TEMPO: Fast Mask Topography Effect Modeling with Deep Learning

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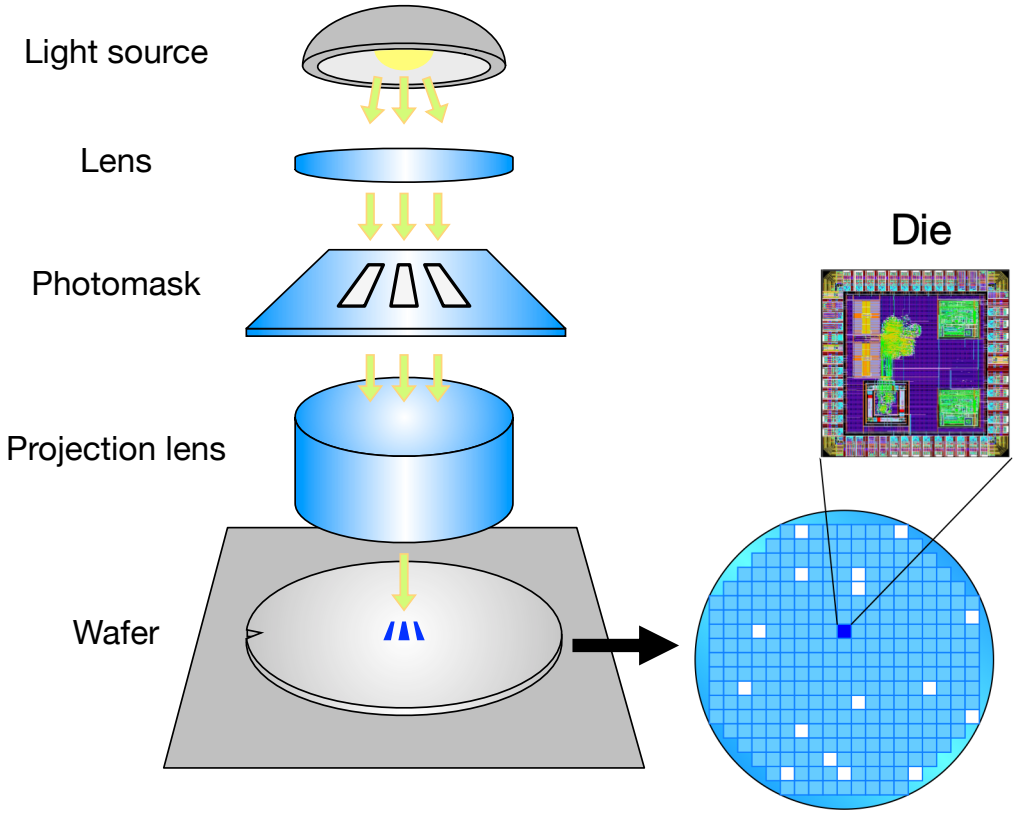
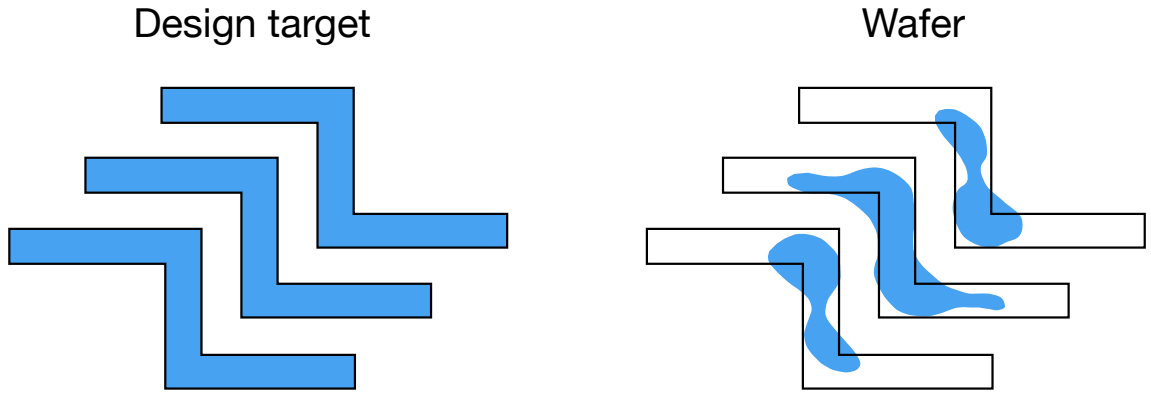
Bottleneck in IC Manufacturing: Lithography

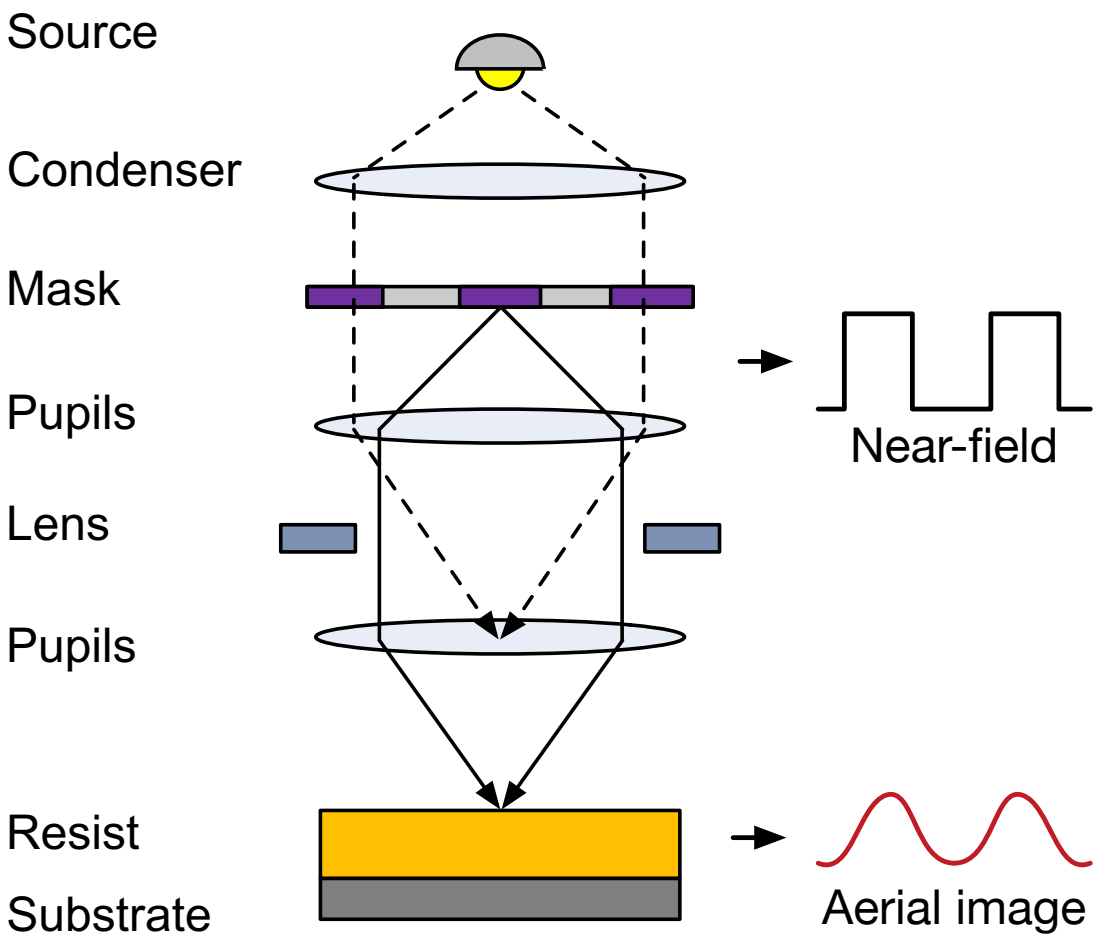
- Moore's law brings increasing manufacturing cost and challenges
- Need to make sure design is manufacturable with high yield



