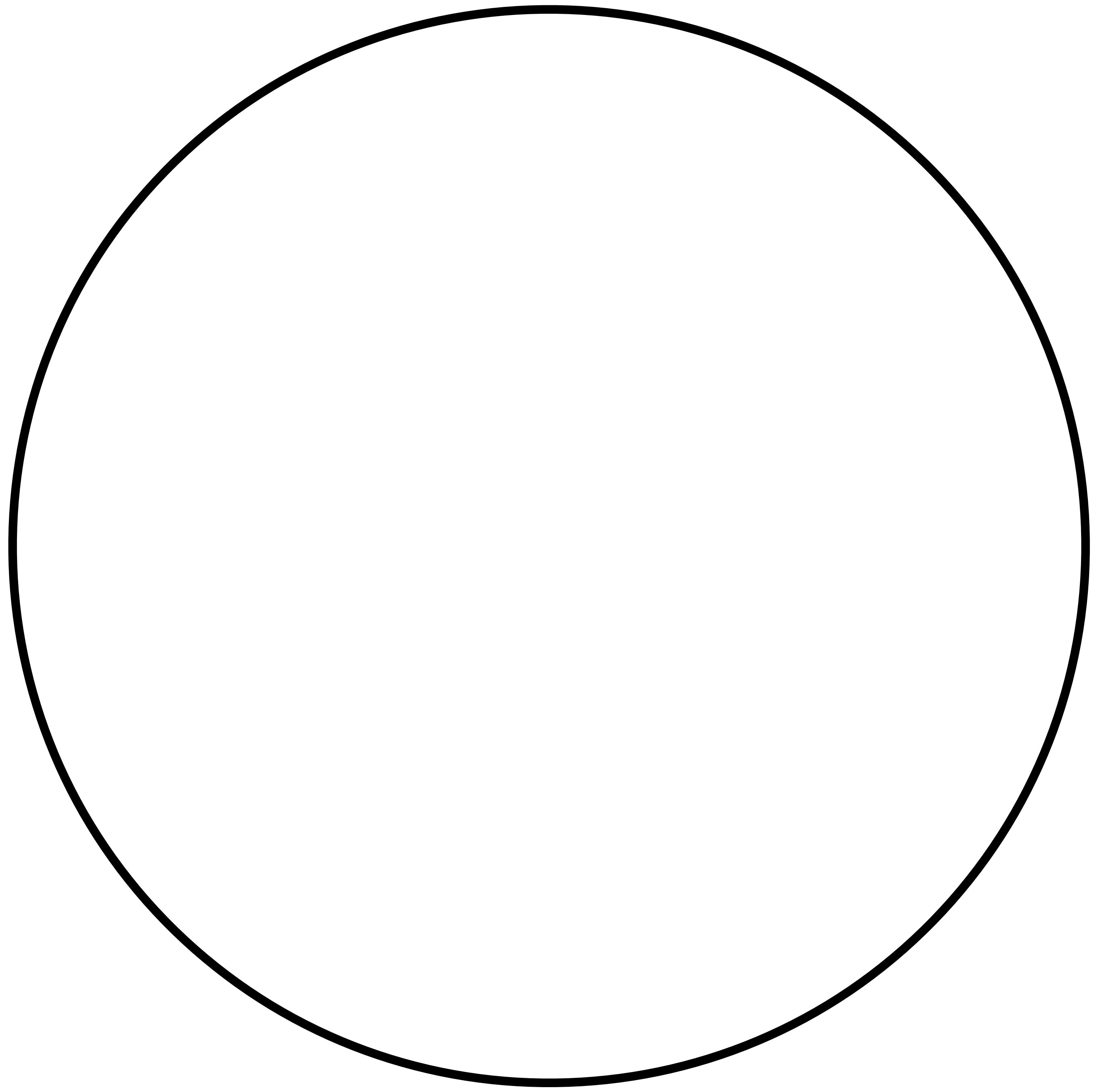


Optimization Decision Making



Optimization Decision Making

semantically equivalent
transformations



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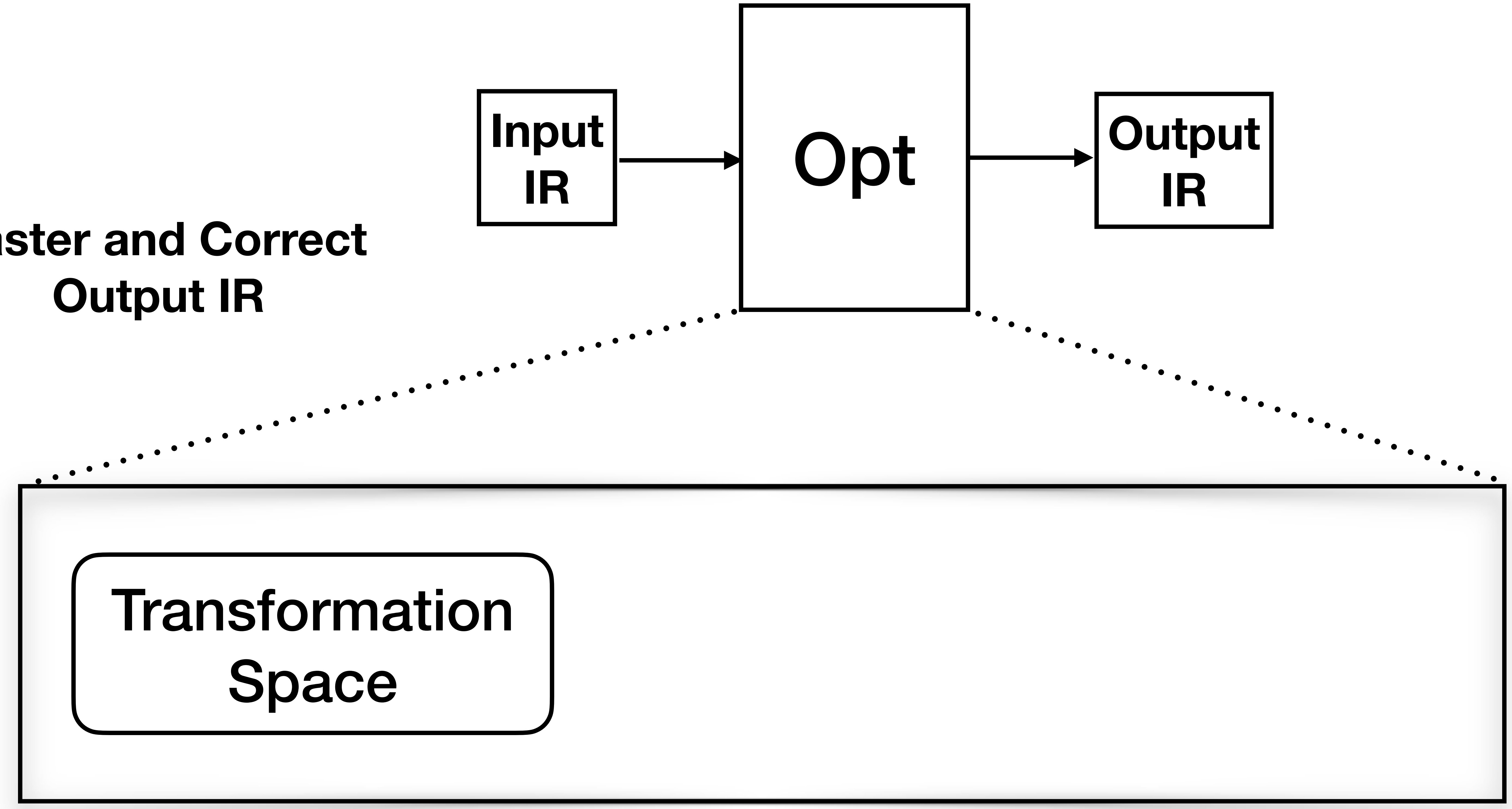
Output IR



