Deep Bilevel Optimization Learning for Medical Image Registration

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Outline

1. Background
2. Bilevel Feature Learning for Image Registration
3. Optimization Learning for Deformable Image Registration
4. Automated Learning for Medical Image Registration
5. Summary and Outlook

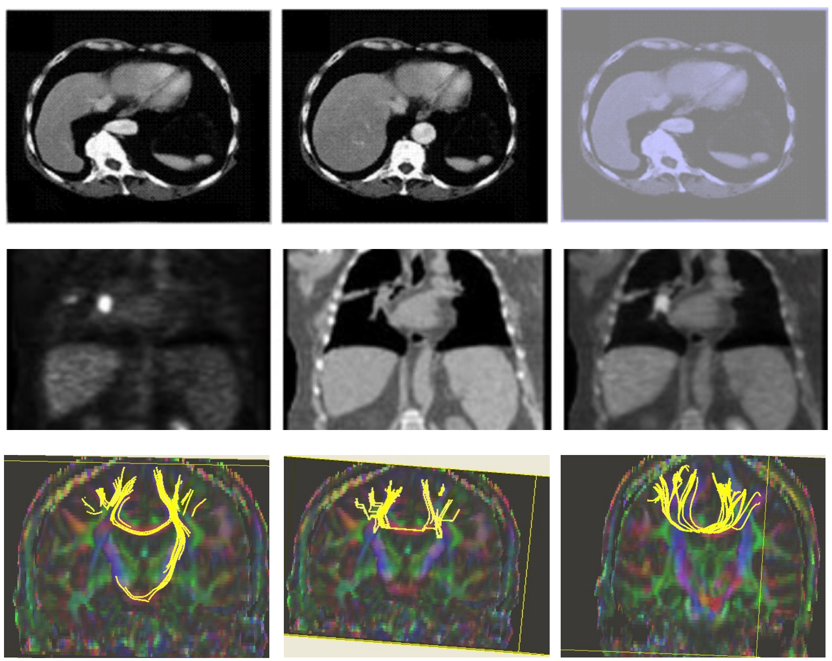
Background

Medical Image Registration

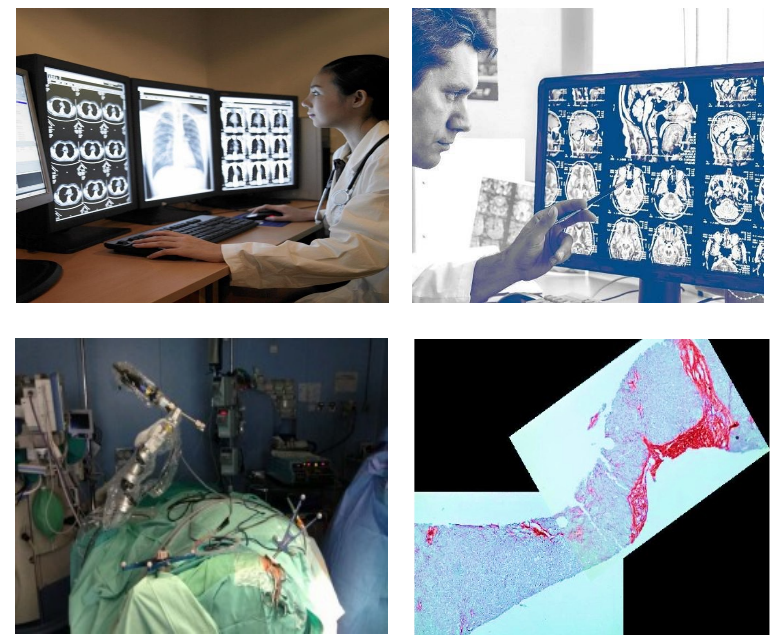
(MIR)

Background

Image Registration



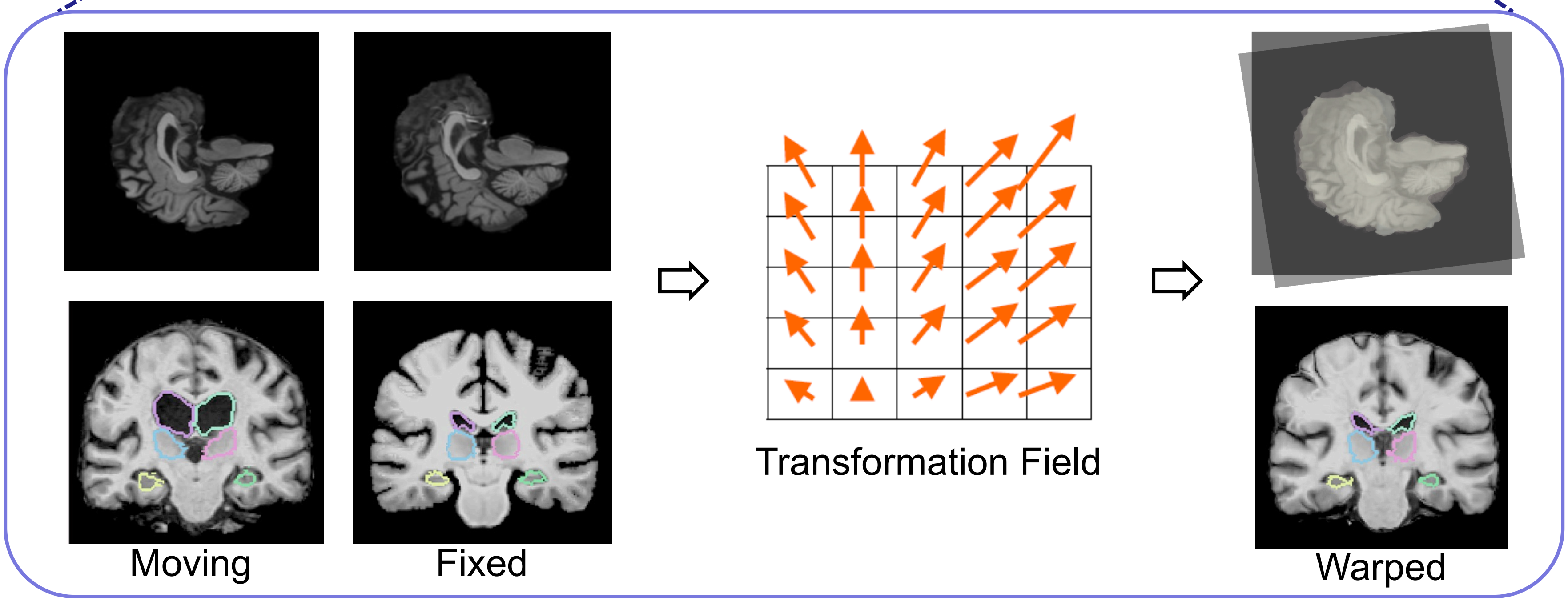
Diagnosis and Surgery



Problem Formulation

- **Objective of deformable registration**

$$\min_{\varphi} \underbrace{E_D\big(\varphi; F, M(\varphi)\big)}_{\text{Data Match}} + \lambda \underbrace{E_R(\varphi)}_{\text{Regularization}}$$

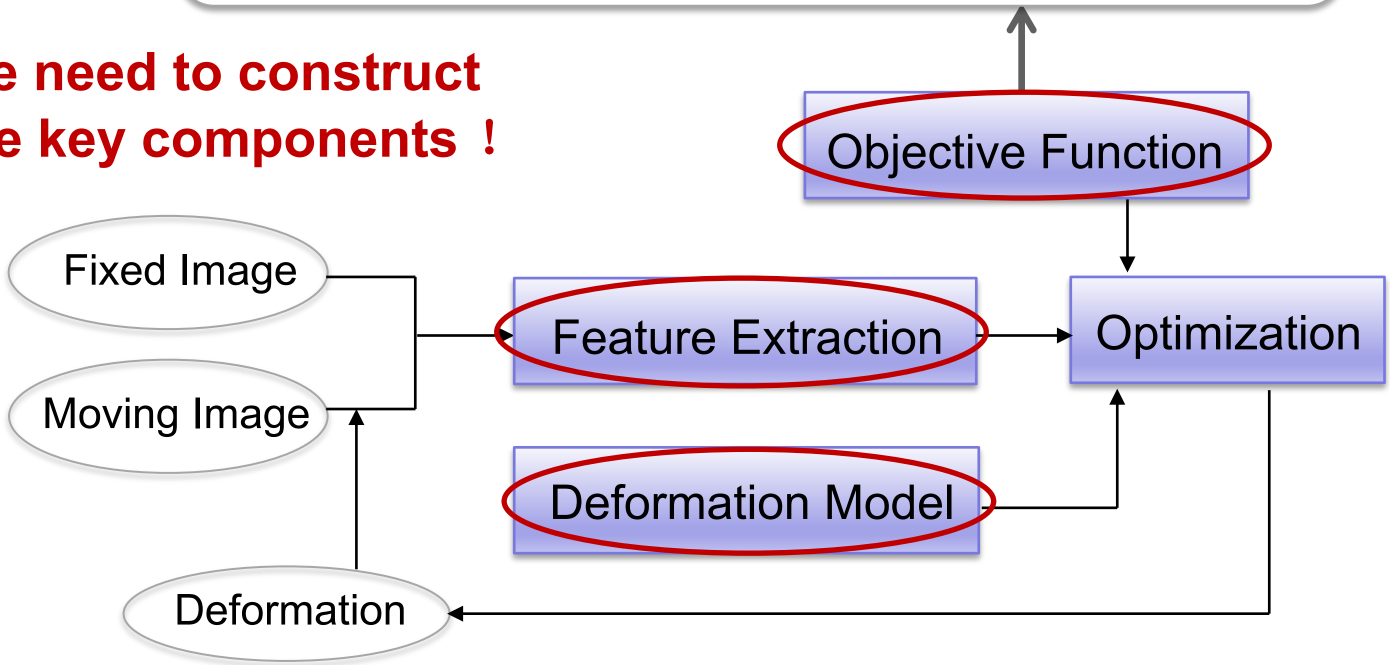


Problem Formulation

- **Objective of deformable registration**

$$\min_{\varphi} \underbrace{E_D\big(\varphi; F, M(\varphi)\big)}_{\textbf{Data Match}} + \lambda \underbrace{E_R(\varphi)}_{\textbf{Regularization}}$$