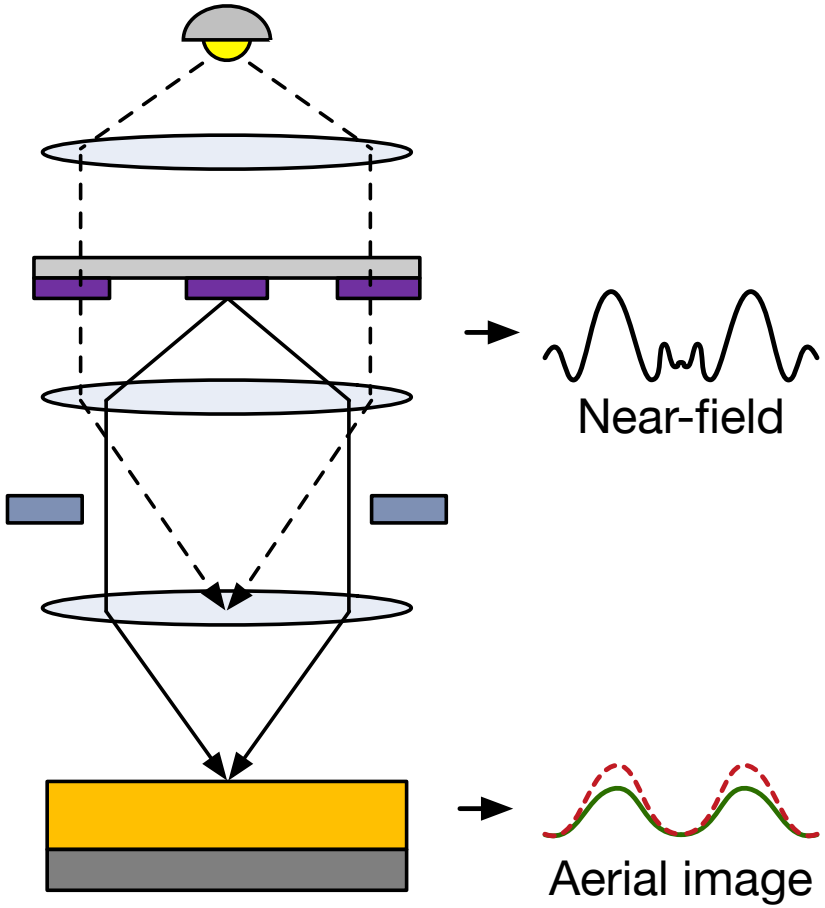


What you see (at design) ≠ what you get (at fab)

Mask Topography Effects in Advanced Lithography

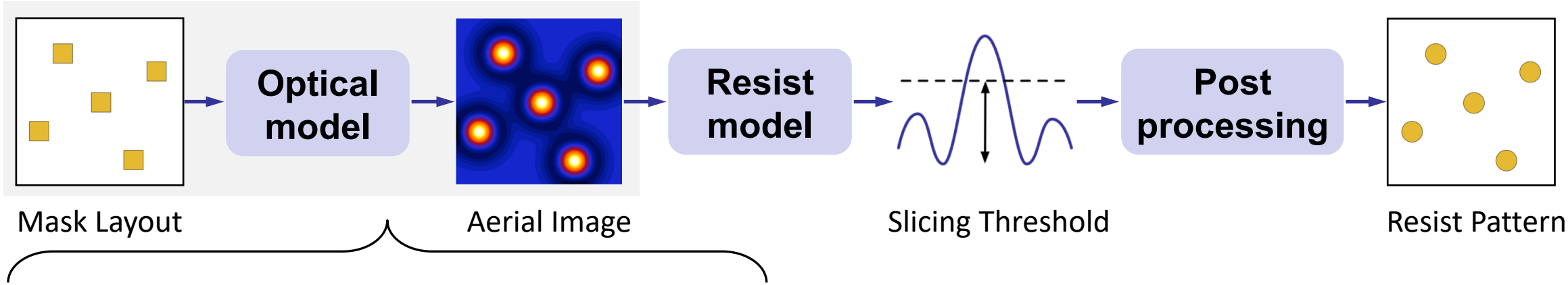


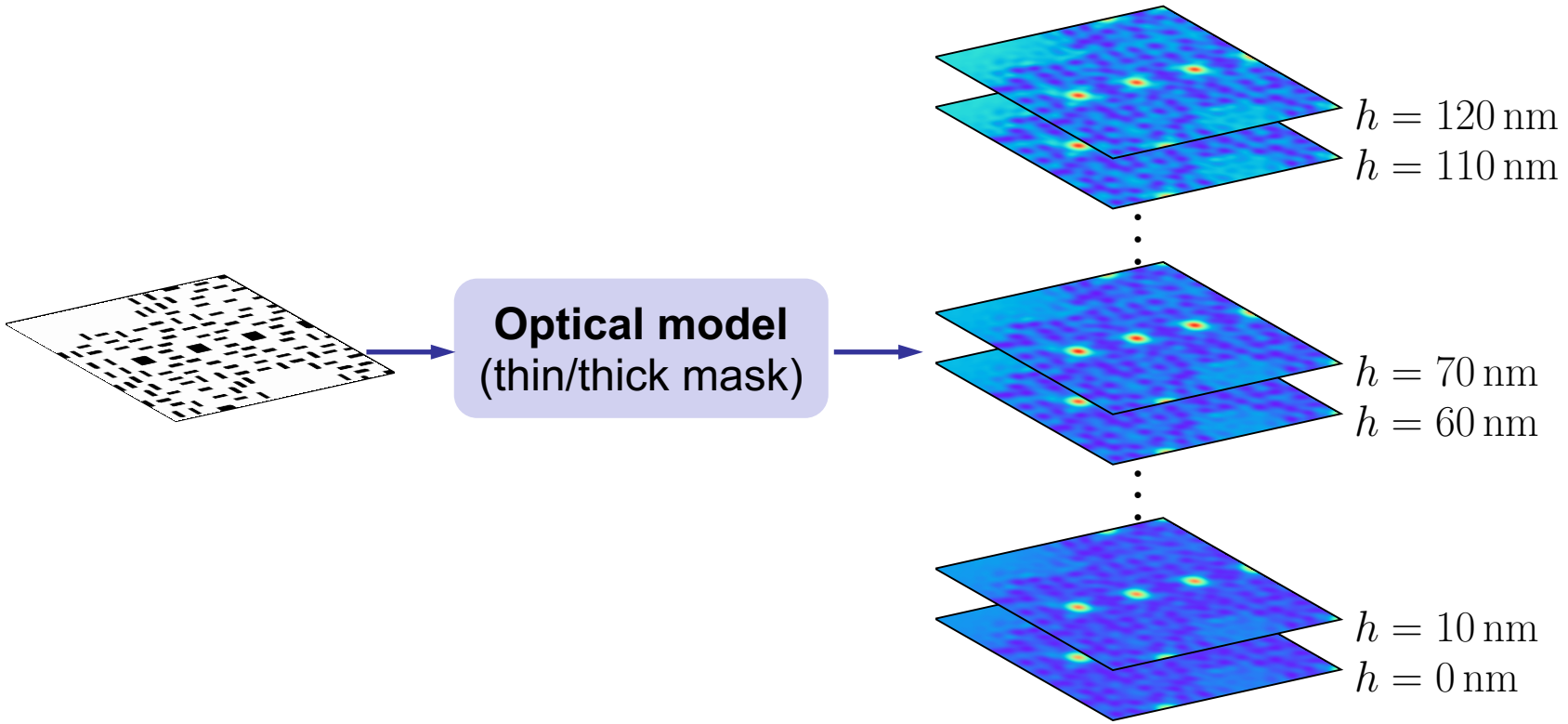
Thin mask approximation (Kirchhoff)

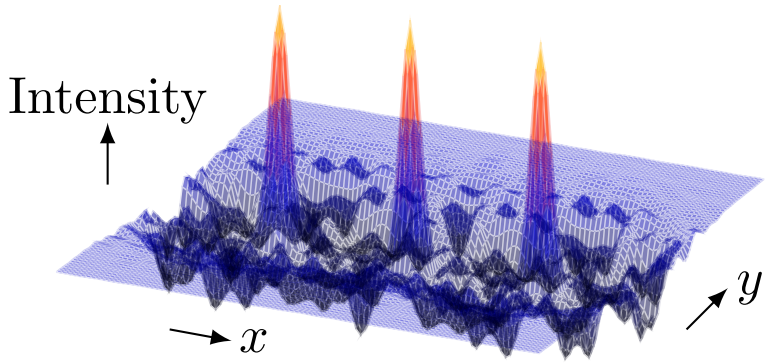


Thick mask approximation

Aerial Image Generation

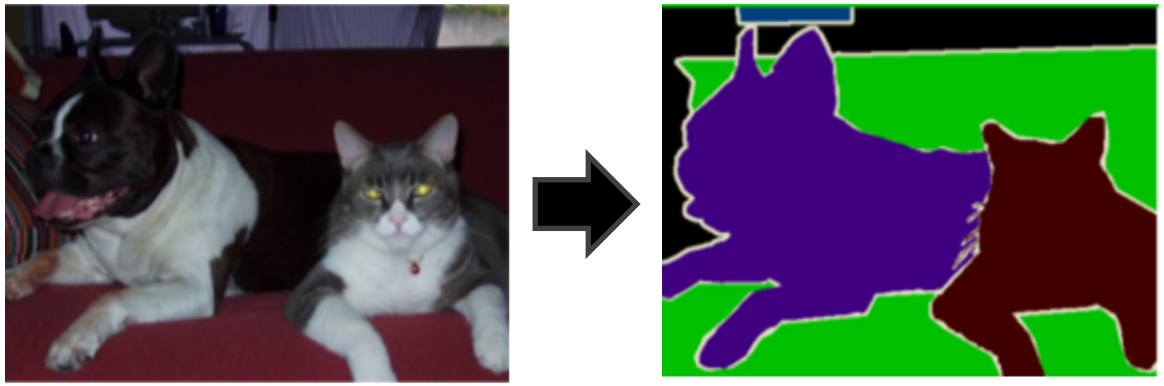






2D aerial image at certain resist height

Image-to-Image Translation Problems



Semantic labeling [Long et al. 15']