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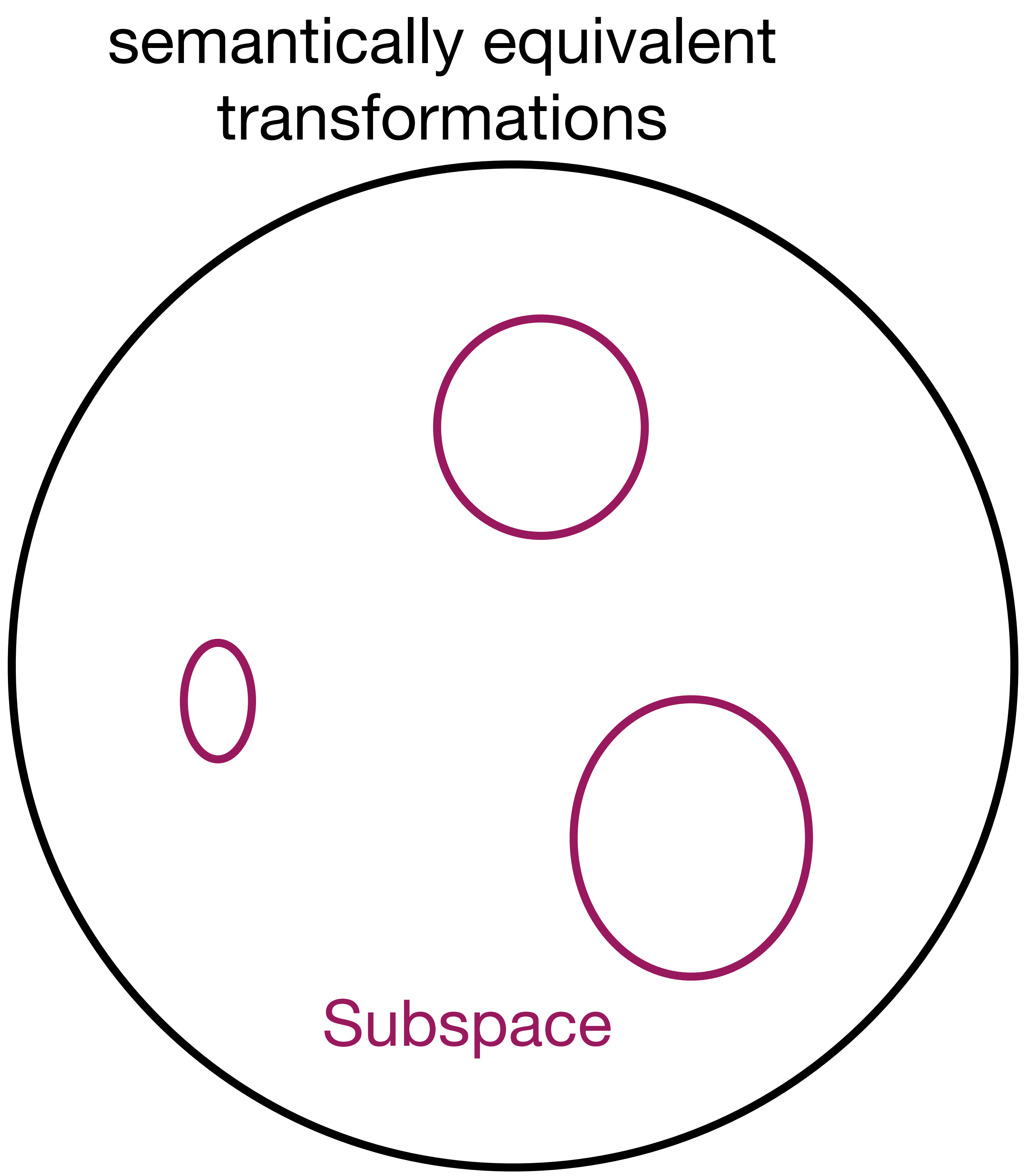
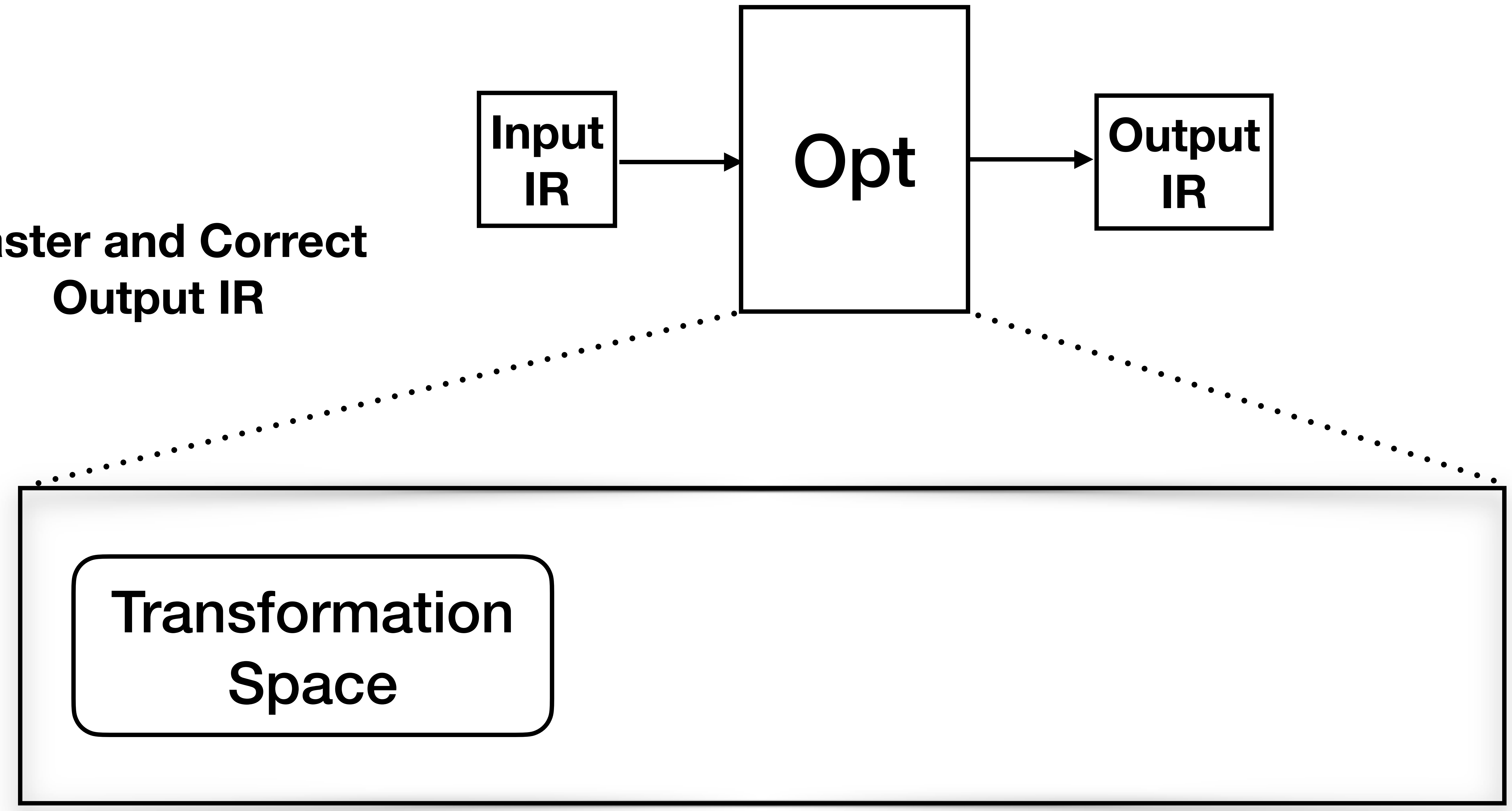


Faster and Correct Output IR



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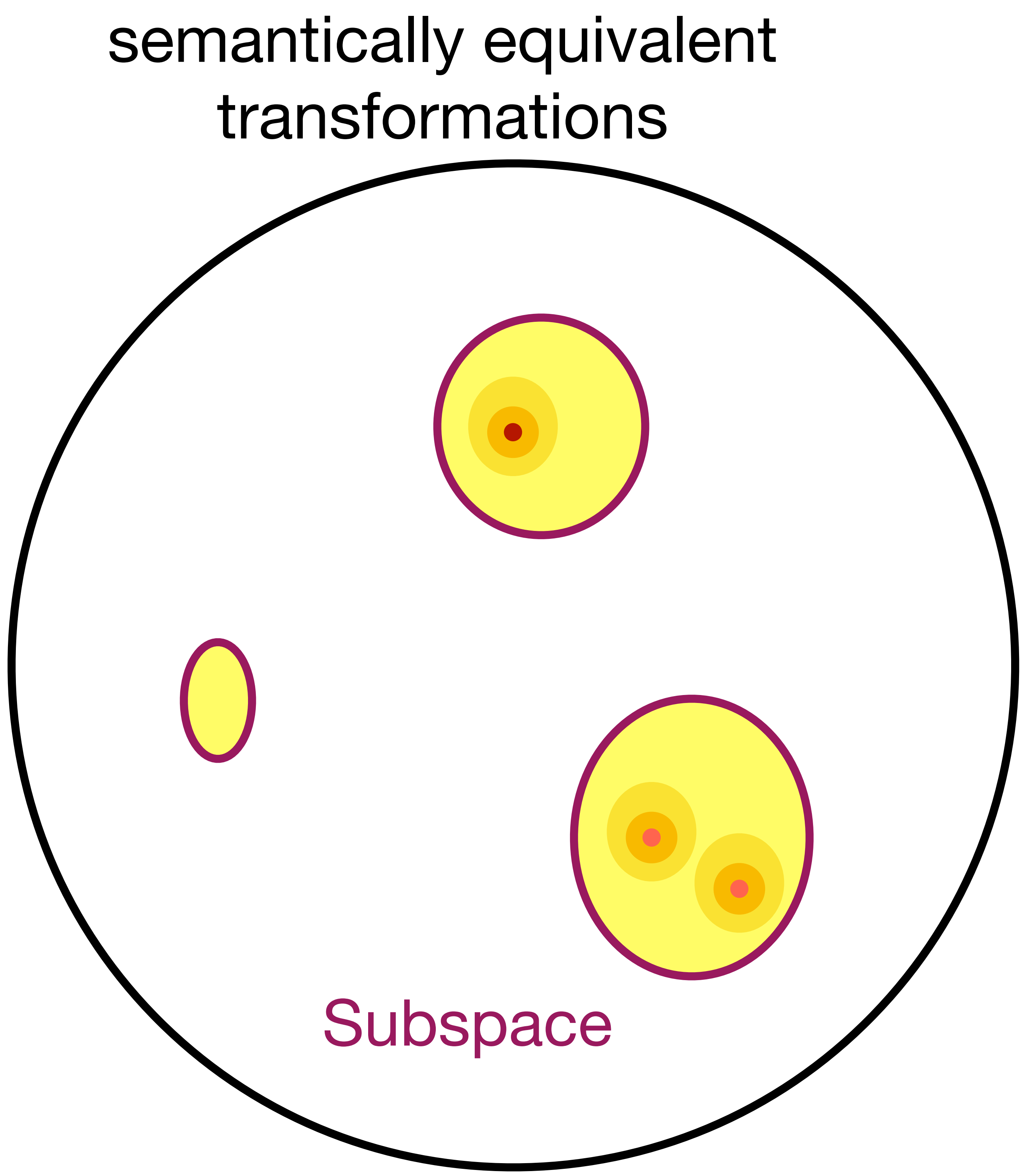