We need to construct three key components！



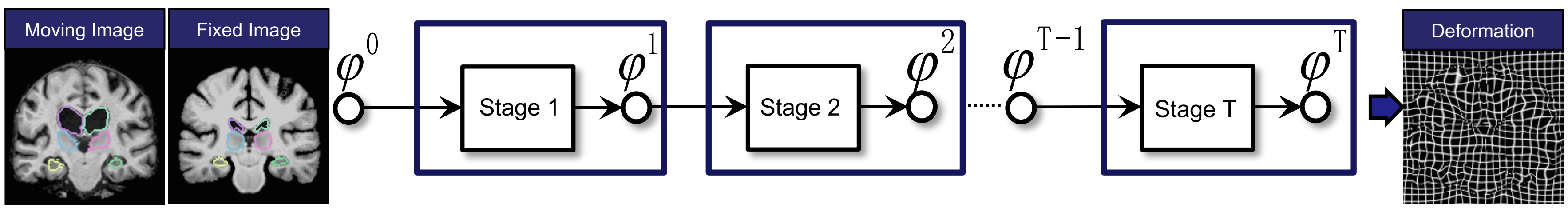
Related Works

■ Optimization based methods

Translate  into

knowledge

$$\min_{\boldsymbol{\varphi}} \underbrace{E_D\big(\boldsymbol{\varphi}; F, M(\boldsymbol{\varphi})\big)}_{\textbf{Data Match}} + \boldsymbol{\lambda} \underbrace{E_R(\boldsymbol{\varphi})}_{\textbf{Regularization}}$$

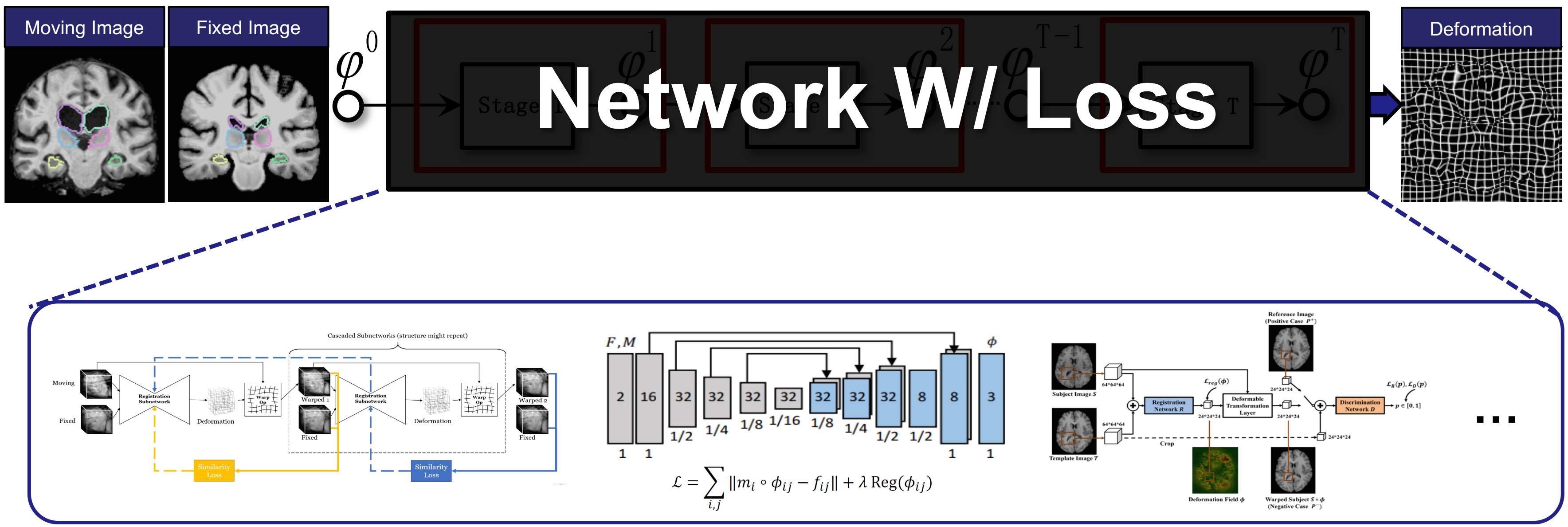


Satisfying accuracy

High computational cost

Related Works

- Deep learning based methods



Fast estimate transformation

Ignore explicit constraints

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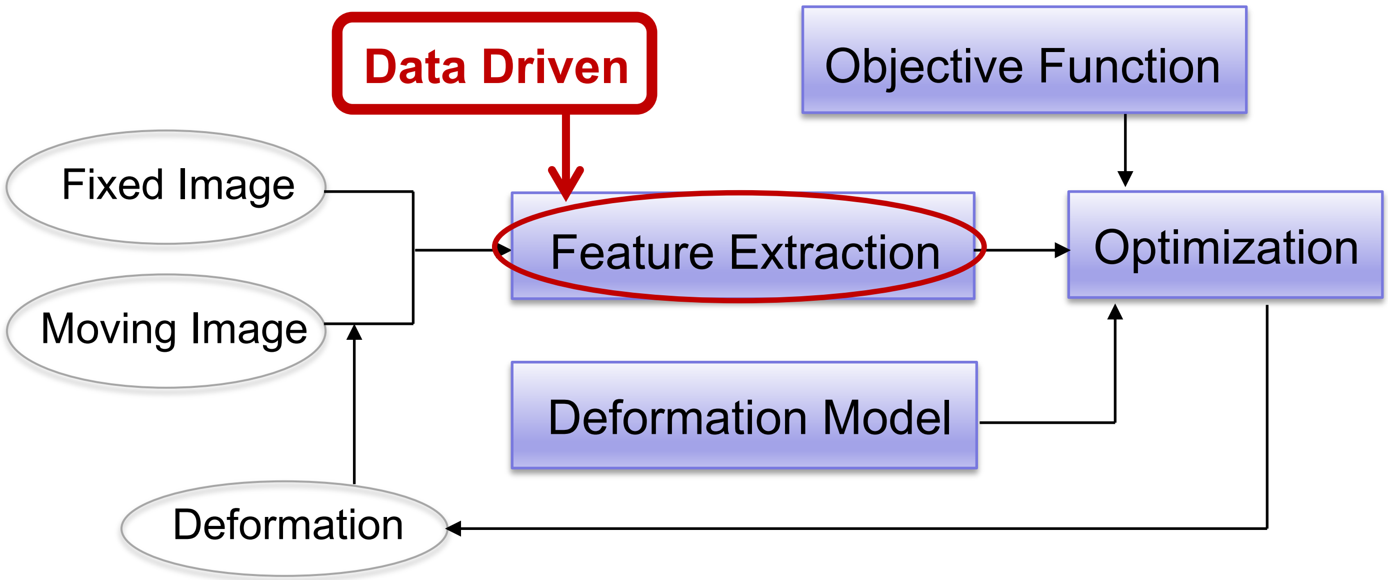


[1] Bi-level probabilistic feature learning for deformable image registration. ***IJCAI. 2020***: 723-730.