Boundary detection [Xie and Tu. 15']

Computer Vision &
Machine Learning

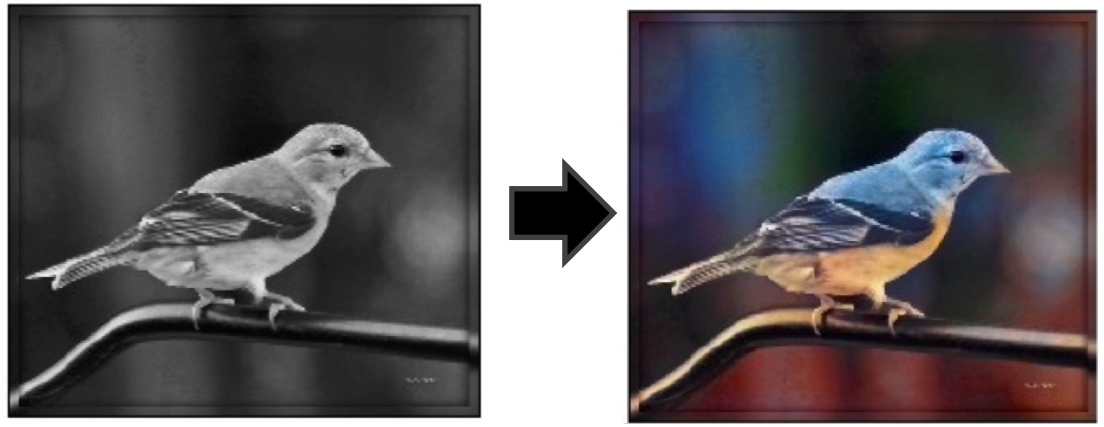
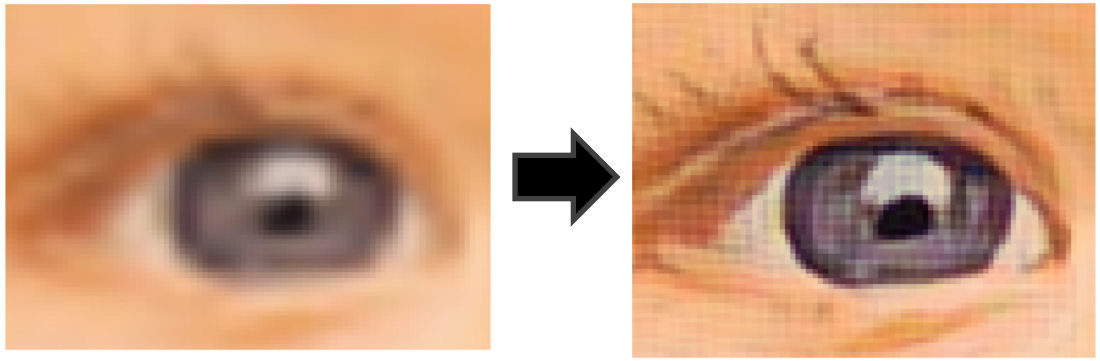


Image colorization [Zhang et al. 16']

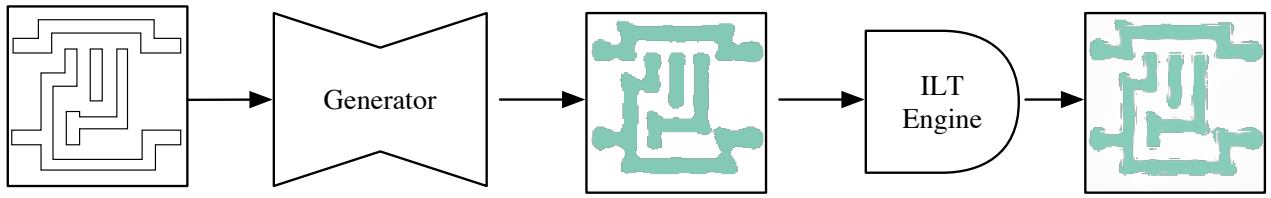


Super-resolution [Johnson et al. 16']

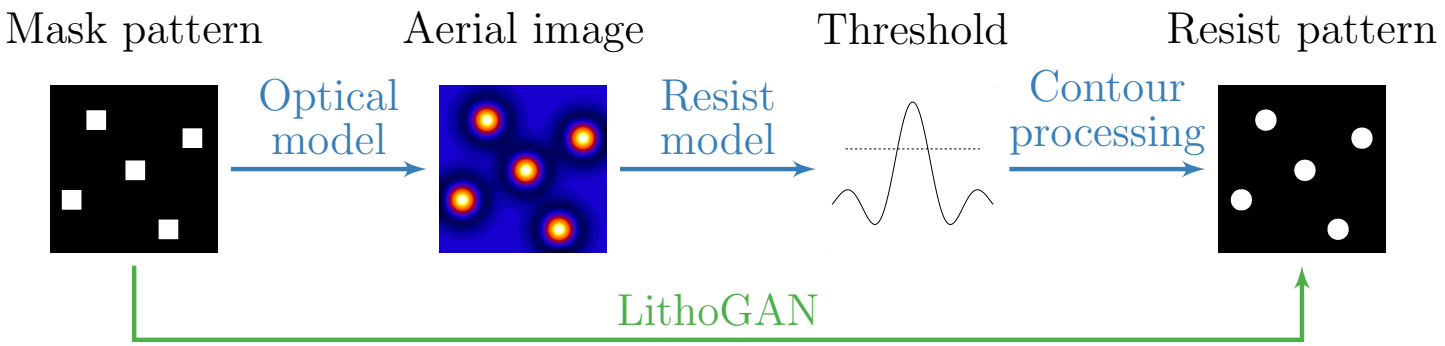
Computer Graphics &
Computational Photography

["On Image-to-Image Translation", Jun-Yan Zhu]

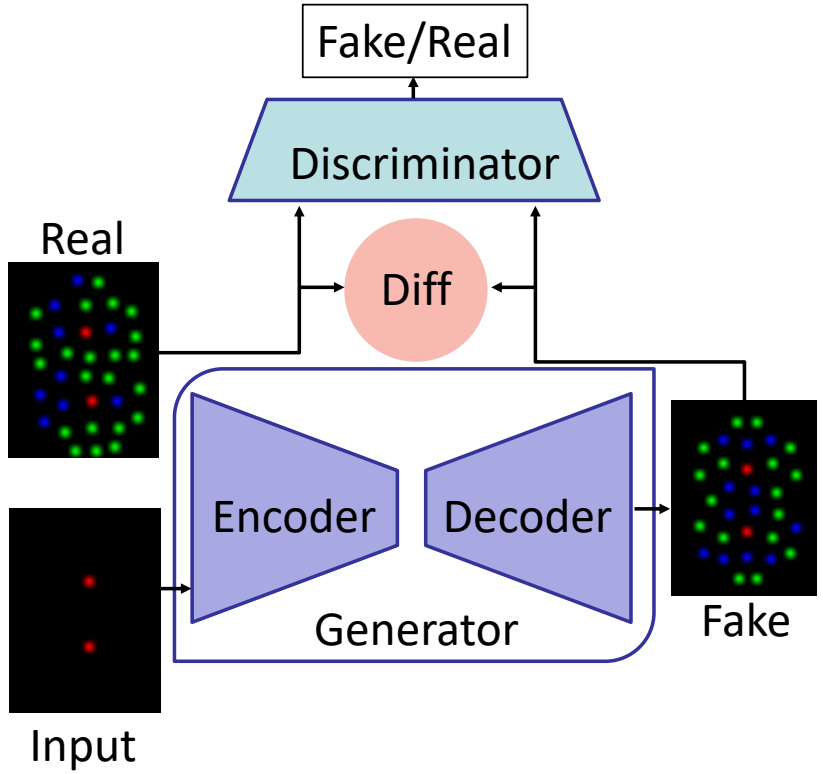
Image-to-Image Translation In Lithography