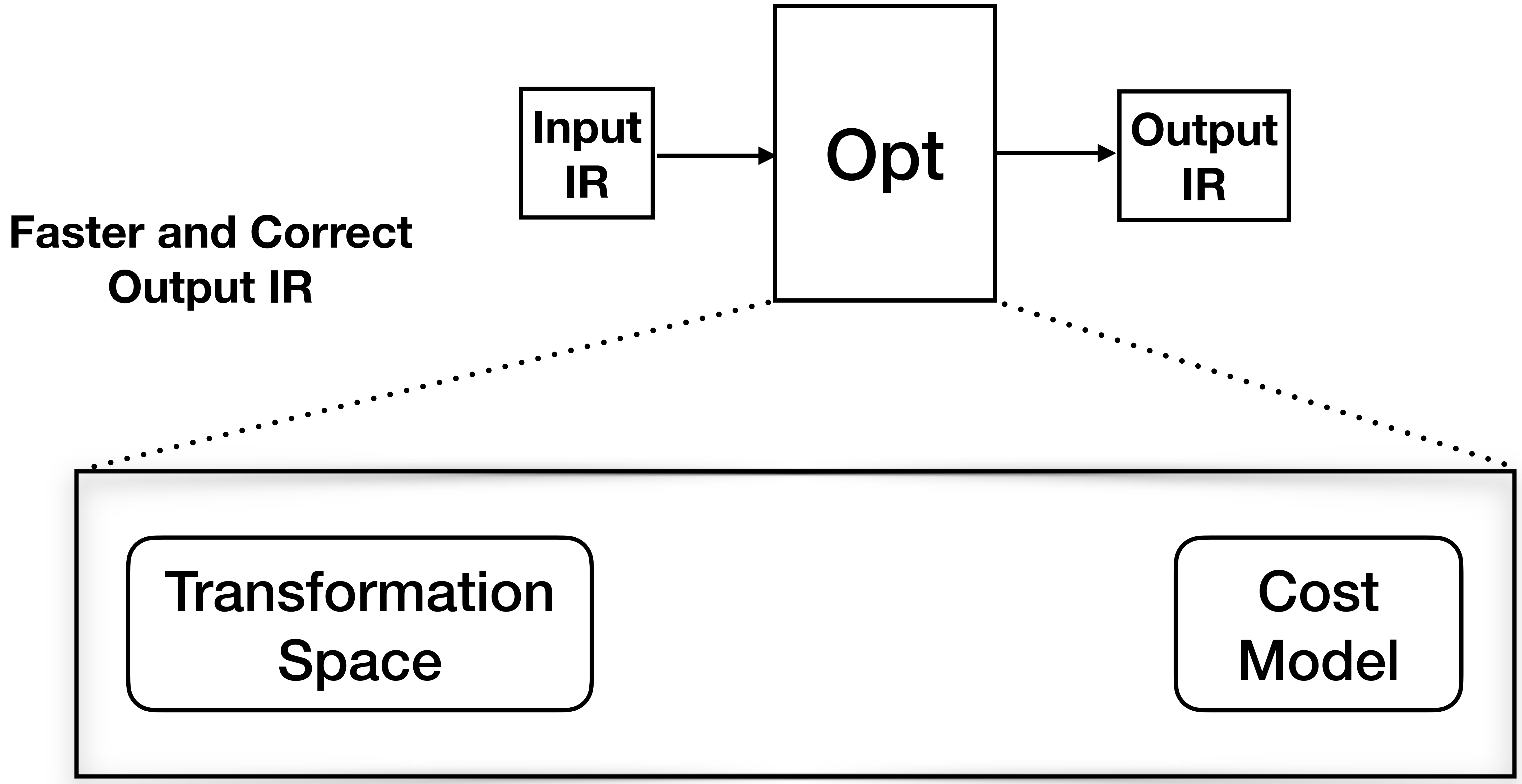

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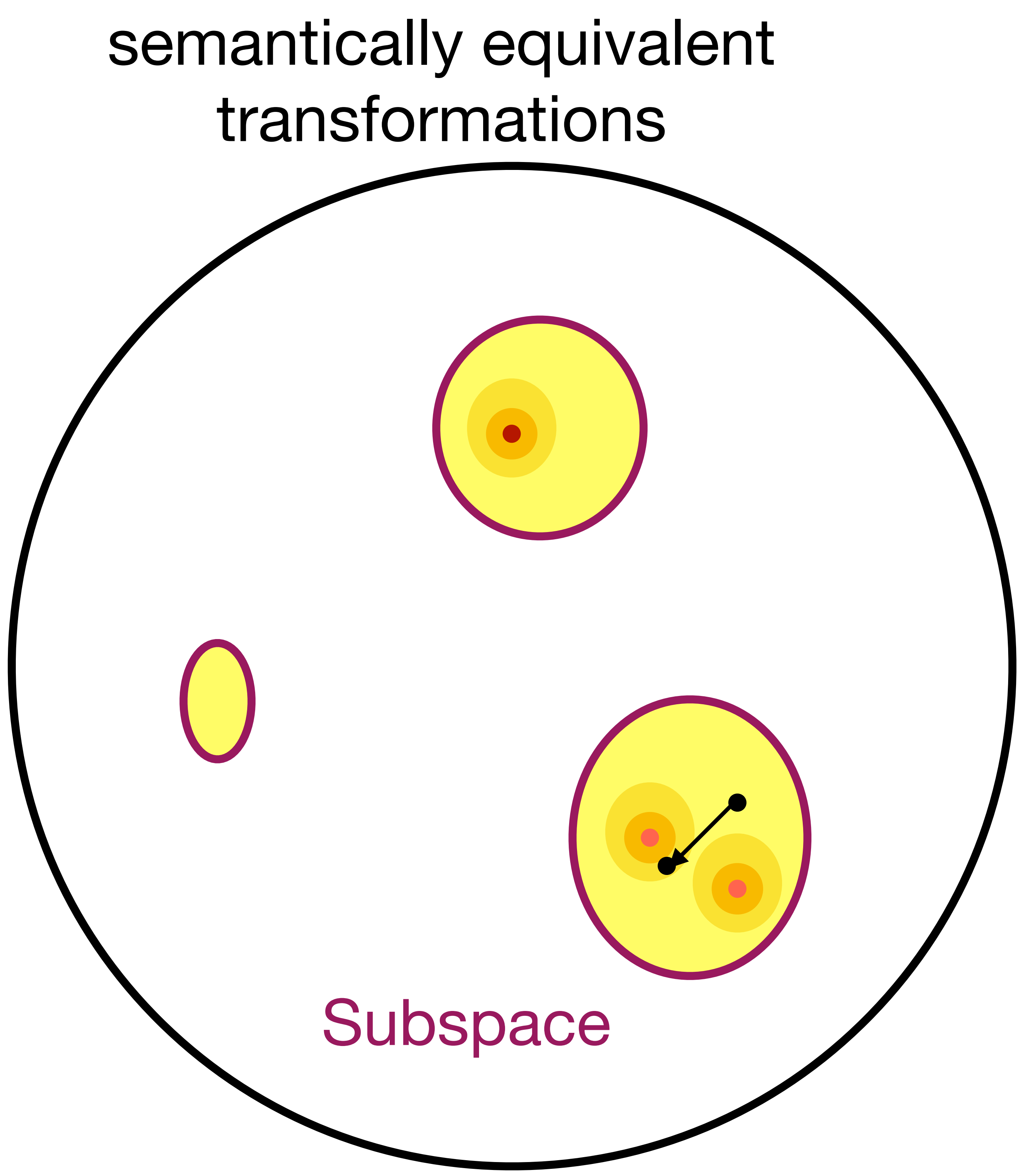

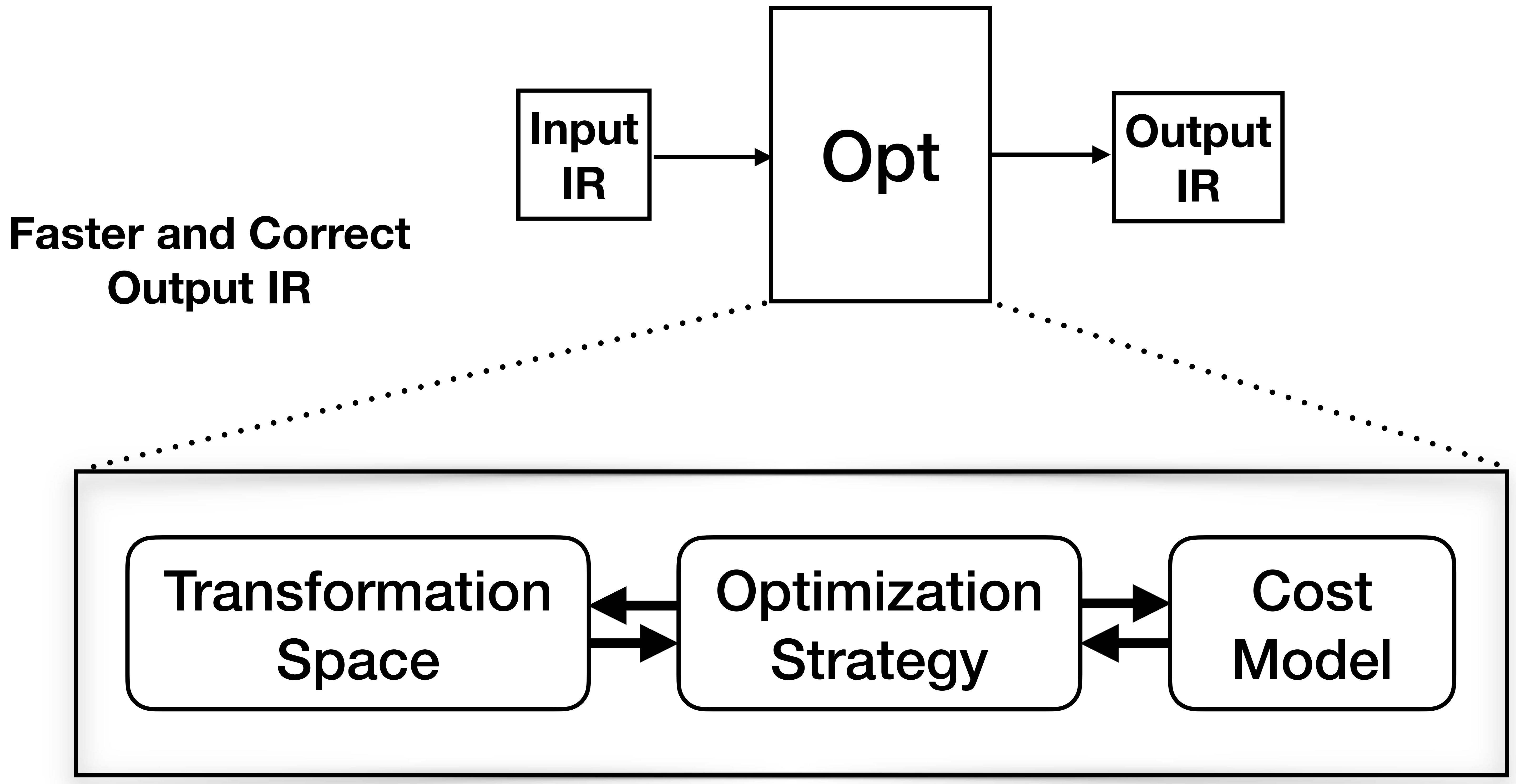

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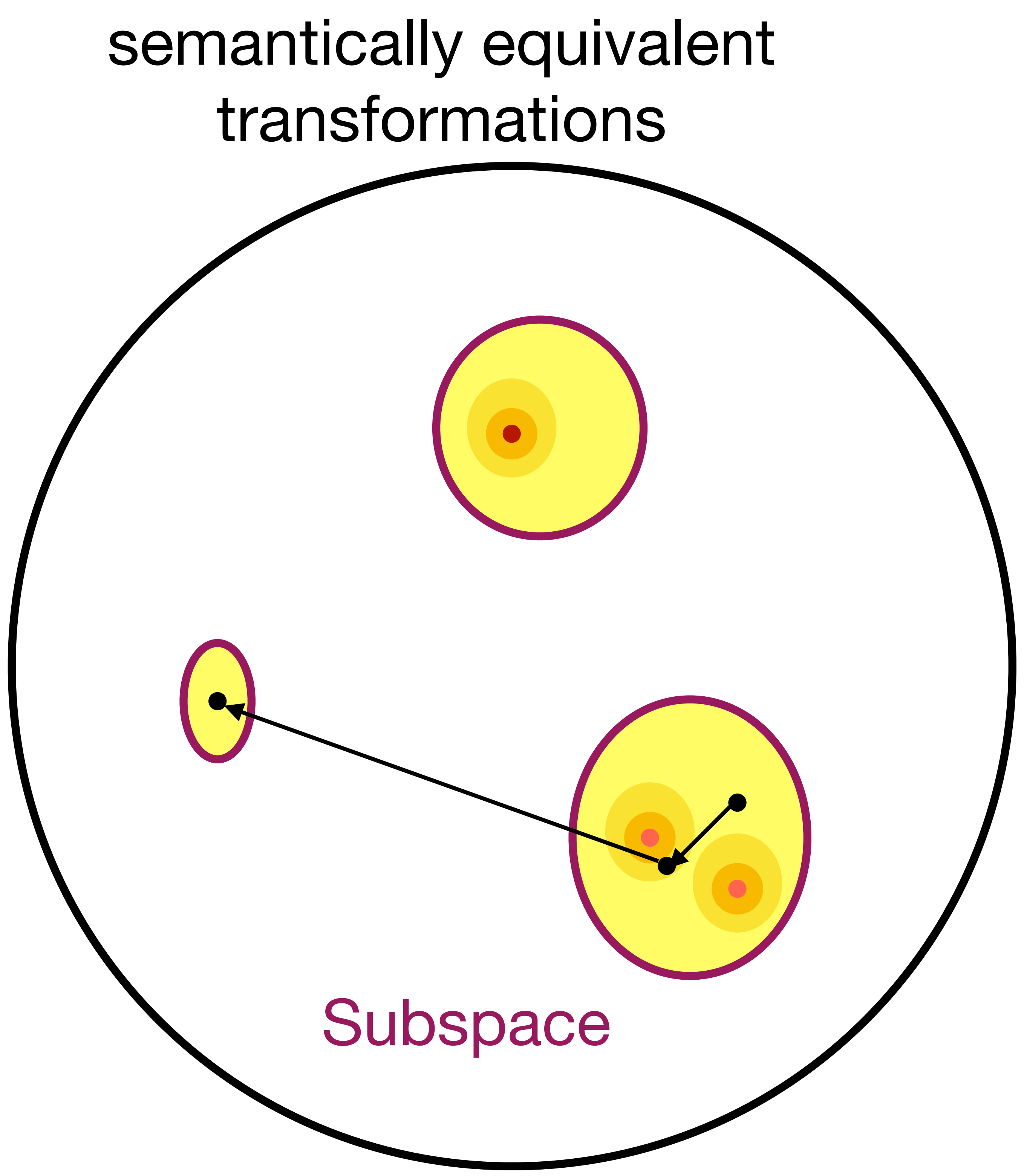