Feature Learning for MIR

- **Upper-level:** Optimization of Deformable Registration

  Lower-level: Probabilistic Feature Learning (**constraint**)

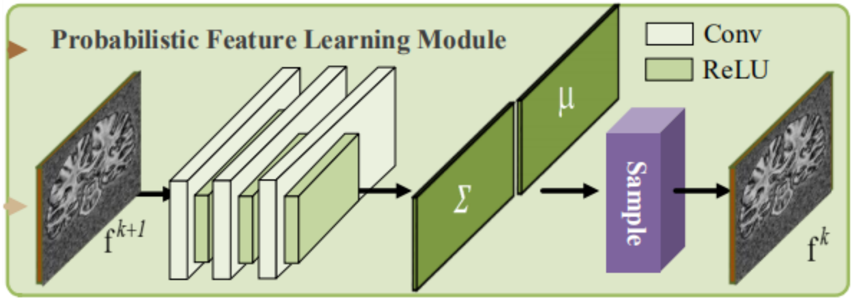
$$\min_{\varphi} E_D(\varphi; f_s, f_t) + E_R(\varphi),$$

$$s.t.\ f_s, f_t = \arg\max_{f_s, f_t}\ p(f_s|I_s, f_t|I_t, \varphi).$$

- **Probabilistic Feature Learning** Module

$$f = \arg\min_f \ln p\,(f|I,\varphi)$$

$$= \arg\min_f \underbrace{\ln p\,(I|f,\varphi)}_{\text{Data Likelihood}} + \underbrace{\ln p\,(f)}_{\text{Prior}}$$



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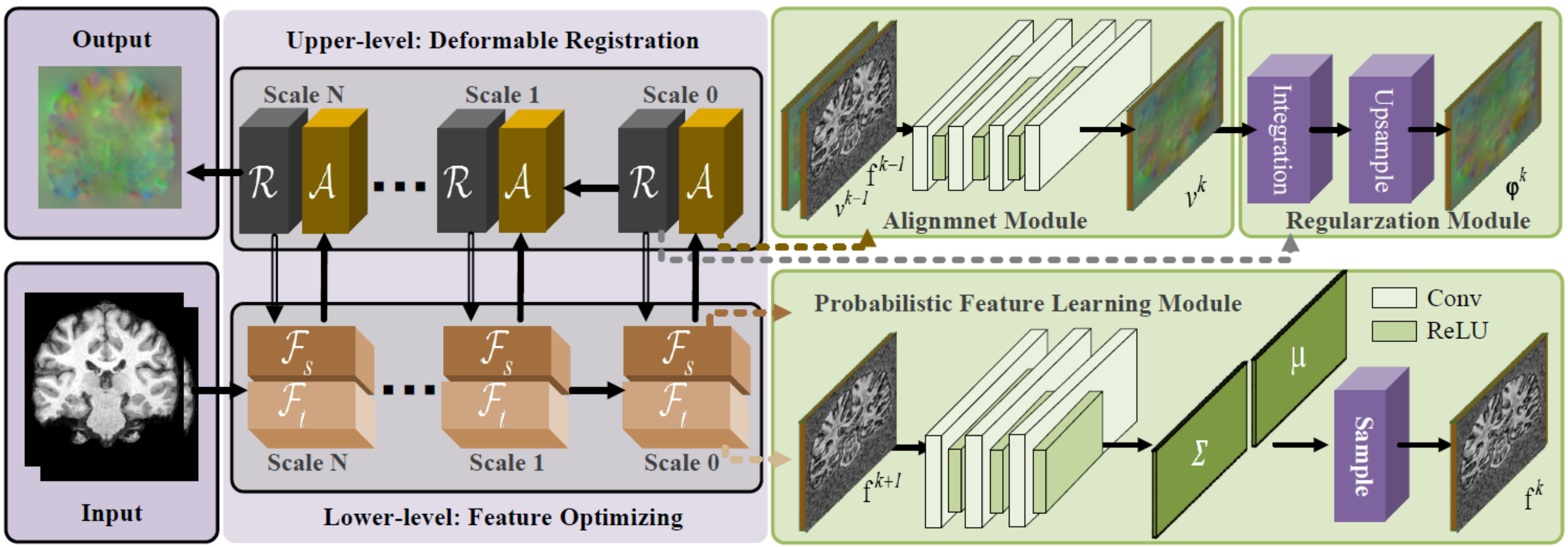
Feature Learning for MIR

- **Our Paradigm**



Loss Function

Feature space: $l_{KL}(\mu, \Sigma) = 1/2\big(tr(\Sigma) + \big||\mu|\big| - log\,det(\Sigma) - m\big)$

Image space: $l(I_s, I_t; \varphi) = l_{NCC}(I_s \circ \varphi, I_t) + l_{smooth}(\varphi).$

[1] Bi-level probabilistic feature learning for deformable image registration. ***IJCAI. 2020***: 723-730.

Feature Learning for MIR

- **Quantitative comparison**

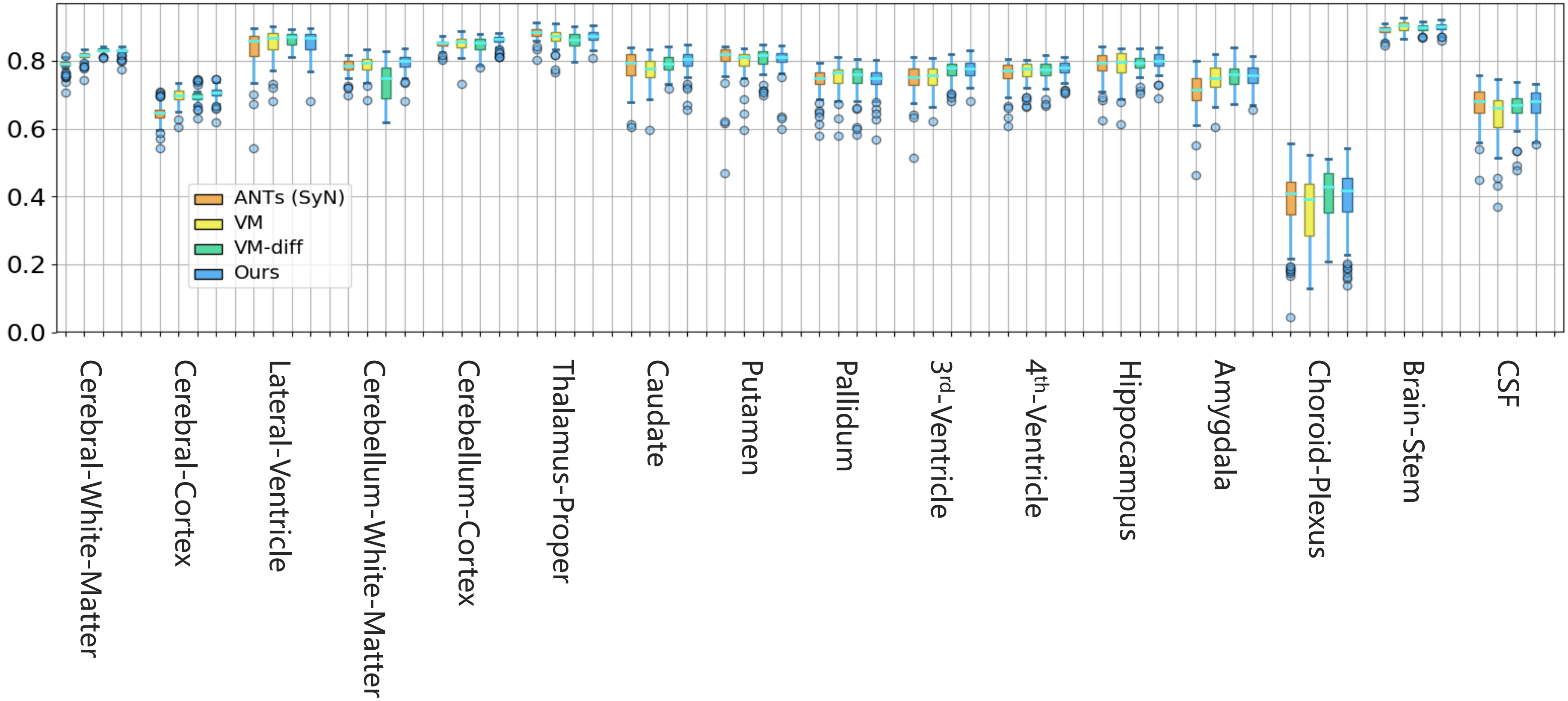
Dice score	Elastix[1]	NiftyReg[2]	ANTs[3]	VM[4]	VM-diff[5]	Ours
OASIS	0.709	0.748	0.765	0.765	0.757	**0.777**
ABIDE	0.699	0.747	0.728	0.754	**0.773**	0.764
ADNI	0.697	0.737	0.761	0.761	0.768	**0.773**
PPMI	0.730	0.765	0.778	0.775	0.781	**0.787**

Runtime (s)	Elastix	NiftyReg	ANTs	VM	VM-diff	Ours
Img-to-Atlas	90	486	4529	0.615	0.512	**0.351**

[1] Elastix: A toolbox for intensity-based medical image registration.
[2] Free-form deformation using lower-order B-spline for nonrigid image registration.
[3] A reproducible evaluation of ants similarity metric performance in brain image registration.
[4] Voxelmorph: A learning framework for deformable medical image registration.
[5] Unsupervised learning of probabilistic diffeomorphic registration for images and surfaces.

Feature Learning for MIR

◆ Visualizations of Dice score



[1] Bi-level probabilistic feature learning for deformable image registration. ***IJCAI. 2020***: 723-730.