GAN-OPC [Yang+, DAC'18]



LithoGAN [Ye+, DAC'19]

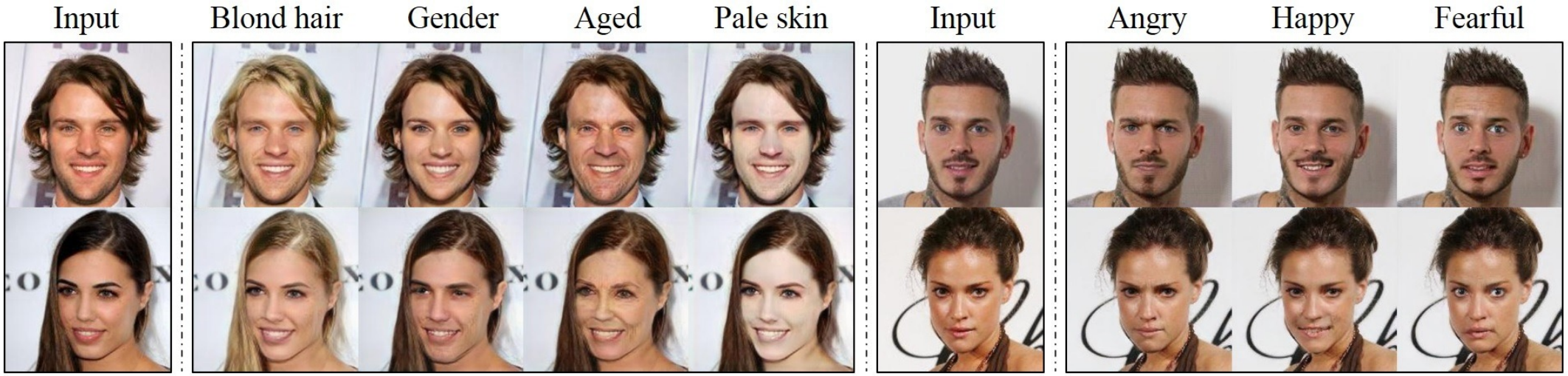


GAN-SRAF [Alawieh+, DAC'19]

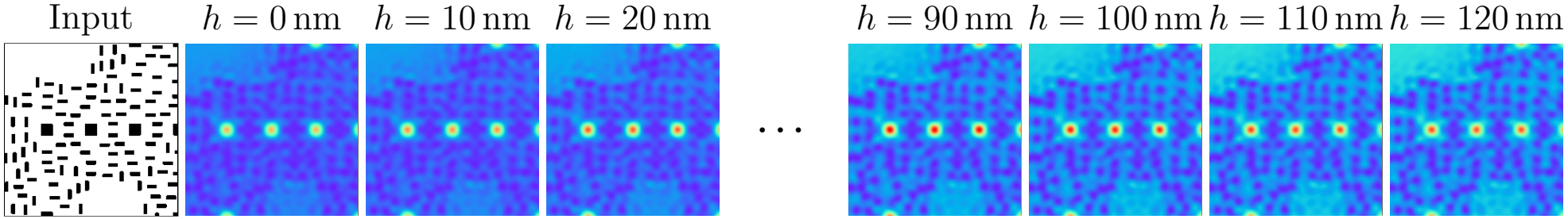
These applications are all single-domain transfer

Cast as Multi-Domain Image-to-Image Translation

- Facial image translation (facial attributes/expressions)
  - Bidirectional translation: original domain ⇔ target domain

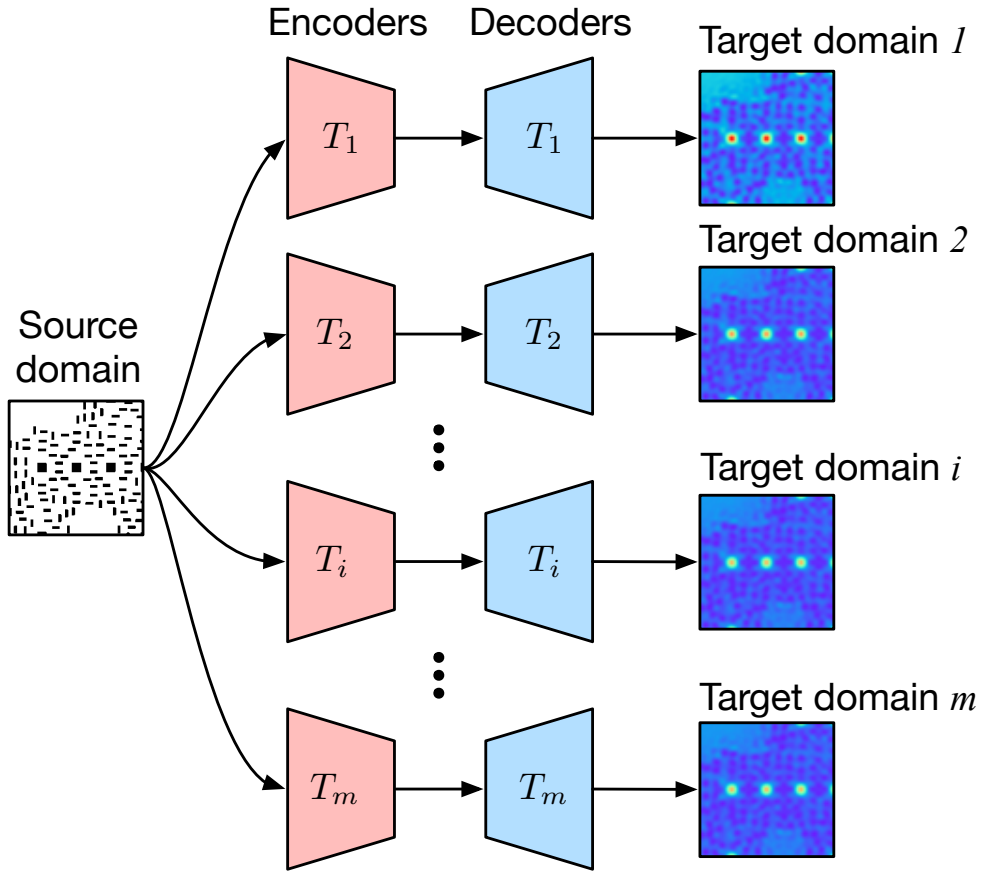


- Single mask pattern to multiple resist heights
  - Unidirectional translation: original domain ⇒ target domain