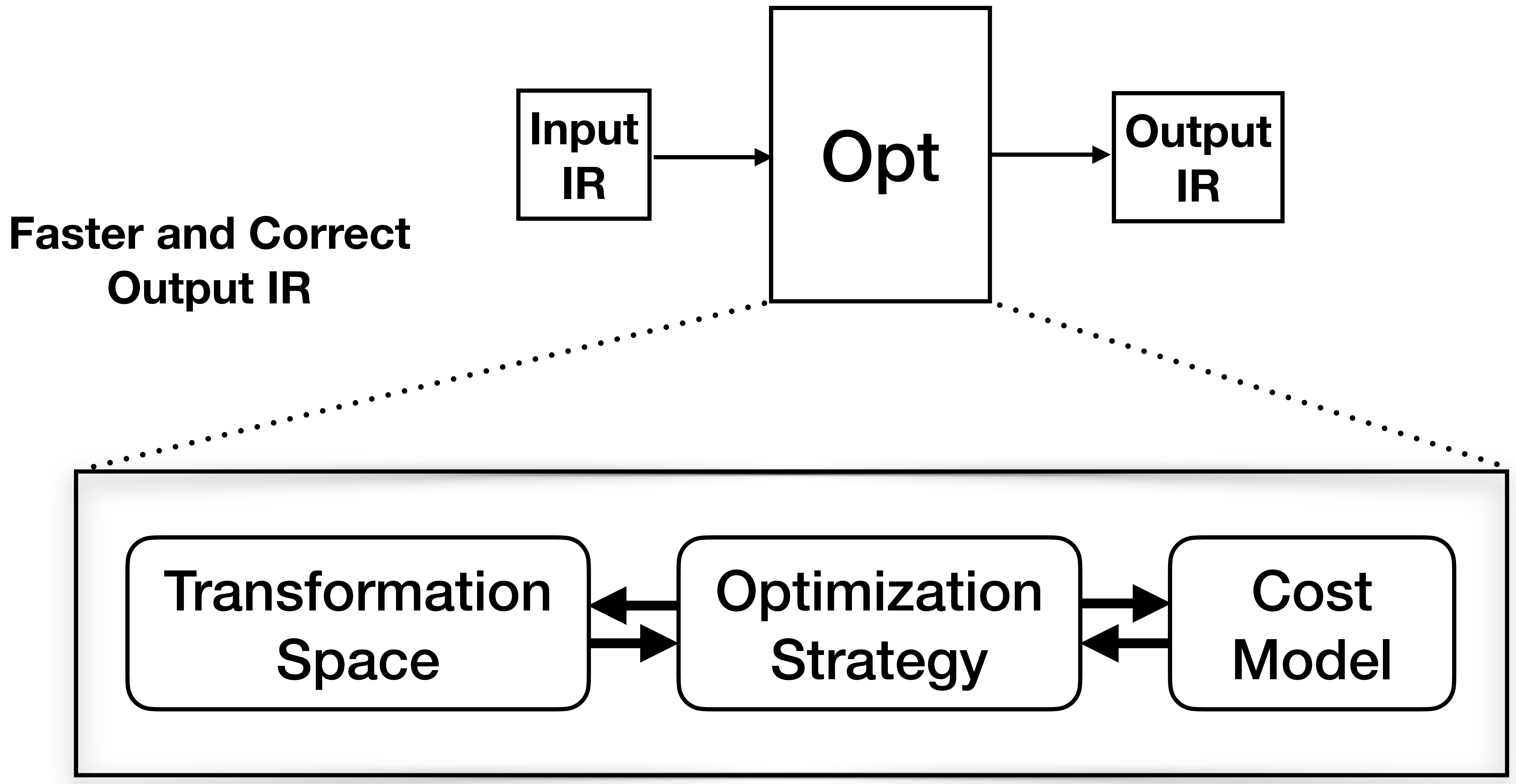

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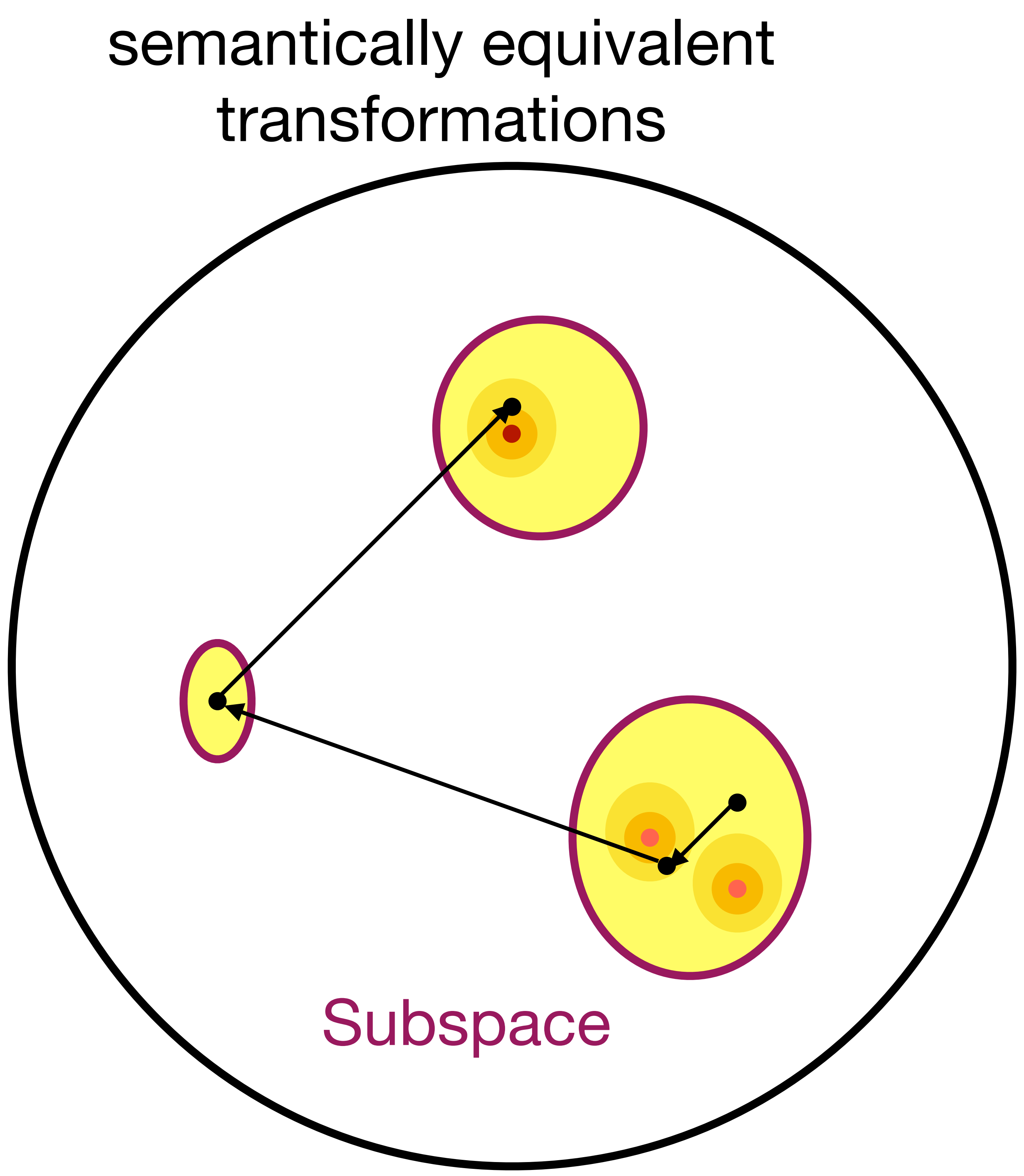