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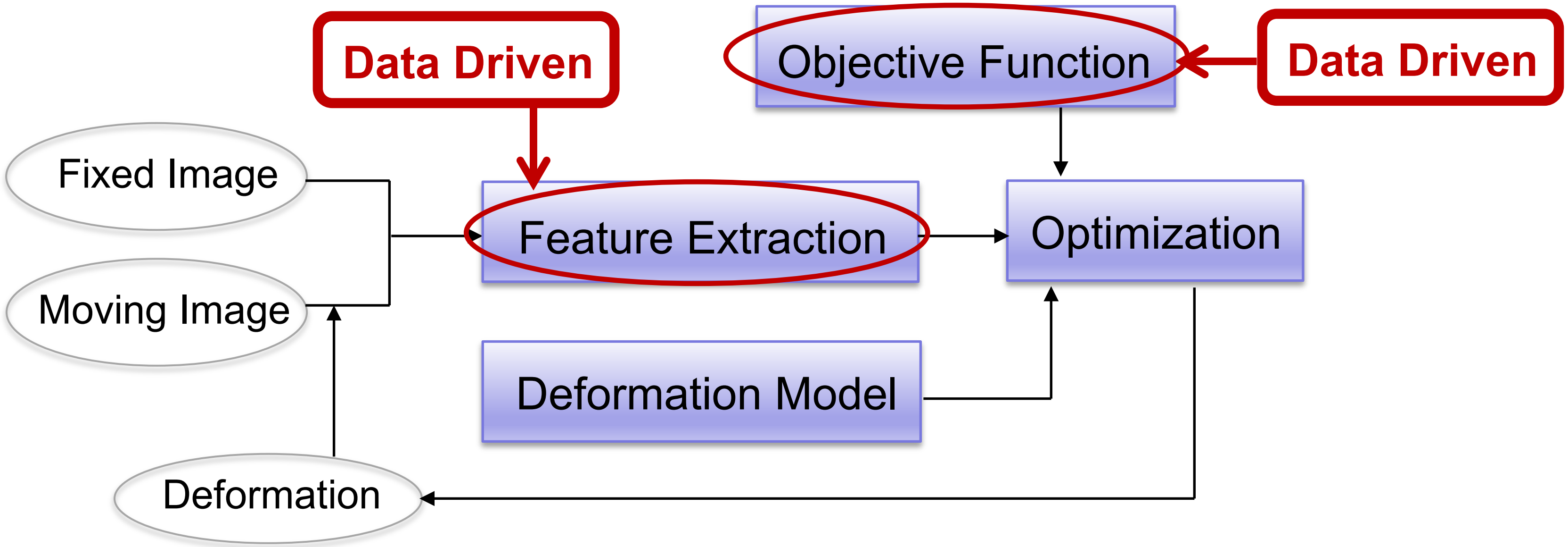


[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

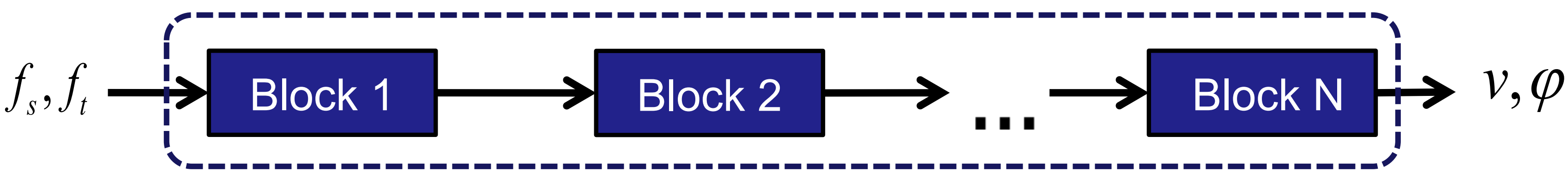
Optimization Learning for MIR

- **Fundamental Optimization Formulation of Diffeomorphic Deformable Registration**

$$\min_{v} \ \overbrace{Mat(\varphi \circ s, t)}^{\text{Data Match}} + \lambda \overbrace{Reg(v)}^{\text{Regularization}},$$

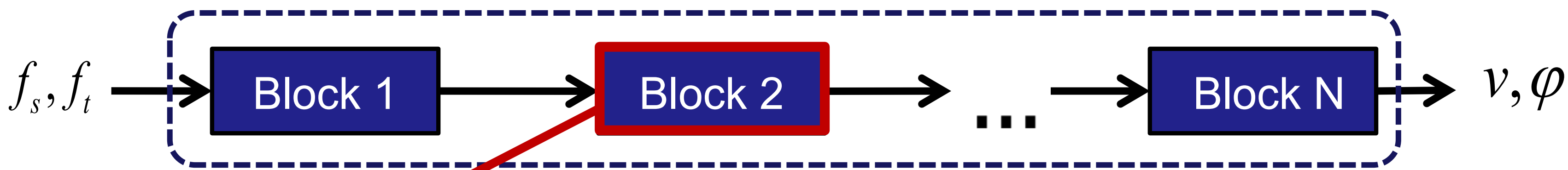
$$\underbrace{s.t.\ \frac{\partial \phi(t)}{\partial t} = v(\phi(t)),\ \phi(0) = Id,\ \varphi = \phi(1).}_{\text{Constraint}}$$

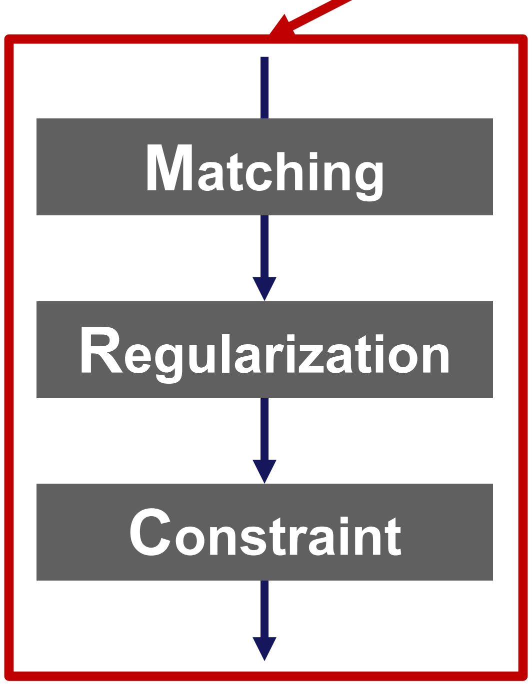
- **Deep Propagation on *Feature Space in Sec.2***



[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

Optimization Learning for MIR





- Error-Based Data **Matching** Module

$$u^{k+1} = \mathcal{M}\left(\varphi^{k}, f_s^{k+1}, f_t^{k+1}, e^{k+1};\ w_{\mathcal{M}^{k+1}}\right),$$