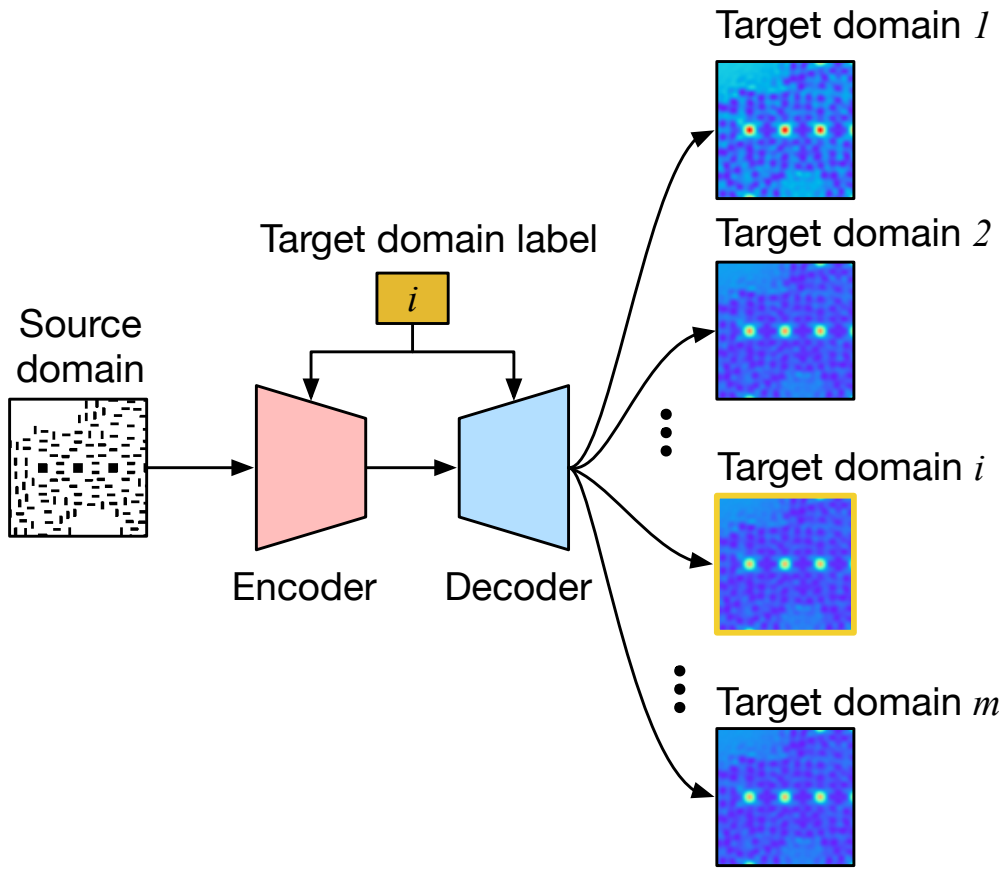
Multi-Domain Image-to-Image Translation

Simple model



- #Models scales up with #domains
- Models are independent

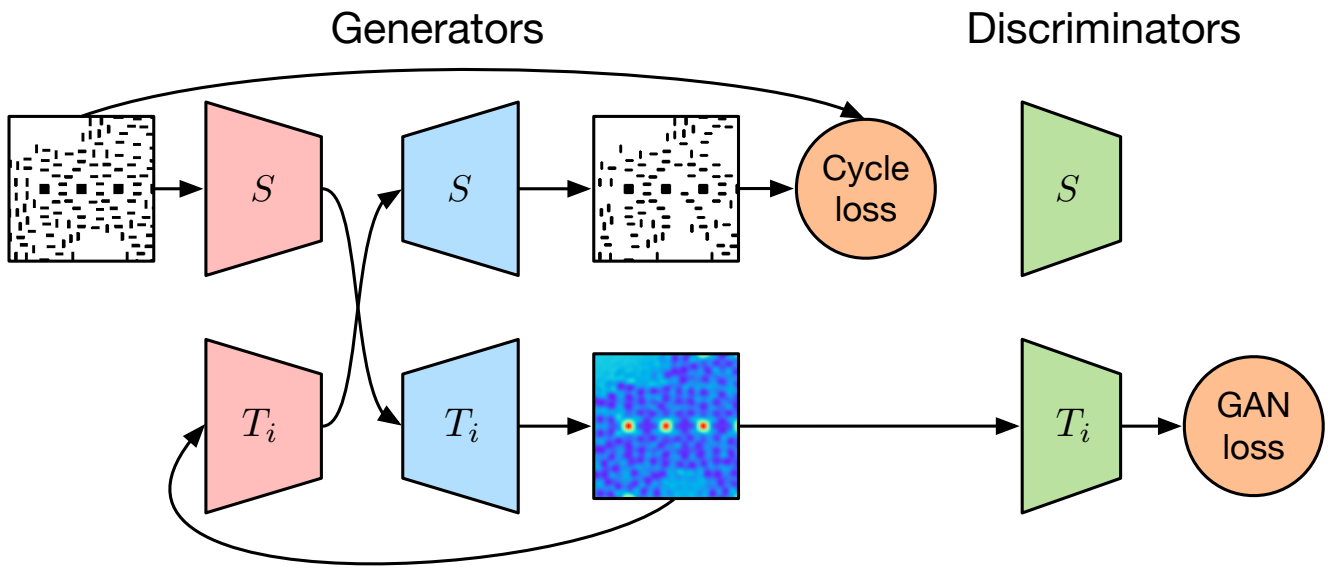
Ideal model

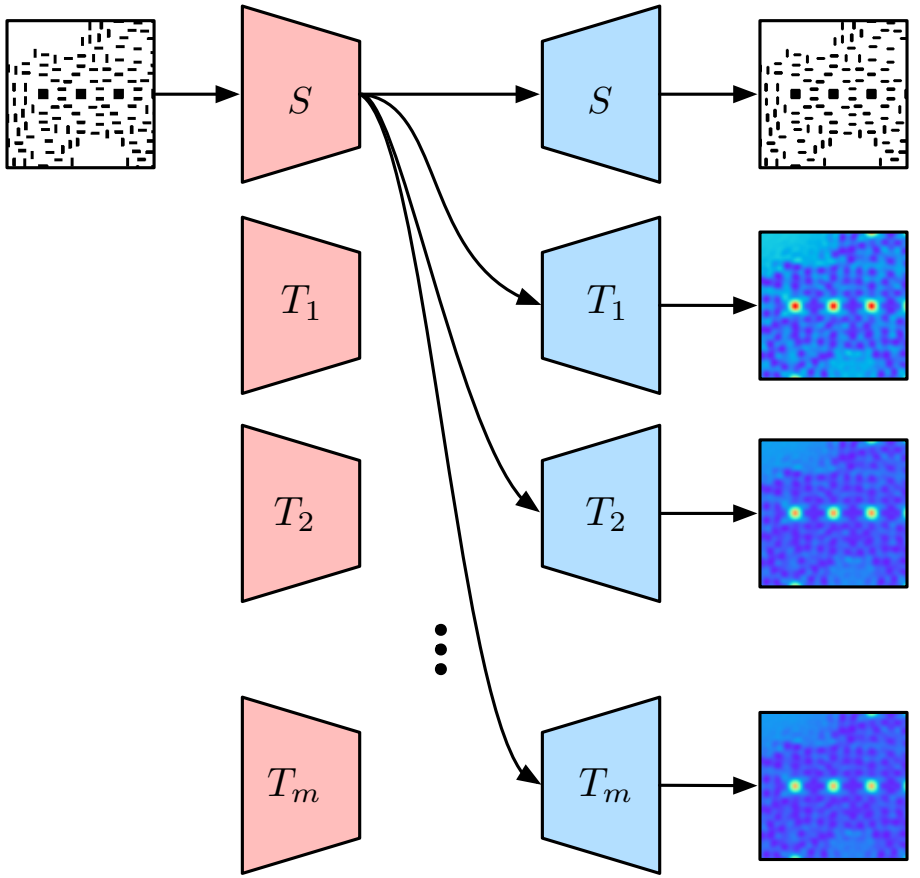


- Exploit the high correlation between different domains

Multi-Domain Image Translation

- ComboGAN [Anoosheh+, arXiv'17]