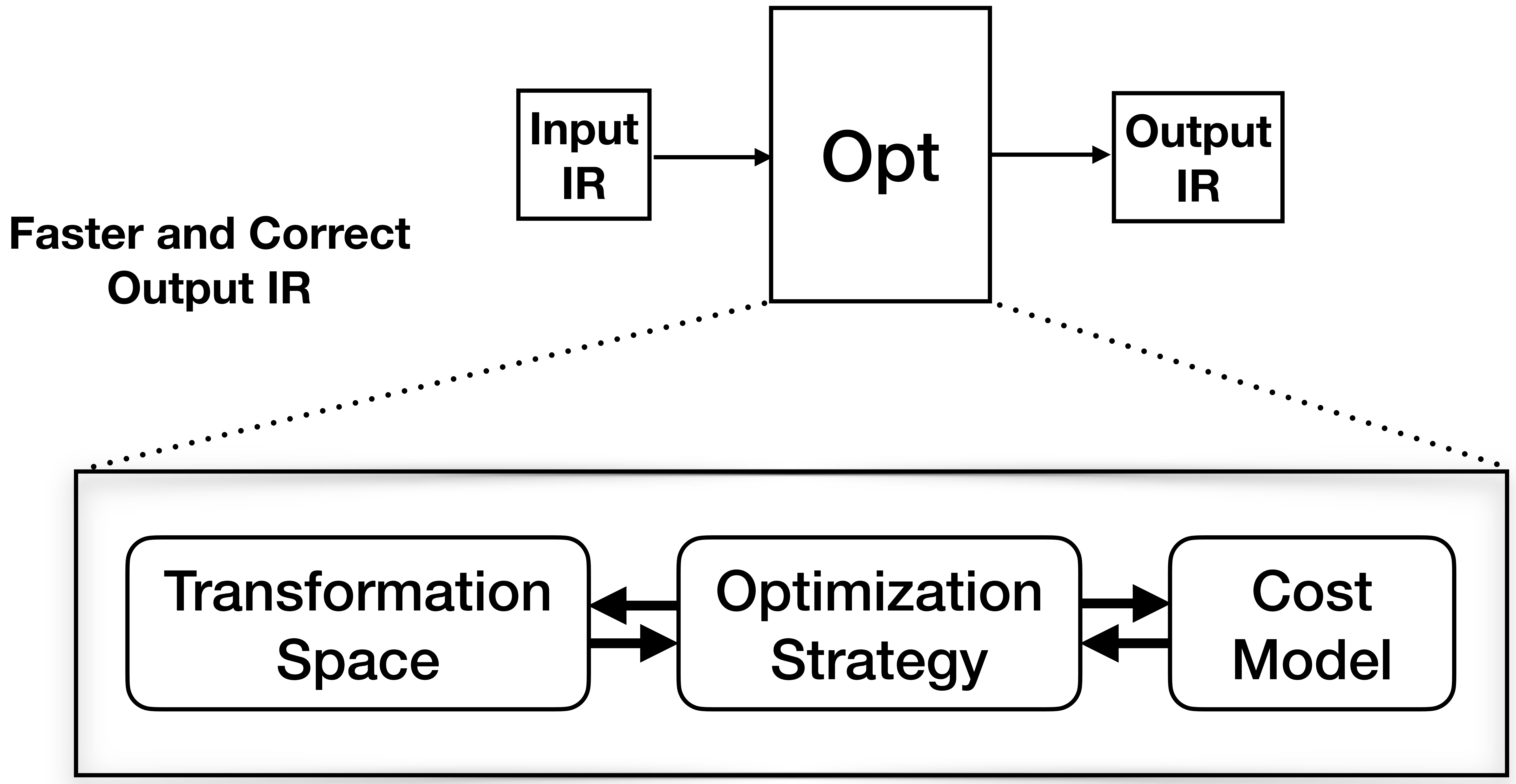

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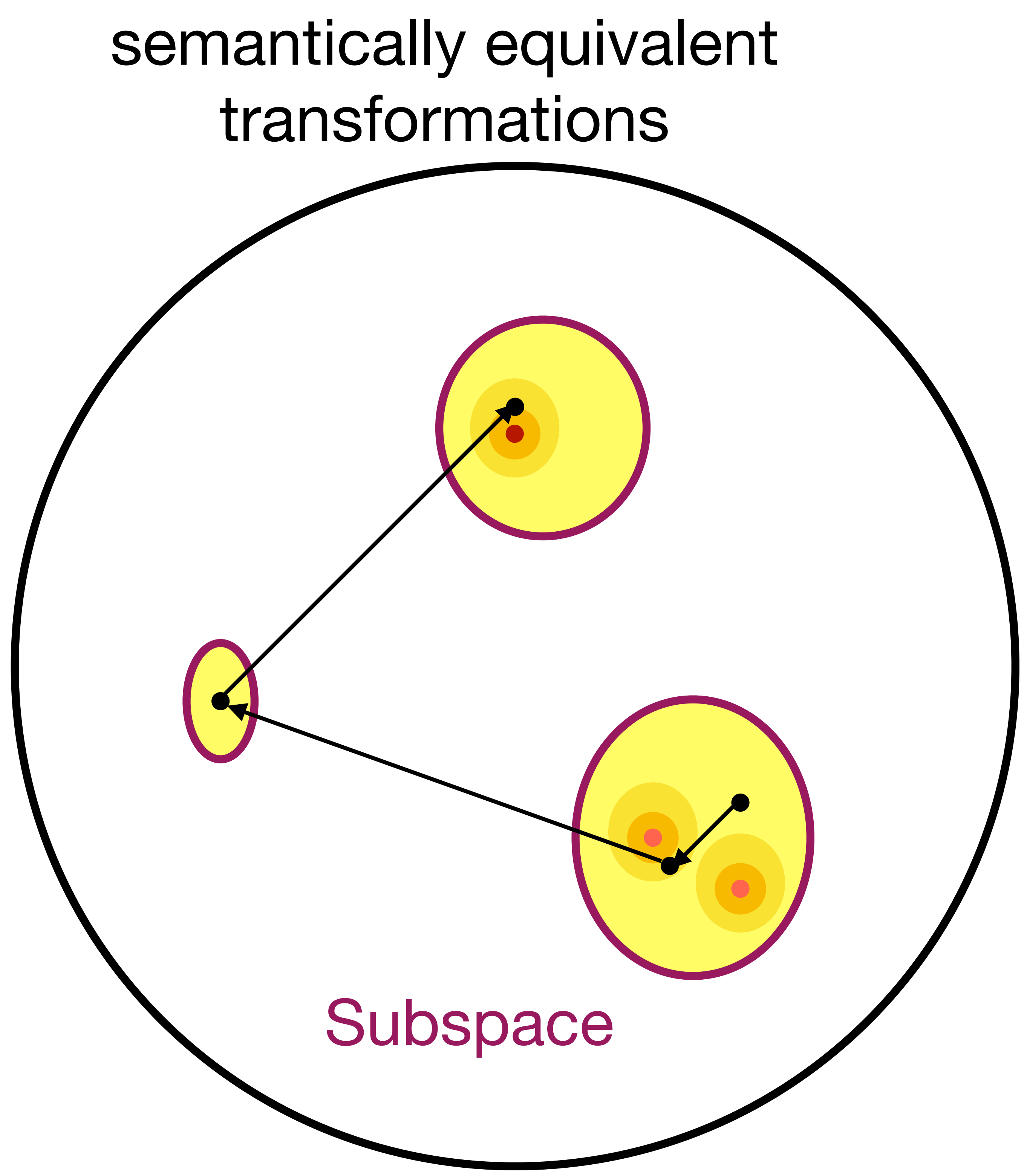

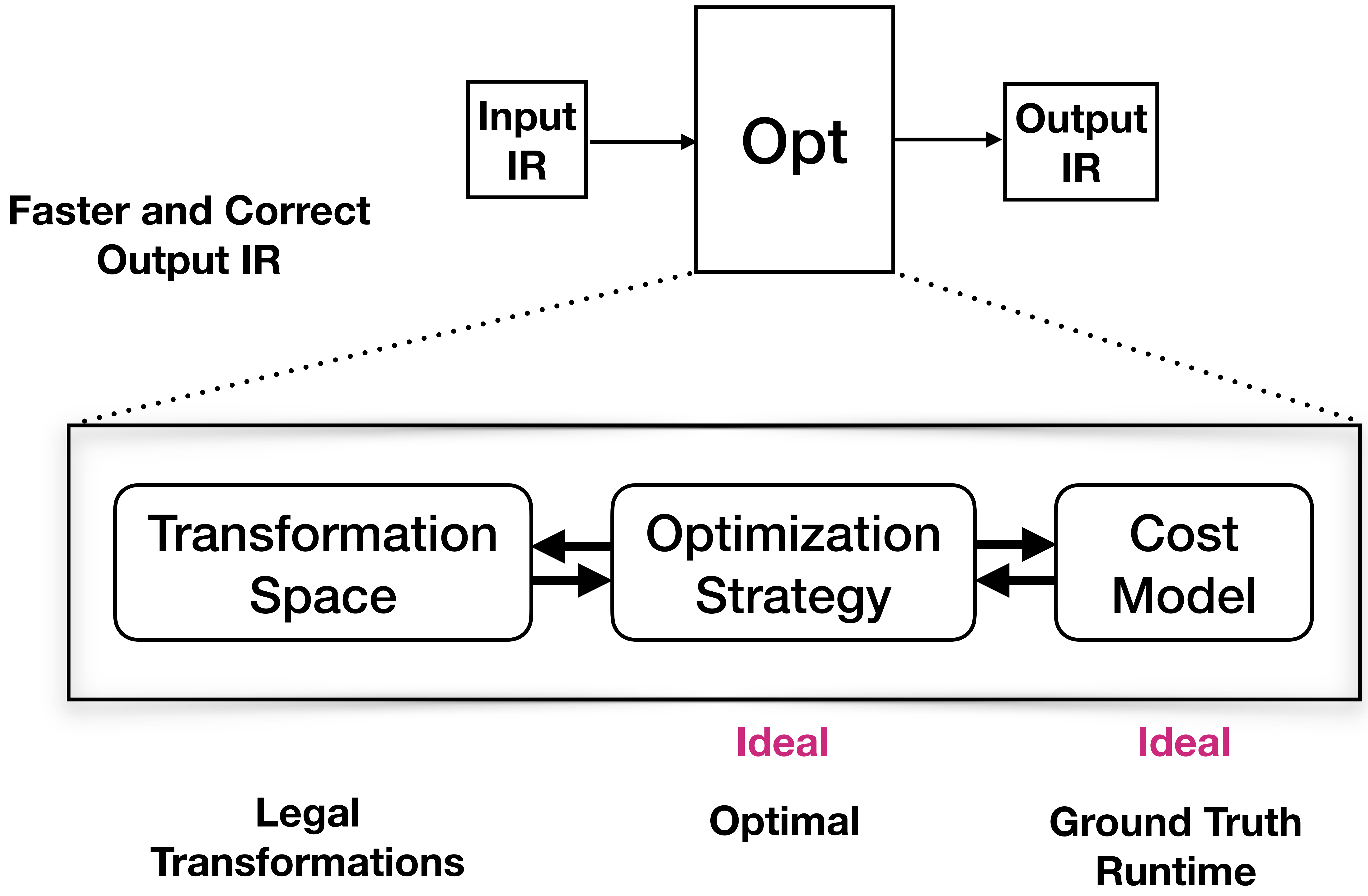

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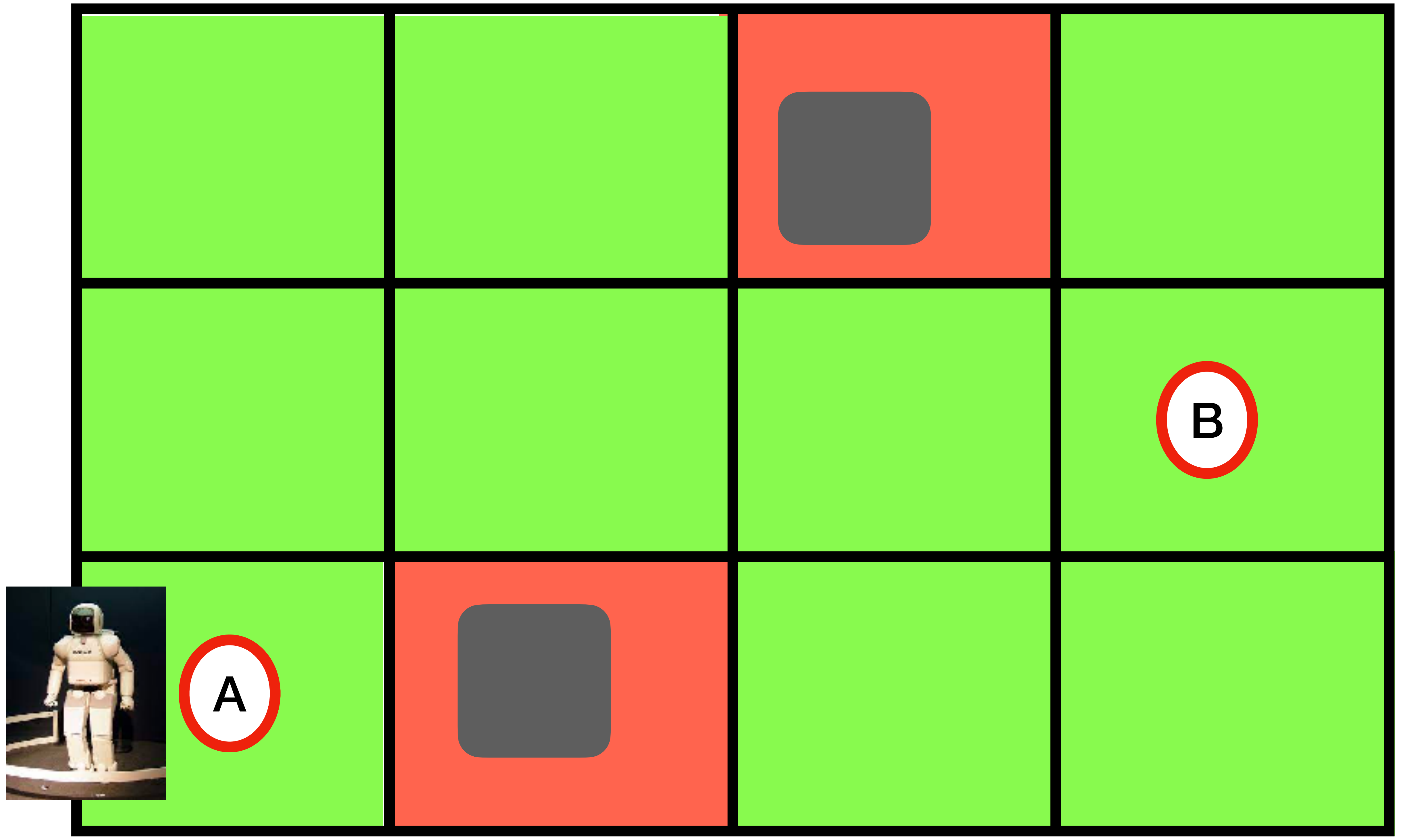
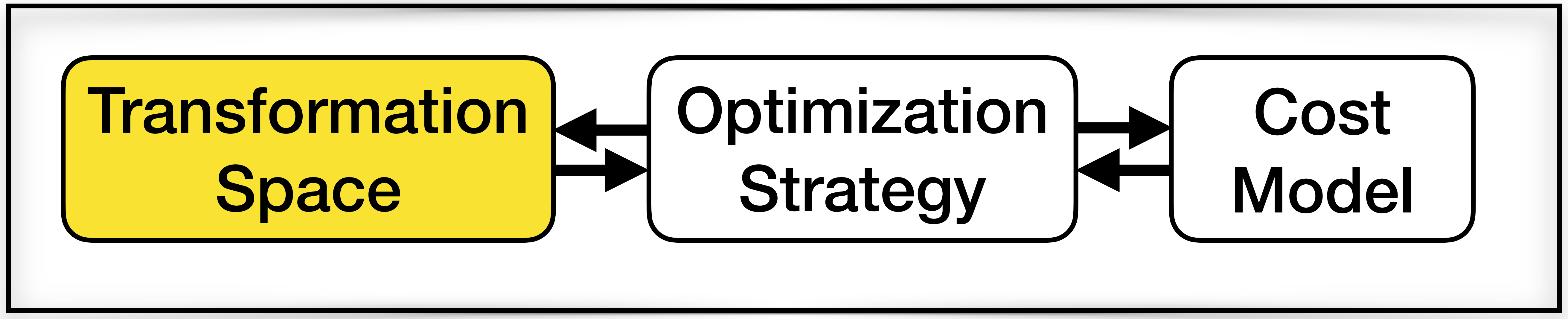