- Context-based **Regularization** Module

$$v^{k+1} = \mathcal{R}\left(u^{k+1};\ w_{\mathcal{R}^{k+1}}\right),$$

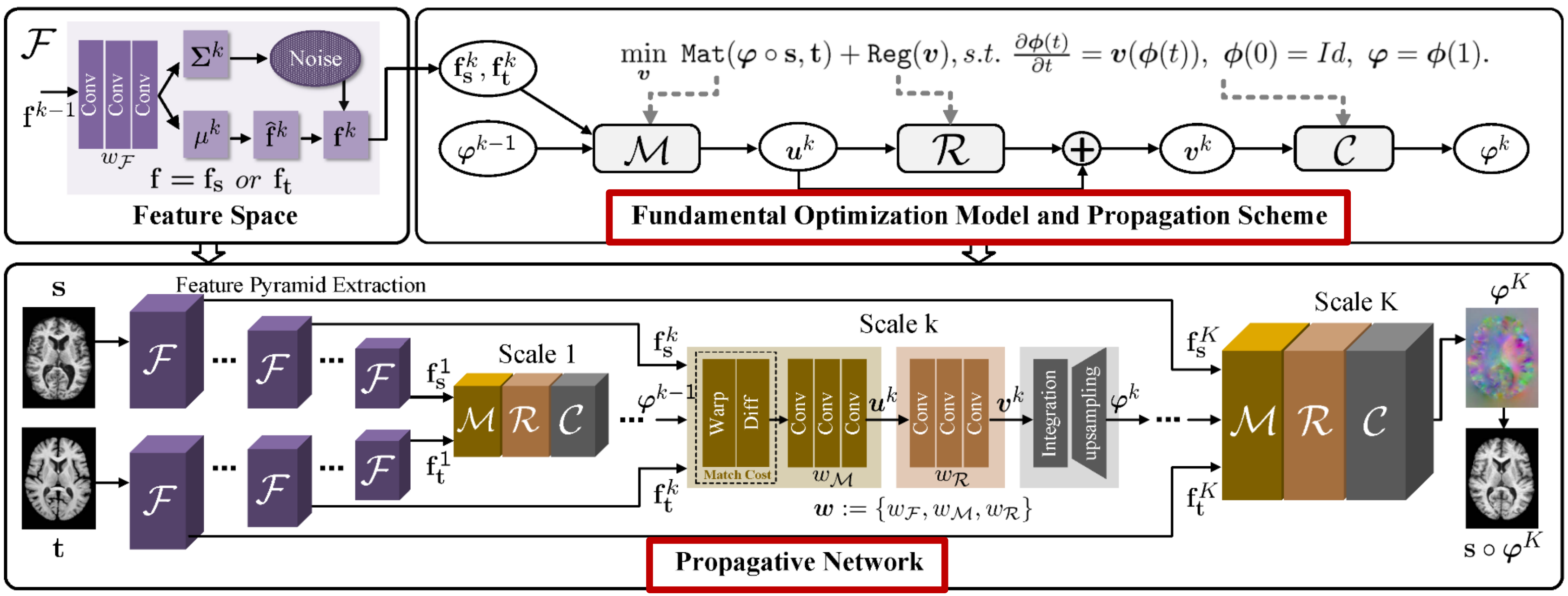
- **Constraint** Module

$$\varphi^{k+1} = \mathcal{C}\left(v^{k+1};\ w_{\mathcal{C}}\right).$$

[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

Optimization Learning for MIR

- **Learning Registration from Optimization on *Feature Space* in *Sec.2***



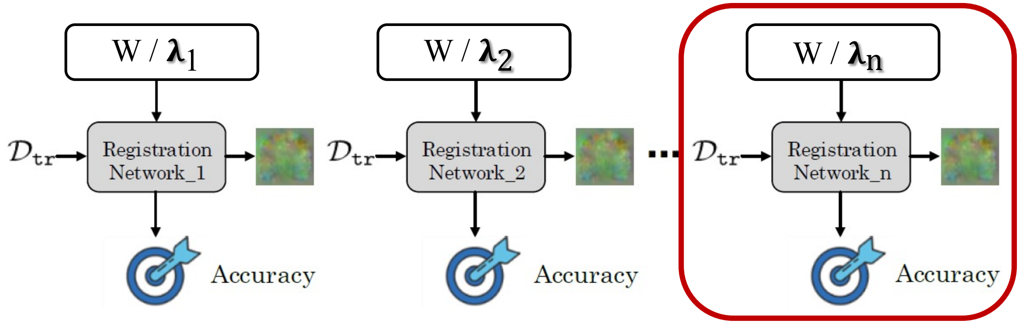
Objective

$$l(w(\lambda), s_i, t_i) = \sum_{0}^{K} \lambda_{sta}^{k} \left(l_{KL}(\mu^k, \Sigma^k) + \lambda_{mat} l_{mat}(s_i \circ \varphi^k, t_i) + \lambda_{reg} l_{reg}(v^k) \right)$$

[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

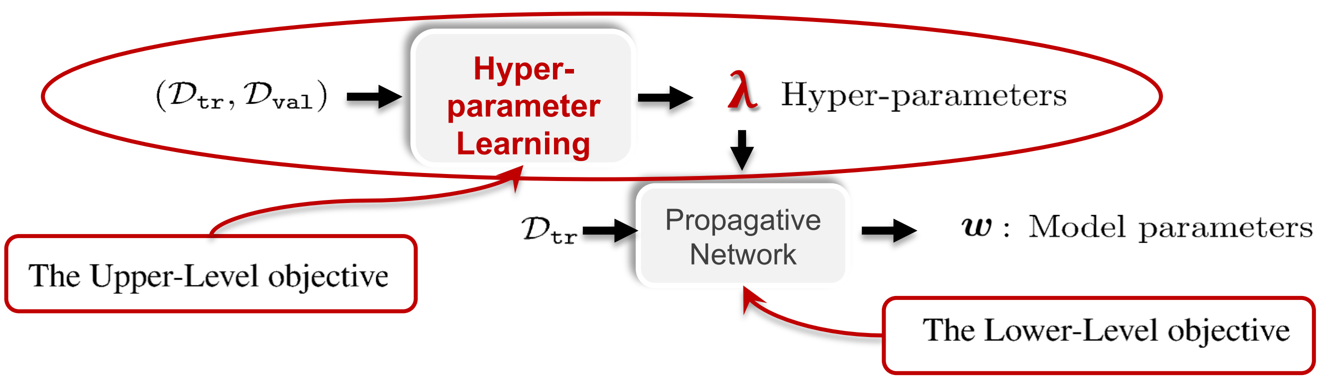
Optimization Learning for MIR

- **Conventional Objective Choosing through *Many Training Runs***



One run costs hours to 1-2 days on a single GPU

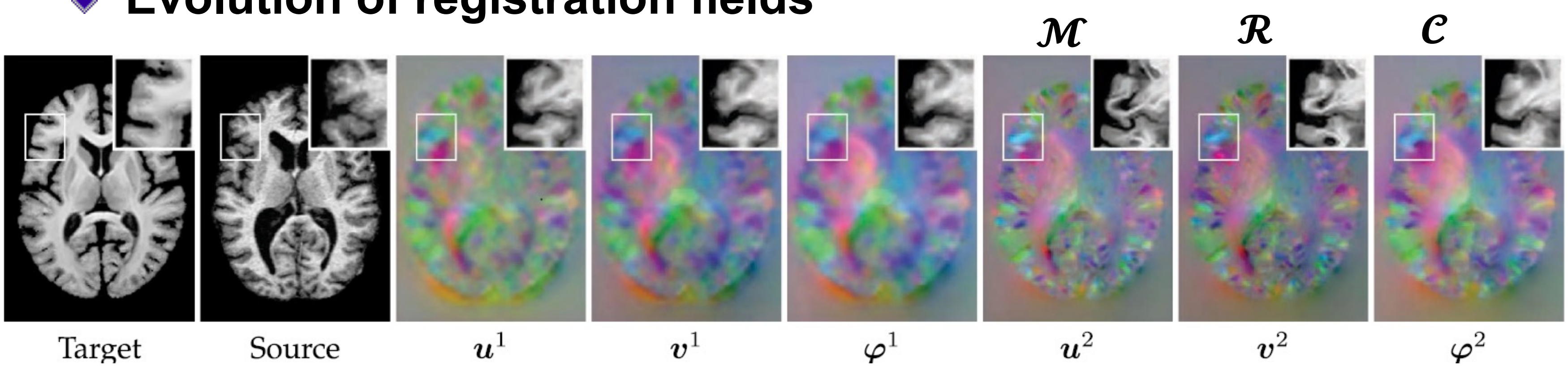
- **Bilevel Self-tuned Training for λ**



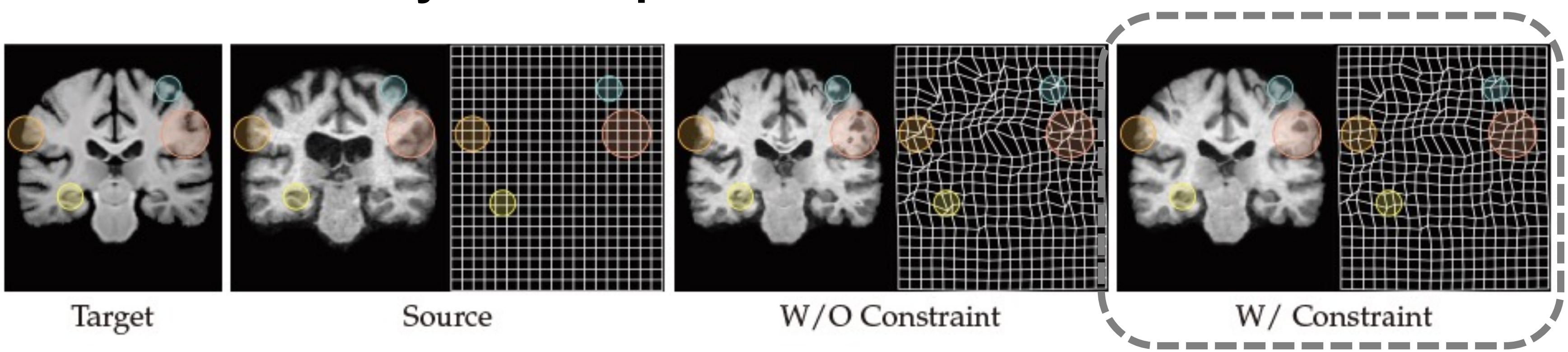
[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