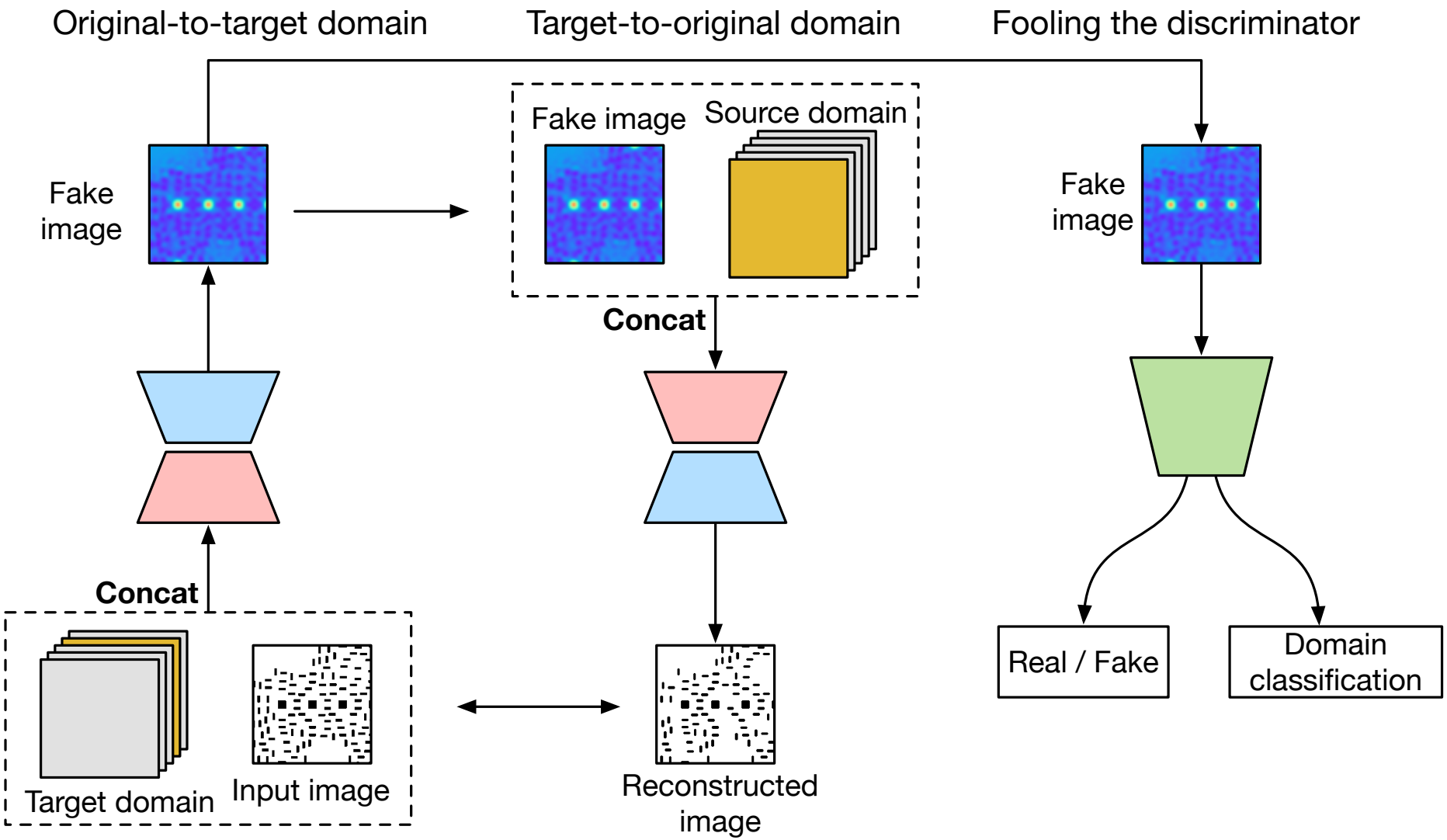


Joint training for the m different 2-domain transfer models, i ∈ {1,2,...,m}

Inference

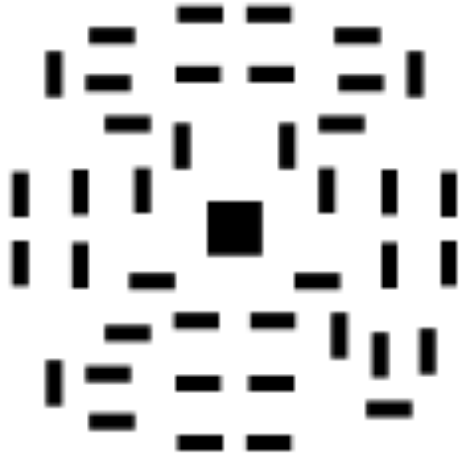
Multi-Domain Image Translation

- StarGAN [Choi+, CVPR'18]

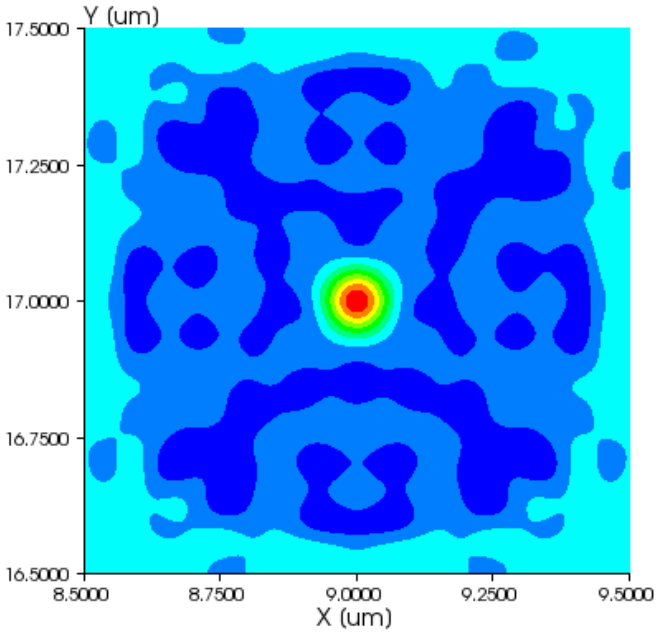


Special Properties about Aerial Image Generation

- Target-to-source domain transfer is difficult
  - Mask shape has sharp edges
  - Model is not guaranteed to generate polygon shapes
  - Sharp edges can complicate gradient propagation



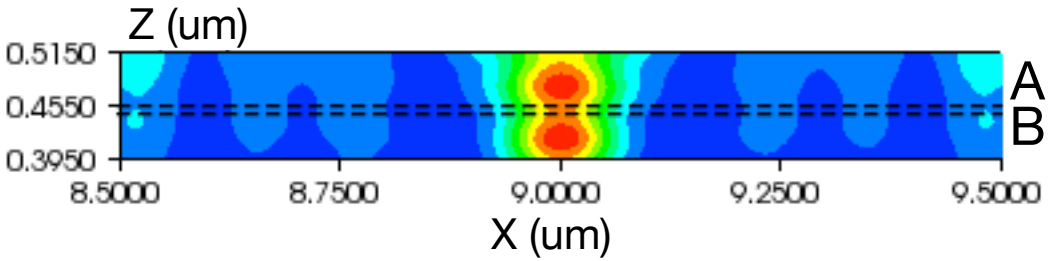
Source domain

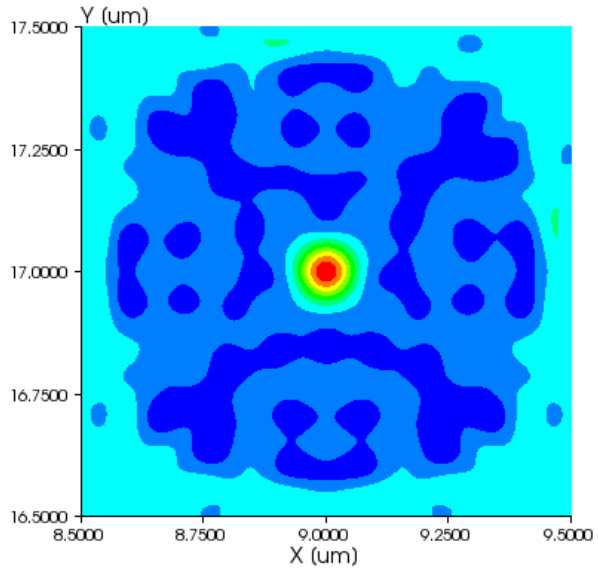


Target domain

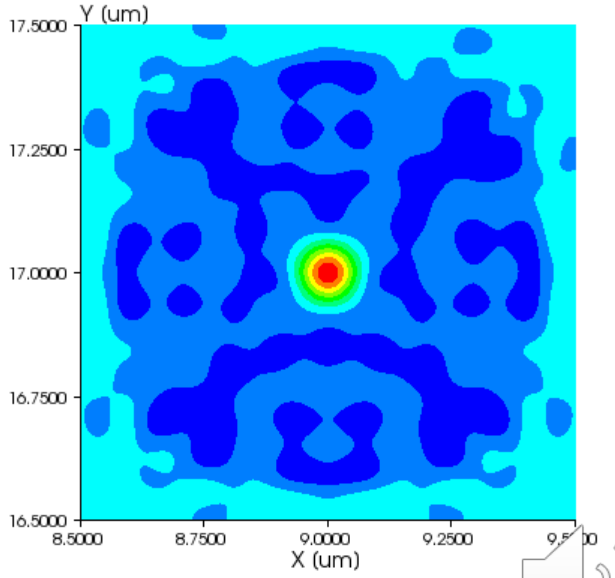
Special Properties about Aerial Image Generation

- Similarity between target domains
  - Intensity values at same (x, y) location change smoothly across target domains
  - Latent space carries the most critical information