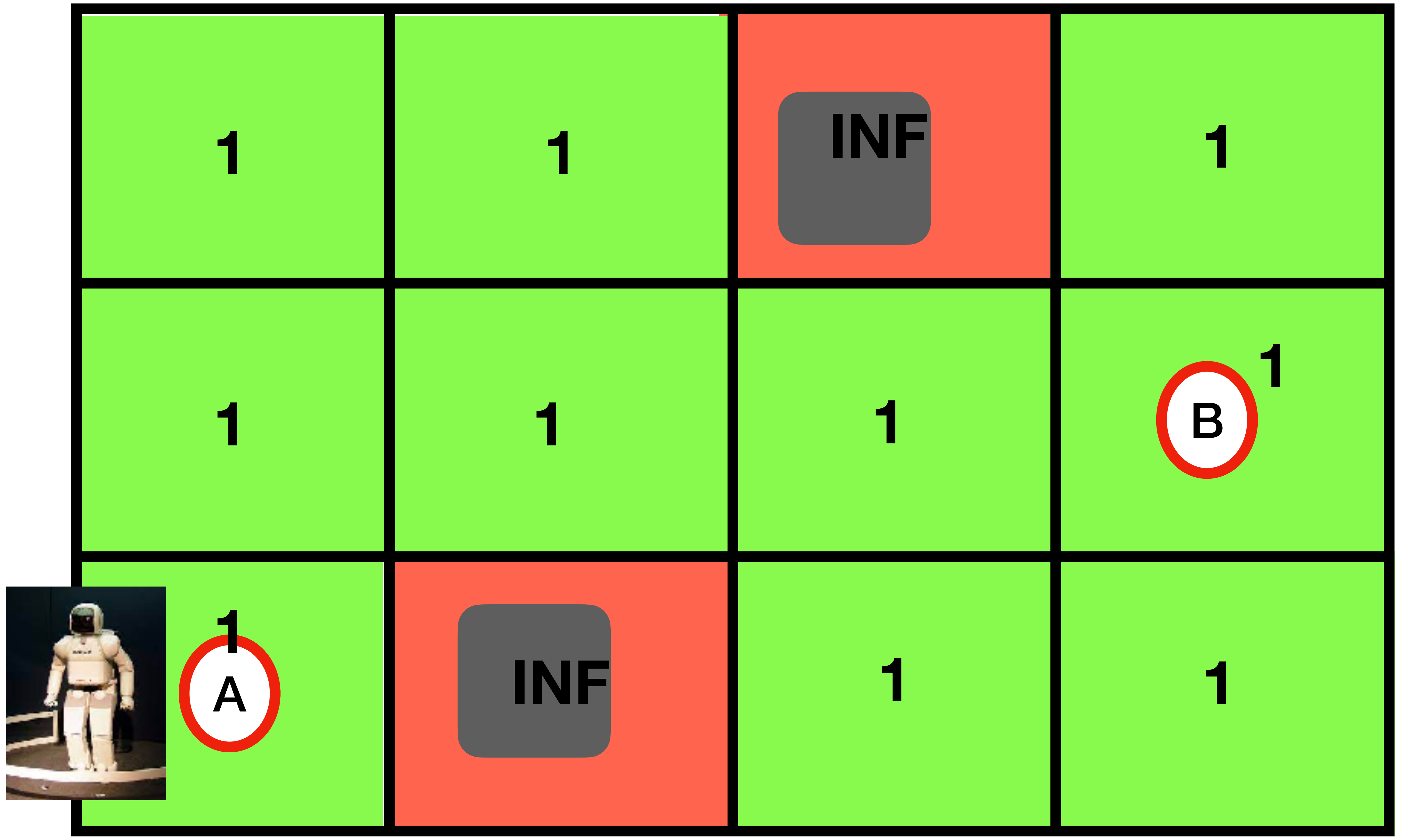
Task: Move from A to B cheaply

1. Plan

2. Execute



Robot Analogy



Task: Move from A to B cheaply

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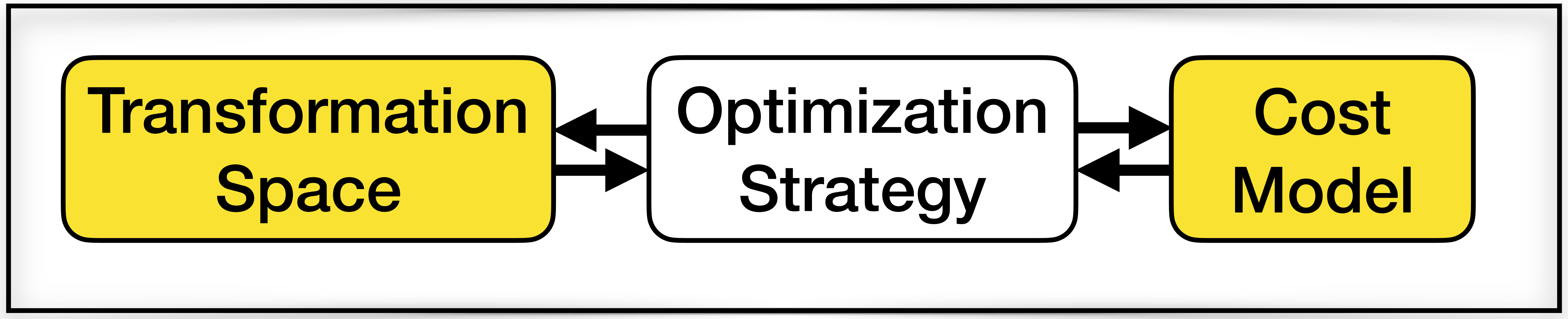

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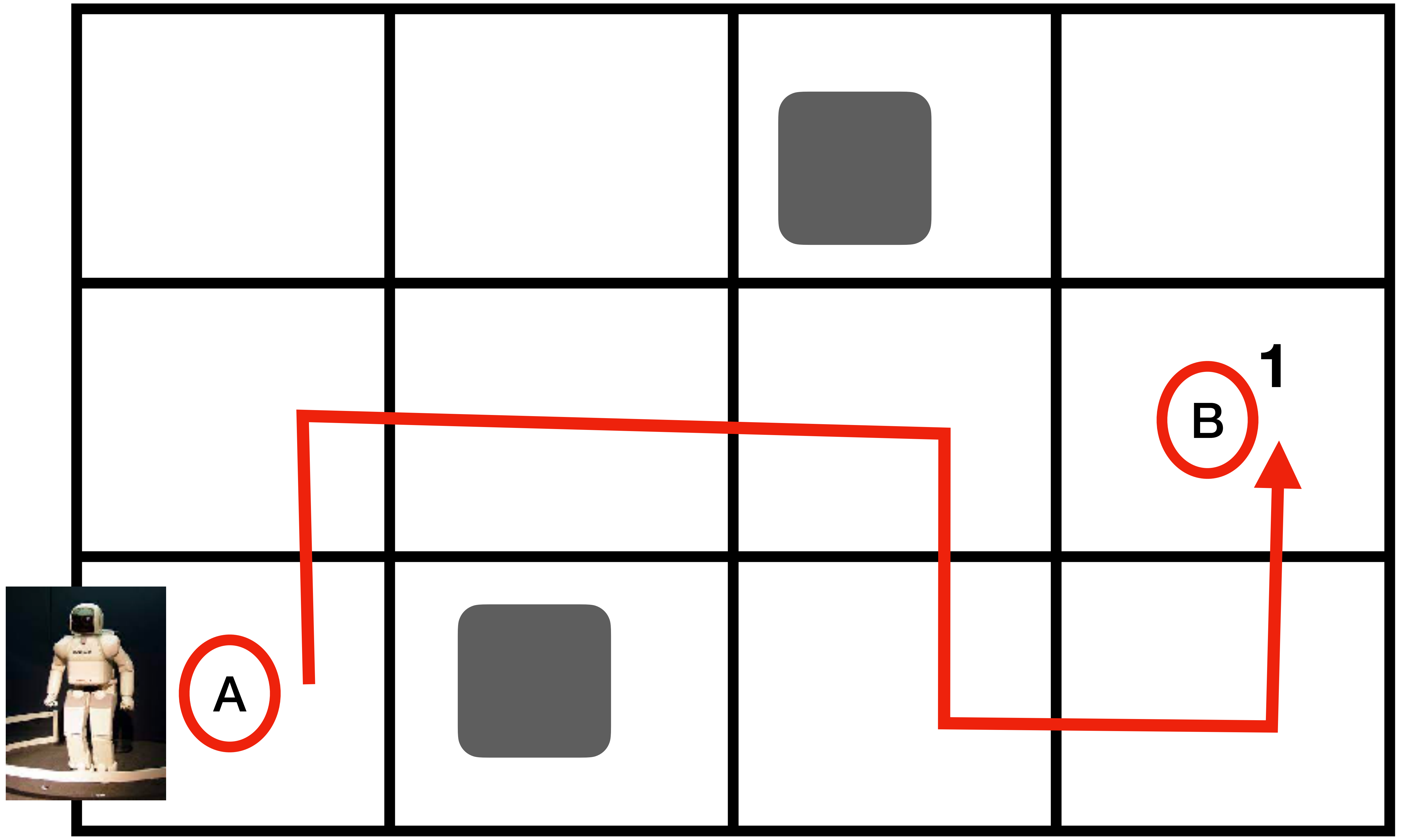
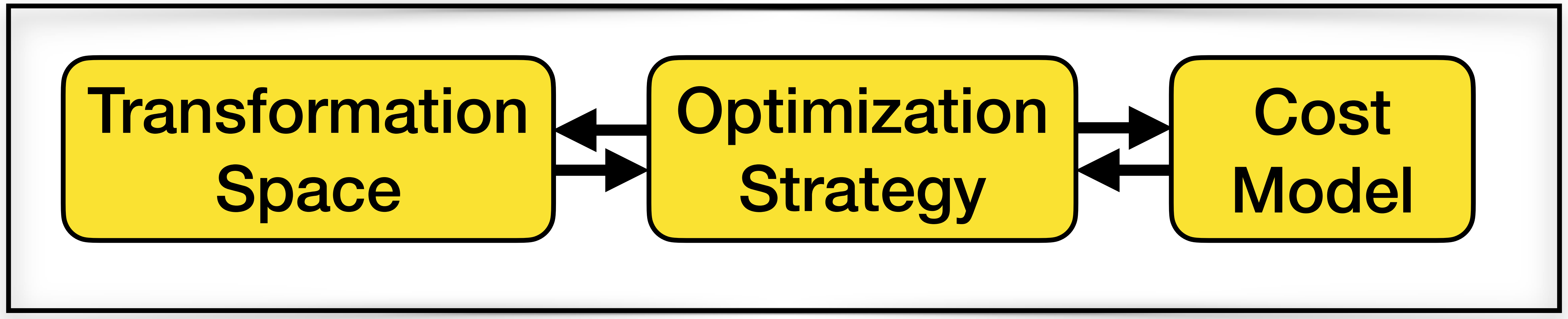