Optimization Learning for MIR

- Evolution of registration fields



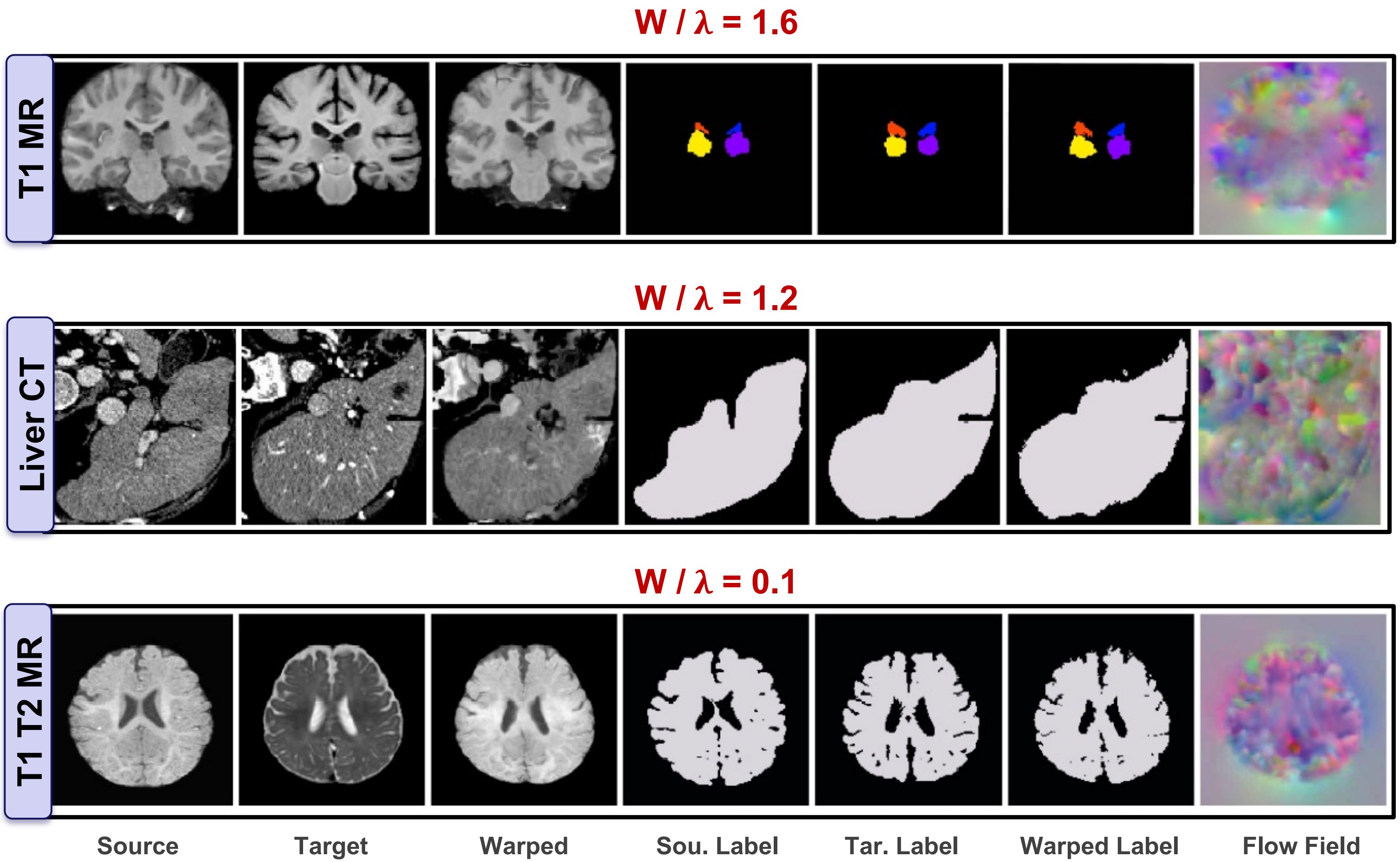
- Ablation analysis of explicit constraints



[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

Optimization Learning for MIR

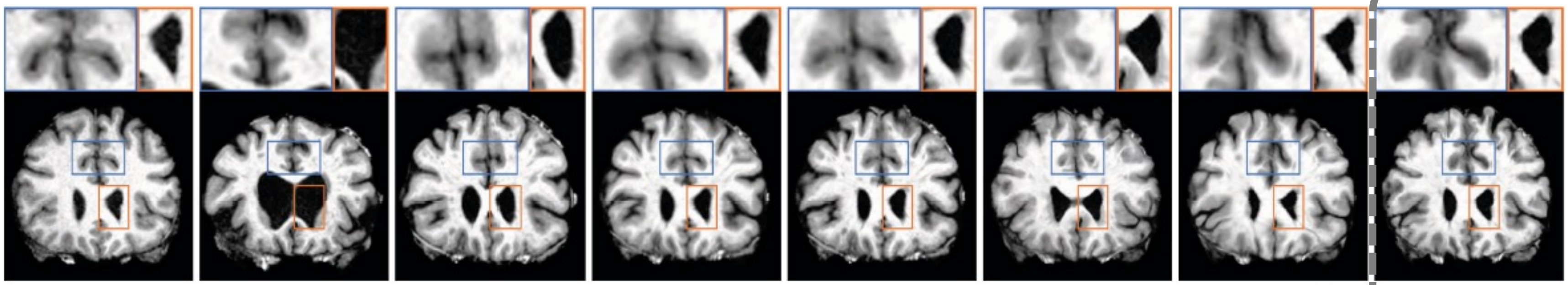
- Searched hyperparameters for three tasks



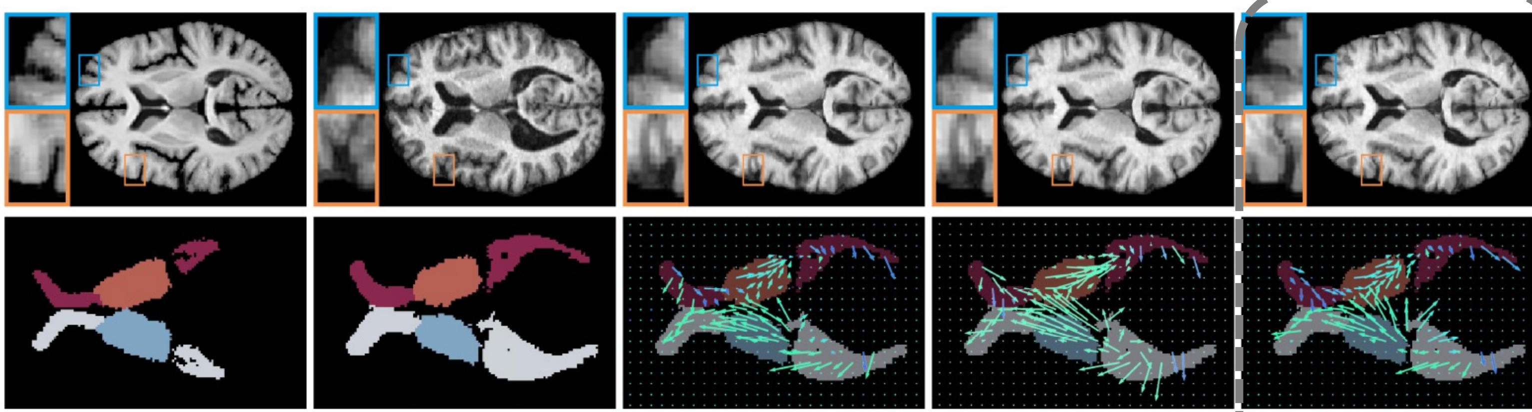
[2] Learning deformable image registration from optimization: perspective, modules, bilevel training and beyond. ***IEEE TPAMI. 2021.***

Optimization Learning for MIR

- **Qualitative comparisons**



Target (1.0) | Source (0.442) | Elastix (0.658) | SyN (0.729) | NiftyReg (0.729) | VM (0.662) | VM-diff (0.720) | Ours (**0.740**)



Target (1.0) | Source (0.596) | VM (0.850) | VM-diff (0.848) | Ours (**0.856**)