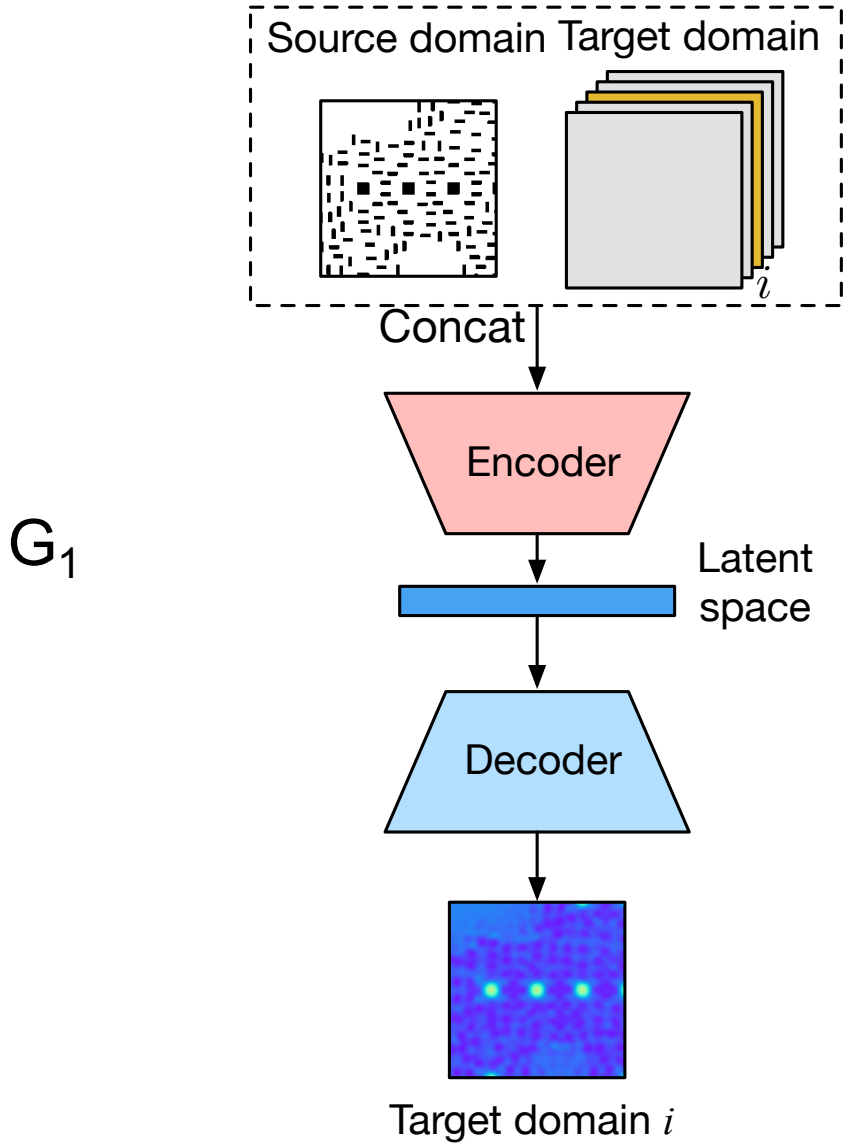


A

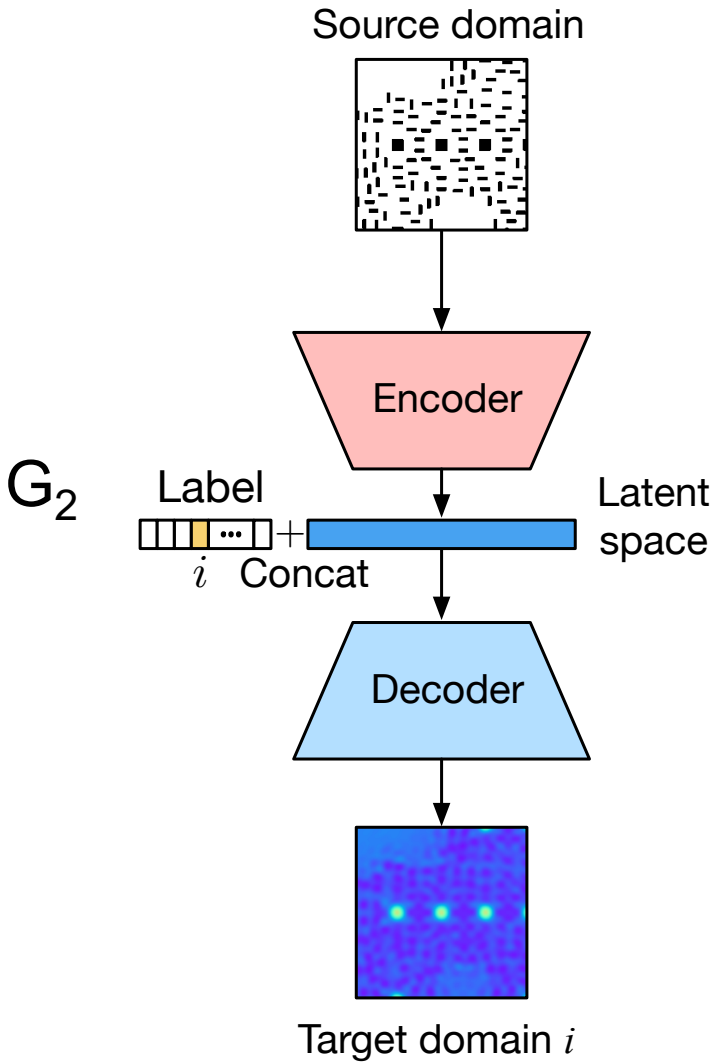


B

Generator Design

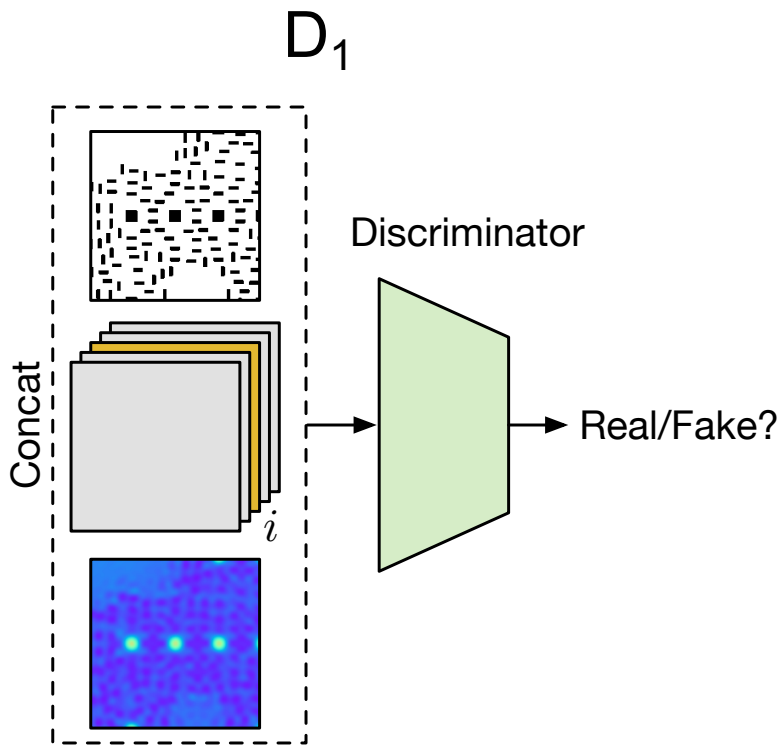


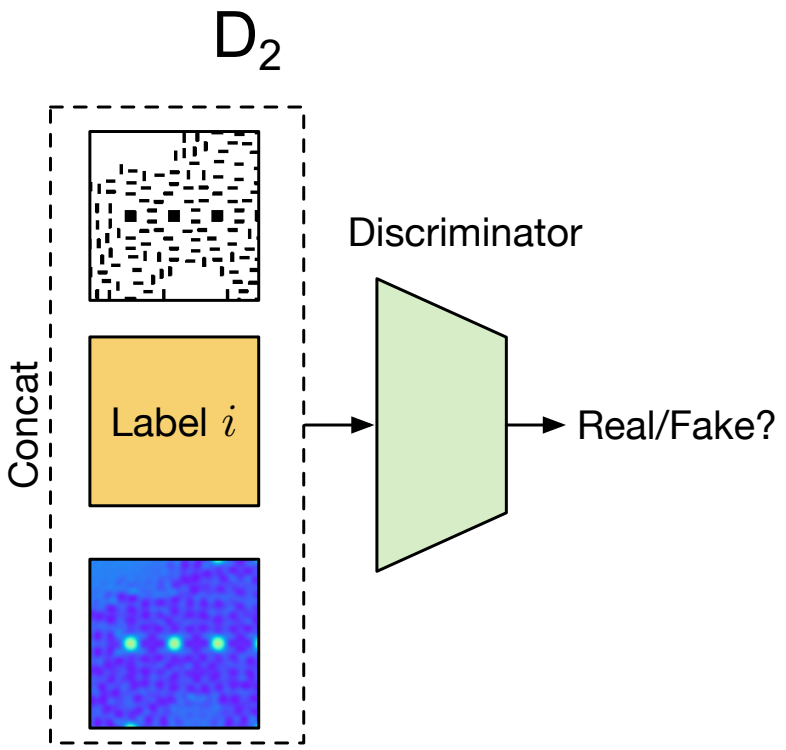
G_1



G_2

Discriminator Design

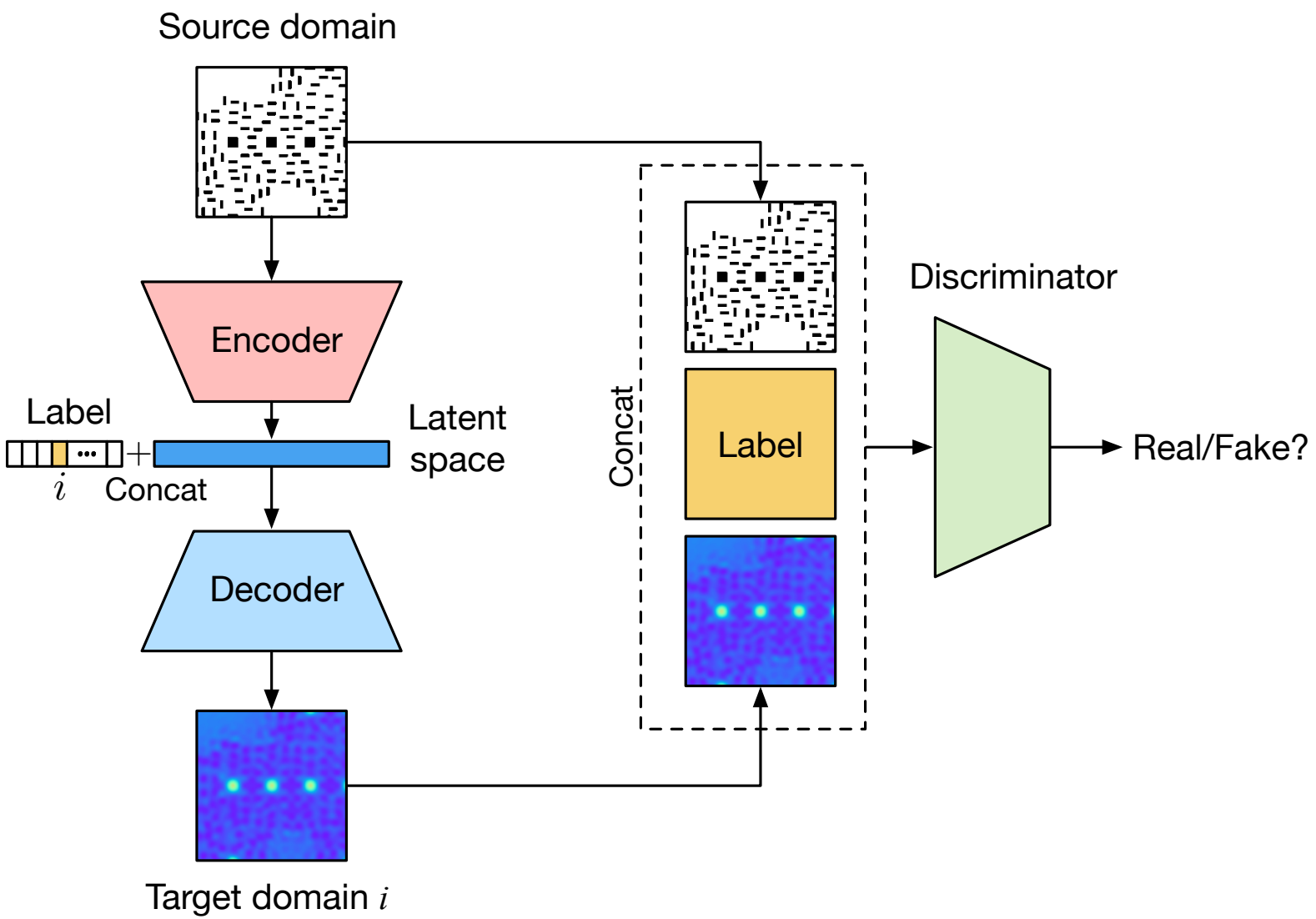