Task: Move from A to B cheaply

1. Plan

2. Execute

Cost: 7



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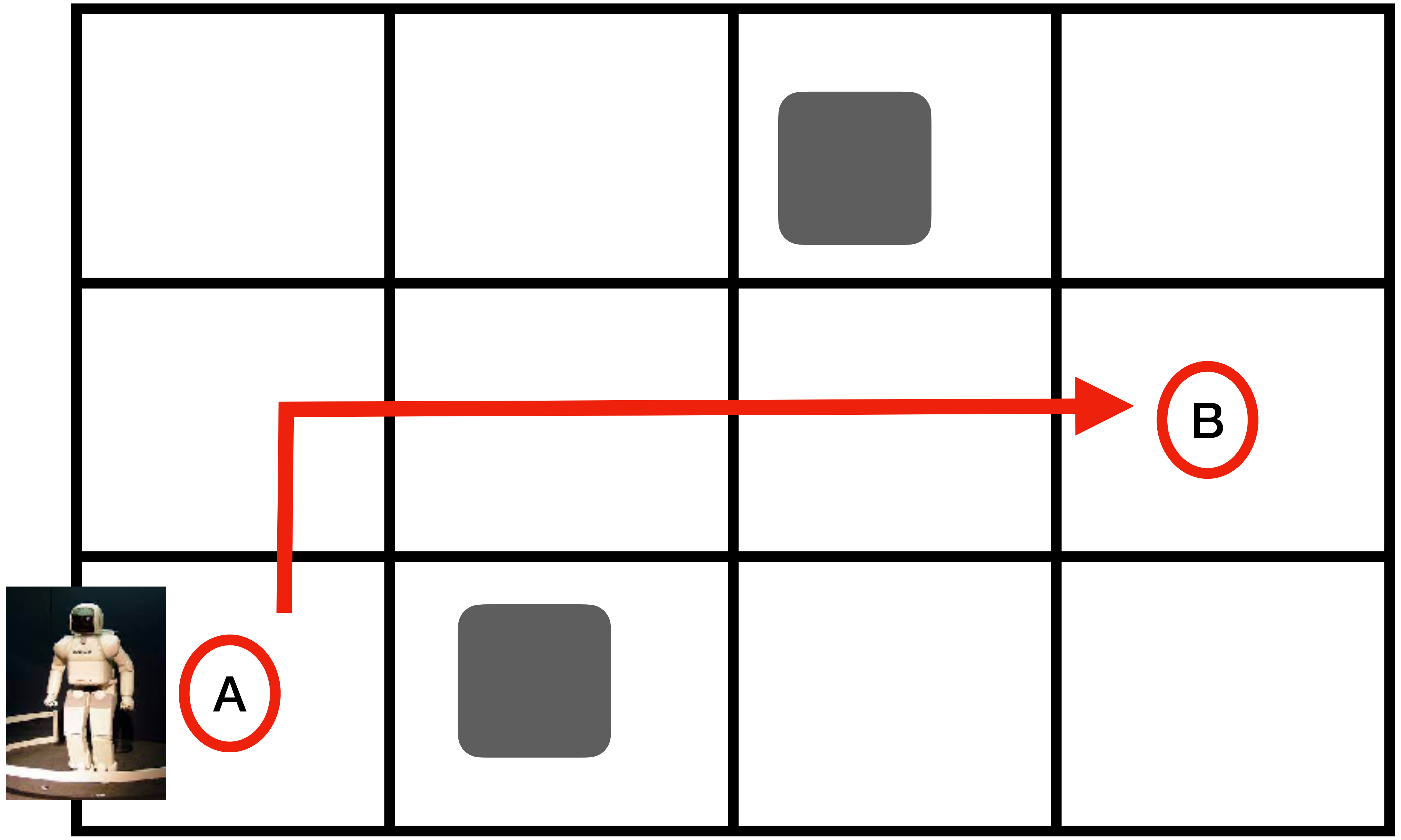
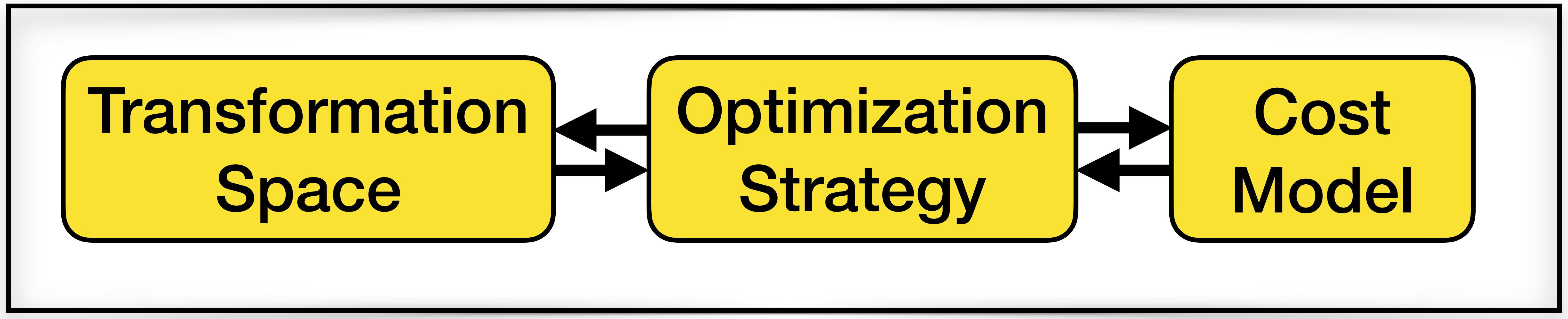


Task: Move from A to B cheaply

1. Plan

2. Execute

Cost: 5



Vectorization

Independent and **Isomorphic** statements can be vectorized

Scalar Code

```
a[0] = b[0] + c[0]
a[1] = b[1] + c[1]
```

Vector Packs

Vector Code

Single **I**nstruction **M**ultiple **D**ata (SIMD)

```
{a[0],a[1]} = {b[0],b[1]} + {c[0],c[1]}
```

Larsen & Amarasinghe "Exploiting Superword Level Parallelism with Multimedia Instruction Sets" [PLDI'00]

Statement Packing Problem

- Find **independent** and **isomorphic** statements
- Not all vector packs can exist with each other
- Need to select the most profitable packing strategy

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

```
{S1,S2}    {S4,S5}
{S2,S3}    {S5,S6}
{S1,S3}    {S4,S6}
```

Transformation Space

Statement packing strategy 1

Scalar code

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

Vector code

```
S1  : A1 = L[5] / L[2]
S2  : A2 = L[6] / L[3]

S3  : A3 = L[7] / L[4]

S4  : A4 = L[1] - A2
S5  : A5 = L[2] - A3
S6  : A6 = L[3] - A1
```

Instruction Breakdown

0 vector
0 packing
0 unpacking

There are costs associated with vectorization

Scalar code

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

Vector code

```
SV1 : {A1,A2} = {L[5],L[6]} / {L[2],L[3]}

S3  : A3 = L[7] / L[4]

S4  : A4 = L[1] - A2
SV2 : {A5,A6} = {L[2],L[3]} - {A3,A1}
```

Non-isomorphic

Instruction Breakdown

4 vector
0 packing
0 unpacking

There are costs associated with vectorization

Scalar code

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

Vector code

```
SV1 : {A1,A2} = {L[5],L[6]} / {L[2],L[3]}
SU1 : A1 = unpack(SV1,1)

S3  : A3 = L[7] / L[4]

S4  : A4 = L[1] - A2
SV2 : {A5,A6} = {L[2],L[3]} - {A3,A1}
```

Instruction Breakdown

4 vector
0 packing
1 unpacking

There are costs associated with vectorization

Scalar code

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

Vector code

```
SV1 : {A1,A2} = {L[5],L[6]} / {L[2],L[3]}
SU1 : A1 = unpack(SV1,1)

S3  : A3 = L[7] / L[4]
SP1 : {A3,A1} = pack(A3,A1)
S4  : A4 = L[1] - A2
SV2 : {A5,A6} = {L[2],L[3]} - {A3,A1}
```

Instruction Breakdown

4 vector
1 packing
1 unpacking

There are costs associated with vectorization

Scalar code

```
S1 : A1 = L[5] / L[2]
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Vector code

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```

Instruction Breakdown

4 vector
1 packing
2 unpacking

Statement packing strategy 2

Scalar code

```
S1 : A1 = L[5] / L[2]
S2 : A2 = L[6] / L[3]
S3 : A3 = L[7] / L[4]
S4 : A4 = L[1] - A2
S5 : A5 = L[2] - A3
S6 : A6 = L[3] - A1
```

Vector code

```
SV1 : {A2,A3} = {L[6],L[7]} / {L[3],L[4]}
SU1 : L[2] = unpack(SLV1,2)
S1  : A1 = L[5] / L[2]
SU2 : L[3] = unpack(SLV2,1)
SV2 : {A4,A5} = {L[1],L[2]} - {A2,A3}
S6  : A6 = L[3] - A1
```

Instruction Breakdown

5 vector
0 packing
2 unpacking

Different vectorization schemes have different profitability

Strategy 1

Liu et. al [PLDI'12]

```
SV1 : {A1,A2} = {L[5],L[6]} / {L[2],L[3]}
SU1 : A1 = unpack(SV1,1)
SU2 : A2 = unpack(SV1,2)
S3  : A3 = L[7] / L[4]
SP1 : {A3,A1} = pack(A3,A1)
S4  : A4 = L[1] - A2
SV2 : {A5,A6} = {L[2],L[3]} - {A3,A1}
```

4 vector
1 packing
2 unpacking

Strategy 2

Optimal