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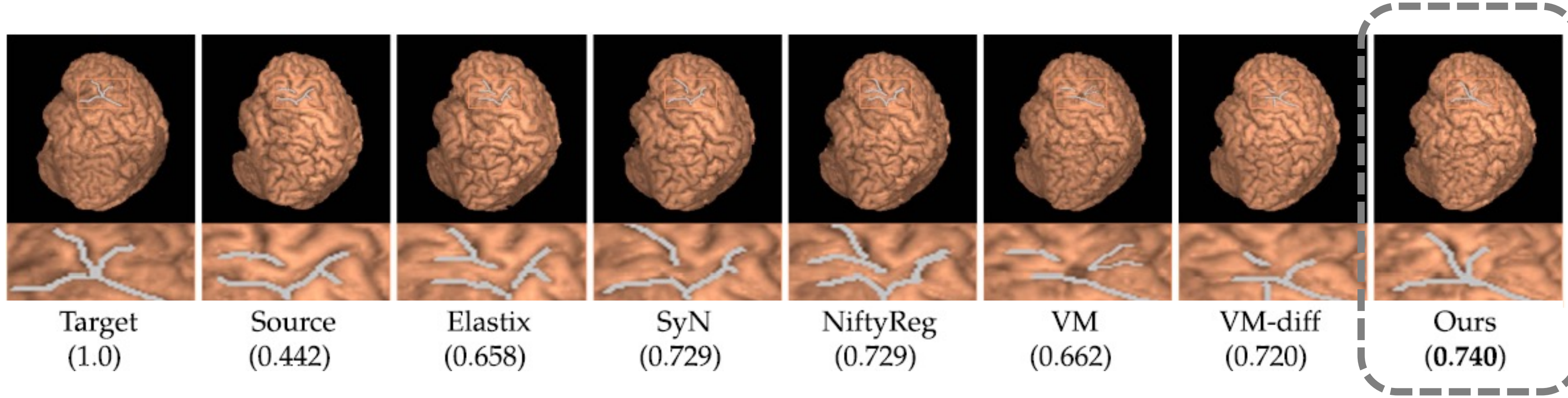
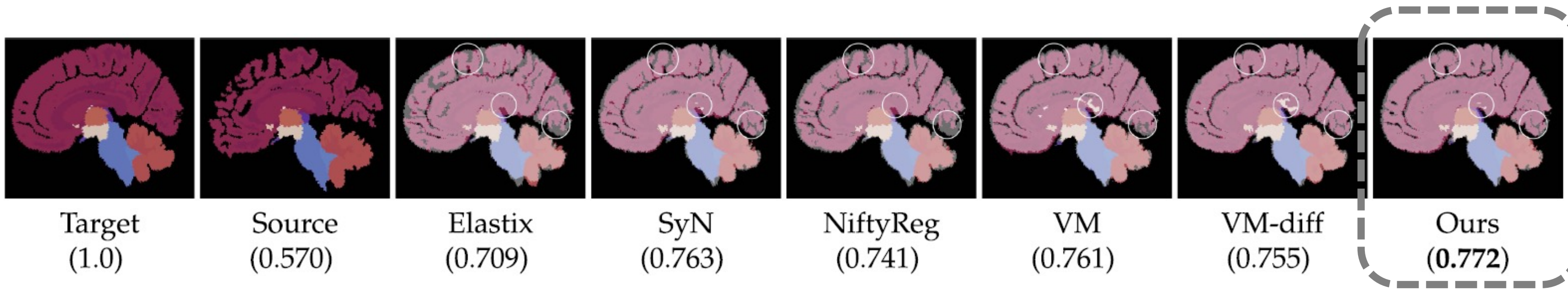
Optimization Learning for MIR

- **Qualitative comparisons**





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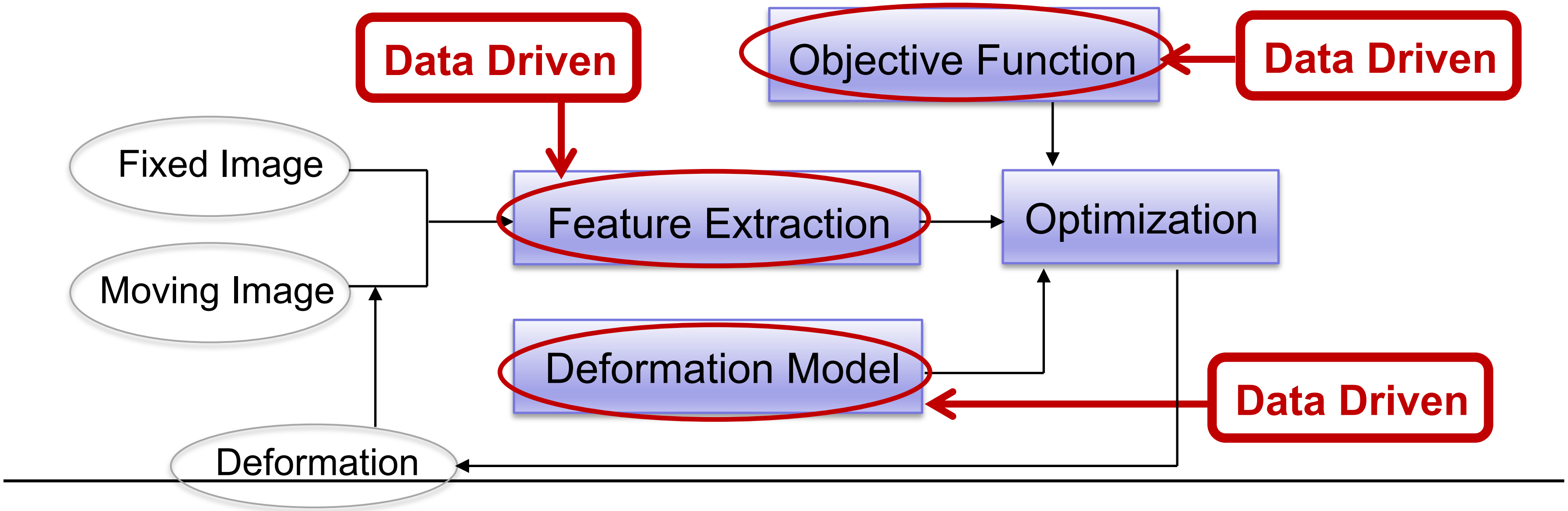
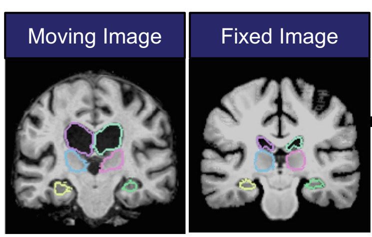
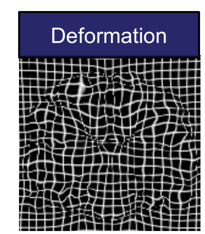




- ✓ **No Rely on Expertise**
- ✓ **Low Validation Costs**



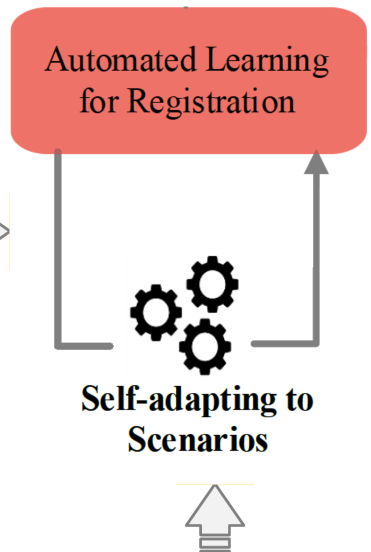
[3] Automated Learning for Deformable Medical Image Registration by Jointly Optimizing Network Architectures and Objective Functions. ***arXiv preprint*** arXiv:2203.06810, ***2022.***

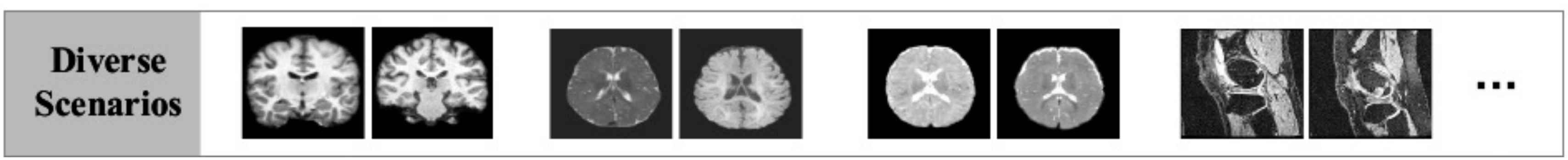
Automated Learning for MIR

- **Triple-level Optimization for AutoReg**

$$\min_{\lambda} \mathcal{L}_{val}^{seg}(\lambda, \alpha^*, \omega^*; s, t),$$

$$s.t. \begin{cases} \boldsymbol{\alpha}^*(\lambda) = \arg\min_{\alpha} \mathcal{L}_{val}^{reg}(\alpha, \omega^*(\alpha); \lambda, s, t), \\ s.t.\ \boldsymbol{\omega}^*(\alpha) = \arg\min_{\omega} \mathcal{L}_{tr}^{reg}(\omega; \alpha, \lambda, s, t). \end{cases}$$





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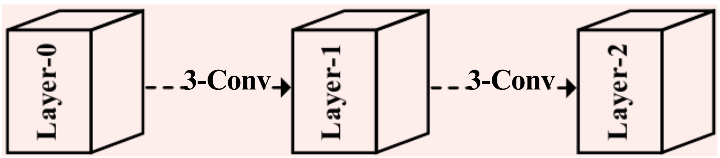
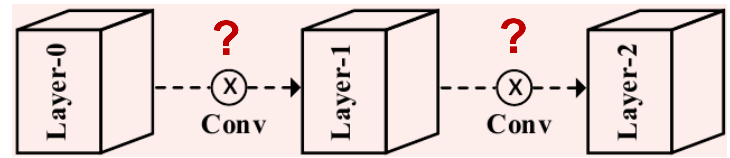
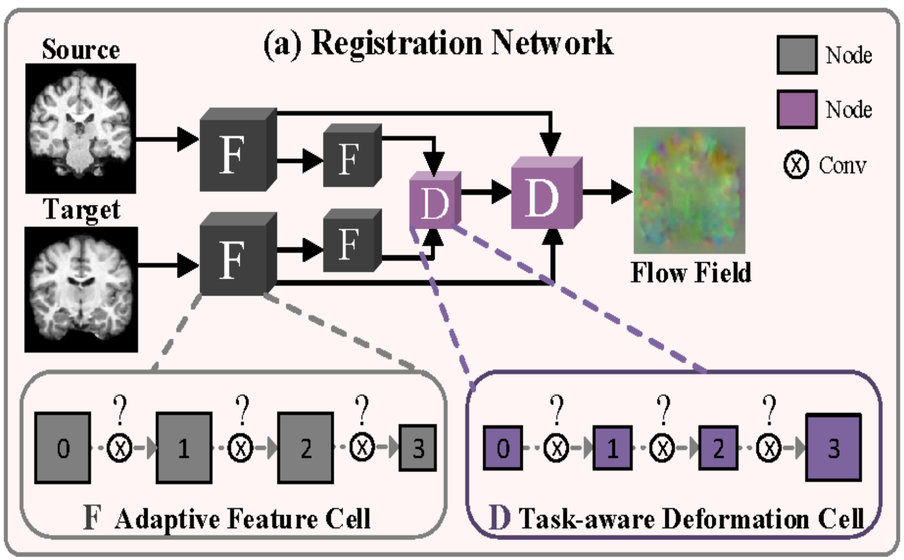
Automated Learning for MIR