```
SV1 : {A2,A3} = {L[6],L[7]} / {L[3],L[4]}
SU1 : L[2] = unpack(SLV1,2)
S1  : A1 = L[5] / L[2]
SU2 : L[3] = unpack(SLV2,1)
SV2 : {A4,A5} = {L[1],L[2]} - {A2,A3}
S6  : A6 = L[3] - A1
```

5 vector
0 packing
2 unpacking

Machine Learning Influence

	Transformation Space	Optimization Strategy	Cost Model
Traditional solutions	Hand-written	• Greedy / Heuristic • Integer Linear Programming • Dynamic Programing	• Analytical Linear Non-linear
Automated solutions	**Program Logics**	**Data-driven** **Imitation Learning** **10/21**	**Data-driven** **LSTM based Cost Model** **10/07**

Domain Specific Languages

- Programming model specific to one domain
  - Image / Array Processing - Halide, MATLAB
  - Sparse Tensor Computations - TACO
  - Tensor Algebra - Tensorflow, Pytorch (frameworks)
  - Graphs - GraphIt, Gunrock
  - Genomic Computations - Seq

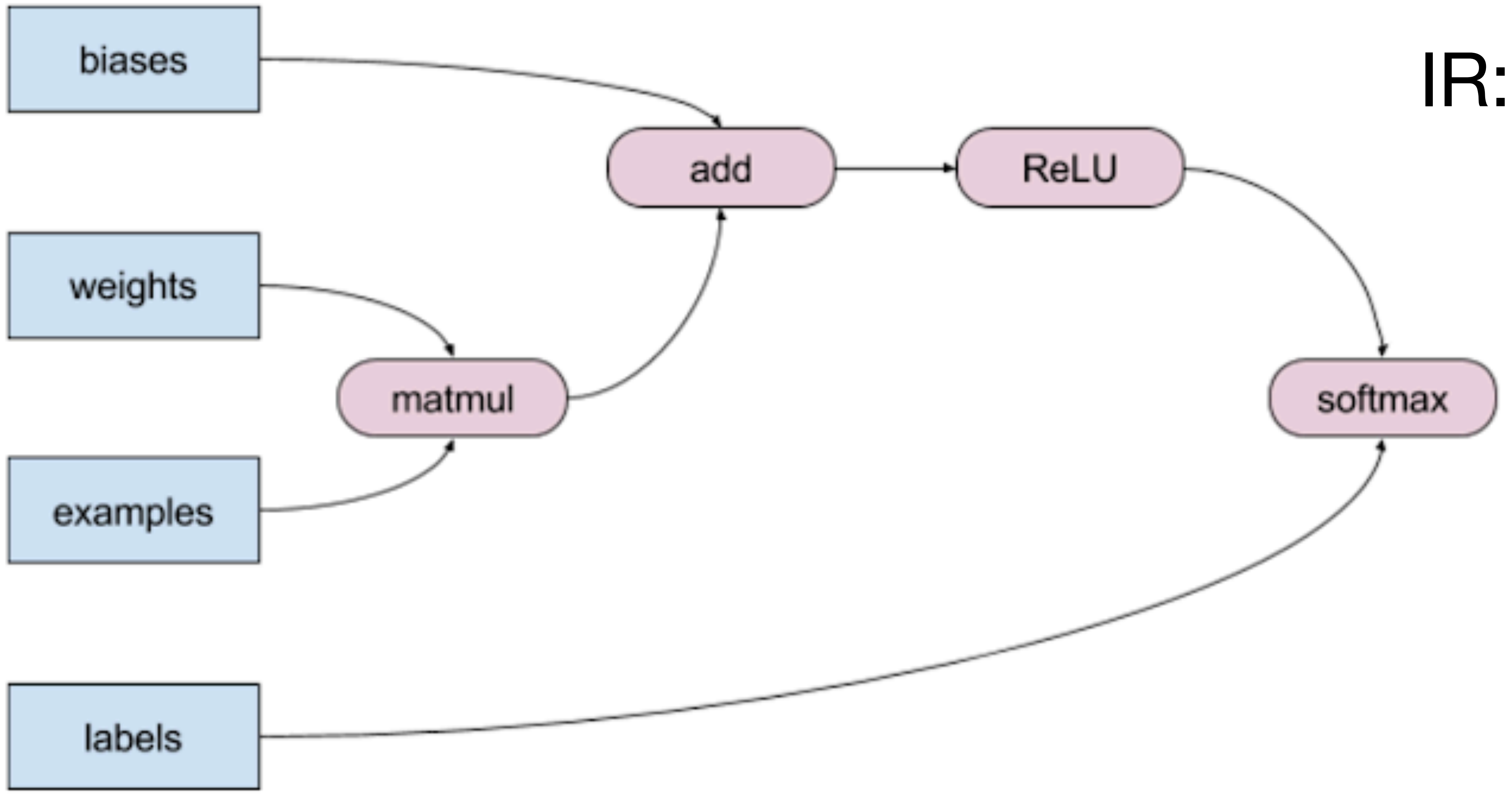
- Usually comes with a set of domain specific optimizations

Halide

- **Main idea:** Separate algorithm specification from optimizations (schedules)
- Halide Video
    - https://www.youtube.com/watch?v=3uiEyEKji0M&t=3s
- **Optimization objective:** find the best schedule or optimization sequence for a given Halide algorithm

Tensorflow

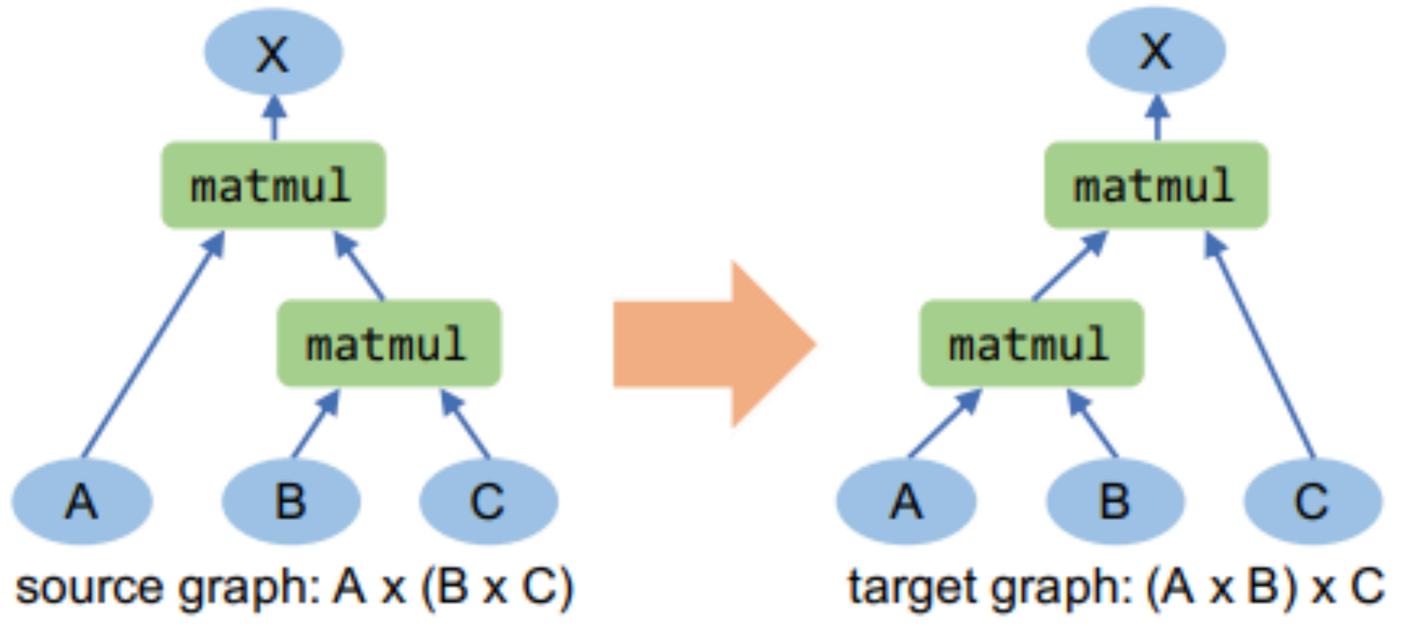
- Model tensor manipulating programs
- Uses the XLA compiler to target GPUs, TPUs and CPUs
- Main abstraction: Computational Graphs



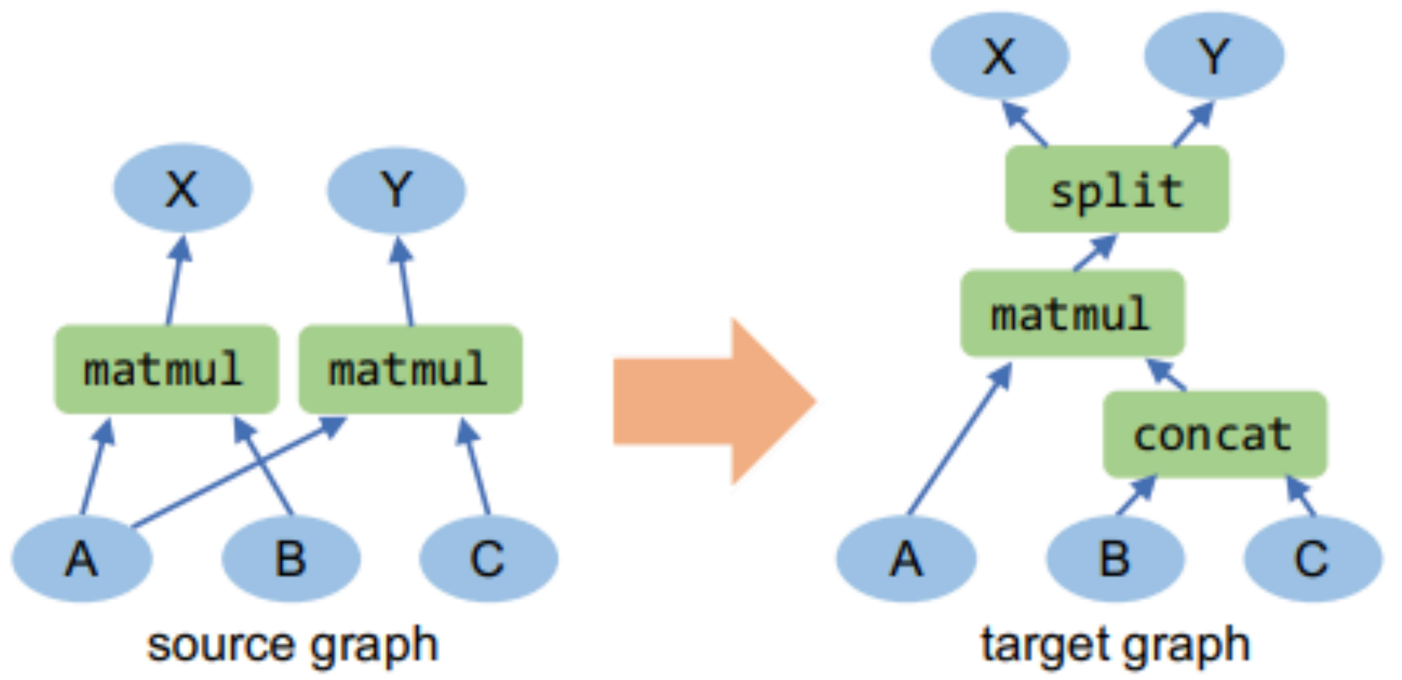
IR: High Level Operations (HLO)

XLA Compiler

- (Most) optimizations can be expressed as computational graph rewrites



(a) Associativity of matrix multiplication.



(b) Fusing two matrix multiplications using concatenation and split.

TASO [SOSP'19]

https://cs.stanford.edu/~padon/taso-sosp19.pdf

Machine Learning Influence

	Transformation Space	Optimization Strategy	Cost Model
Automated solutions	**Program Logics**	**Data-driven**	**Data-driven**
		10/28: Tree Search (Halide) **11/02: Reinforcement Learning (Halide)**	**10/12: GNN based Cost Model (XLA)**

Paper Presentation

- Paper presentations assigned on September 8th

- Week before: Meet instructor to discuss the presentation plan (compulsory!)
  - Use this time to ask questions and discuss the outline
  - Presentation slides are due when reviews are due for that class
  - Submit using the hotCRP system

- During the class: Be present in class (compulsory!)
  - Deliver a 20-30 min presentation on the paper
  - Answer questions for the following 15 min
  - Final 30-40 min for open discussion on the paper (lead by the instructor)

Paper Presentation

- After class: Summarize the discussion of the paper
  - Submit the summary by the start of the next class (hotCRP)
- First presentation on September 14th
  - Matteo Frigo, "A Fast Fourier transform Compiler" (PLDI 1999)
  - 15 min presentation
  - Meet instructor on Thursday 9th to discuss the outline

Any Questions?