- **Architecture Search: From Hand-design to Search**

From 

to 



Search Space

- 1×1×1 Conv (1-Conv)
- 3×3×3 Conv (3-Conv)
- 5×5×5 Conv (5-Conv)
- 3×3×3 Separable Conv (3-SConv)
- 5×5×5 Separable Conv (5-SConv)
- 3×3×3 Dilation Conv (3-DConv)
- 5×5×5 Dilation Conv (5-DConv)
- 7×7×7 Dilation Conv (7-DConv)

[3] Automated Learning for Deformable Medical Image Registration by Jointly Optimizing Network Architectures and Objective Functions. ***arXiv preprint*** arXiv:2203.06810, ***2022.***

Automated Learning for MIR

- **Optimality verification across registration tasks**

Method	Brain T1-to-T1	Brain T2-to-T2	Knee T1-to-T1	Brain T2-to-T1
All-1-Conv	0.700 (0.035)	0.610 (0.009)	0.395 (0.110)	0.579 (0.005)
All-3-Conv	0.769 (0.025)	0.636 (0.010)	0.605 (0.131)	0.617 (0.006)
All-7-Conv	0.761 (0.025)	0.610 (0.009)	0.614 (0.091)	0.613 (0.007)
AutoReg	**0.778 (0.023)**	**0.646 (0.010)**	**0.616 (0.150)**	**0.622 (0.007)**

- **Computation cost**

Strategy	AutoReg + Training	Manual + Training
Runtime	48 + 23 hour	23 * n + 23 hour

Typically set larger than 10

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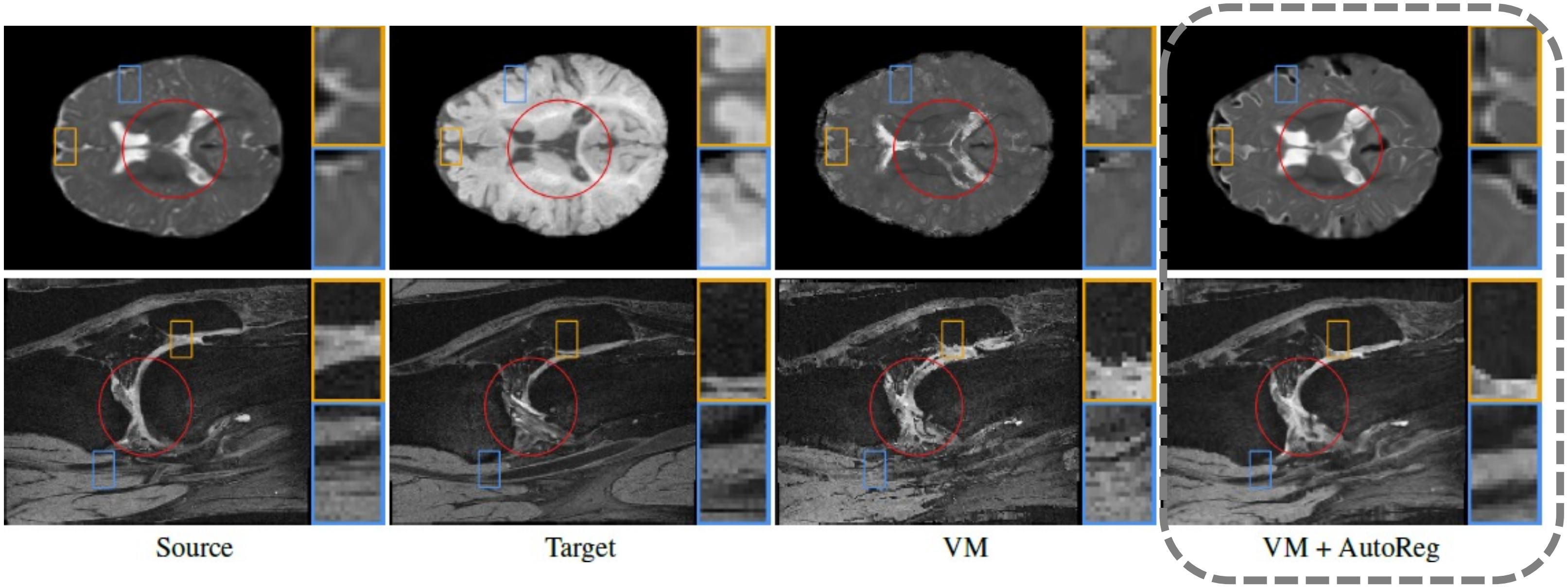
Automated Learning for MIR

◆ **Generalizability analysis**

Method	Brain T1-to-T1	Brain T2-to-T2	Knee T1-to-T1	Brain T2-to-T1
VM	0.757 (0.035)	0.638 (0.012)	0.440 (0.132)	0.579 (0.013)
VM + AutoReg	**0.761 (0.010)**	**0.640 (0.013)**	**0.482 (0.151)**	**0.596 (0.006)**



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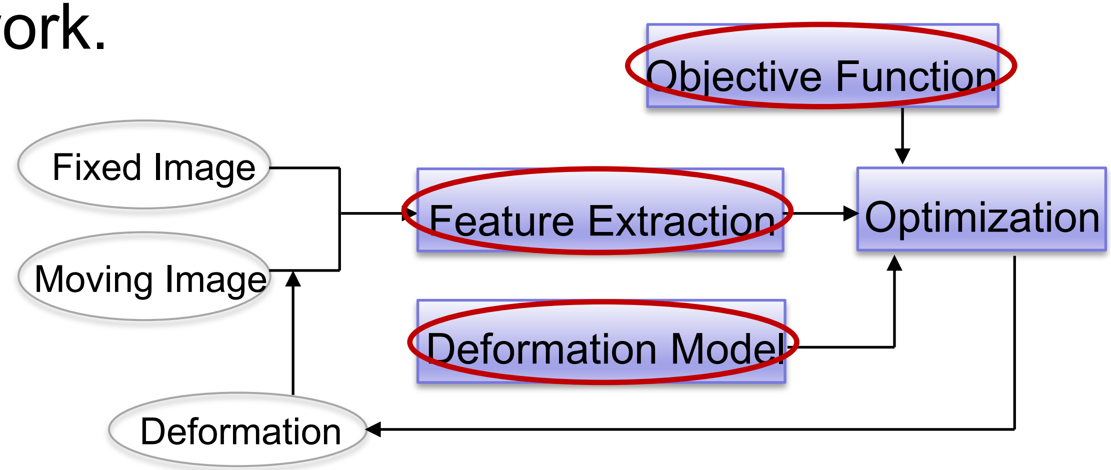
Summary

- Integrates **deep learning** with **bilevel optimization** and proposes algorithms from **three aspects** of registration framework.



- **Feature learning-based** bi-level optimization model
- Novel similarity measurement, bilevel **self-tuned loss function**
- Automated optimization of the **loss function** and **architecture** of feature/deformation learning modules

Future Work

☐ Auto Learning for Registration

$$
\min_{\lambda} \mathcal{L}_{val}^{seg}(\lambda, \alpha^*, \omega^*; s, t),
$$

$$
s.t. \begin{cases} \boldsymbol{\alpha}^*(\lambda) = \arg\min_{\alpha} \mathcal{L}_{val}^{reg}(\alpha, \omega^*(\alpha); \lambda, s, t), \\ s.t.\ \boldsymbol{\omega}^*(\alpha) = \arg\min_{\omega} \mathcal{L}_{tr}^{reg}(\omega; \alpha, \lambda, s, t). \end{cases}
$$

Cover other architectural hyperparameters

- network topology that controls the connections among cells
- number of layers and resolution levels
- …

Acknowledgment

- **Natural Science Foundation of China**
- **Faculty members**
  - **Xin Fan**——Professor, Dalian University of Technology
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  - **Huang Hao**——Professor, University of Pennsylvania
- **Students**
  - **Yuxi Zhang**——Dalian University of Technology
  - **Ziyang Li**——Dalian University of Technology

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Thanks !