Ordinal encoding: single channel to denote all the domains

The i-th domain: $\frac{p_{\max}-p_{\min}}{m} \cdot i + p_{\min}$

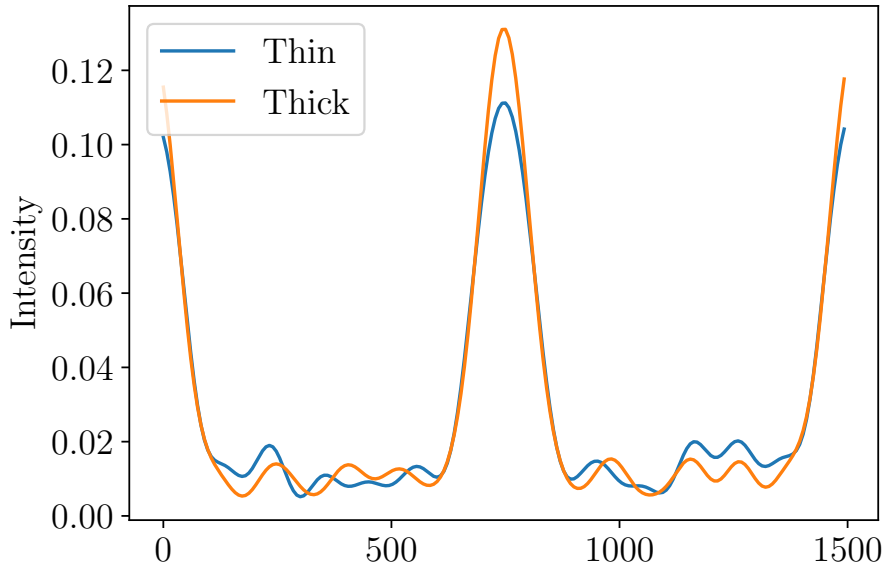
TEMPO

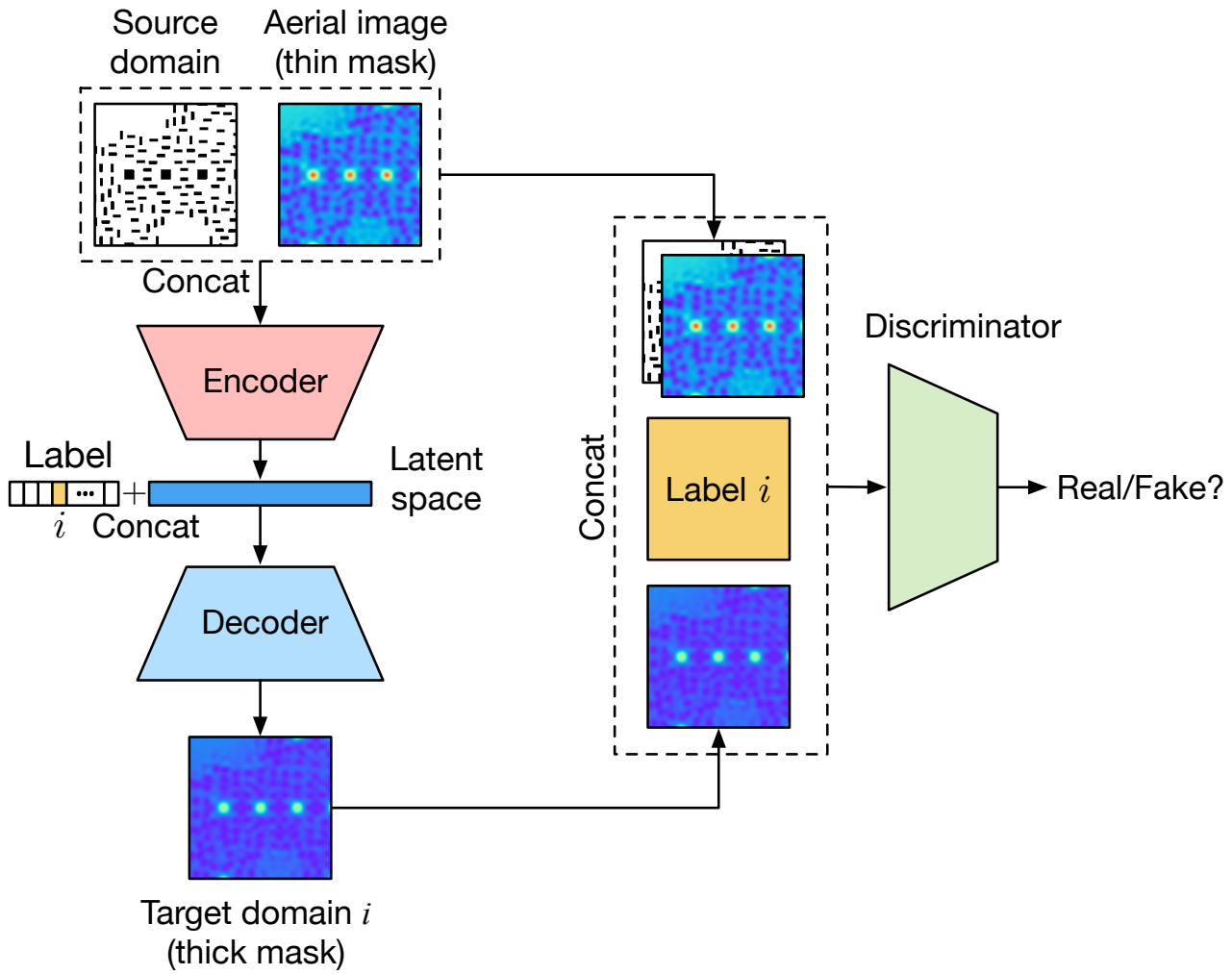


- Combination of G_2 and D_2
- Compact
- Information sharing
- Lower risk of overfitting

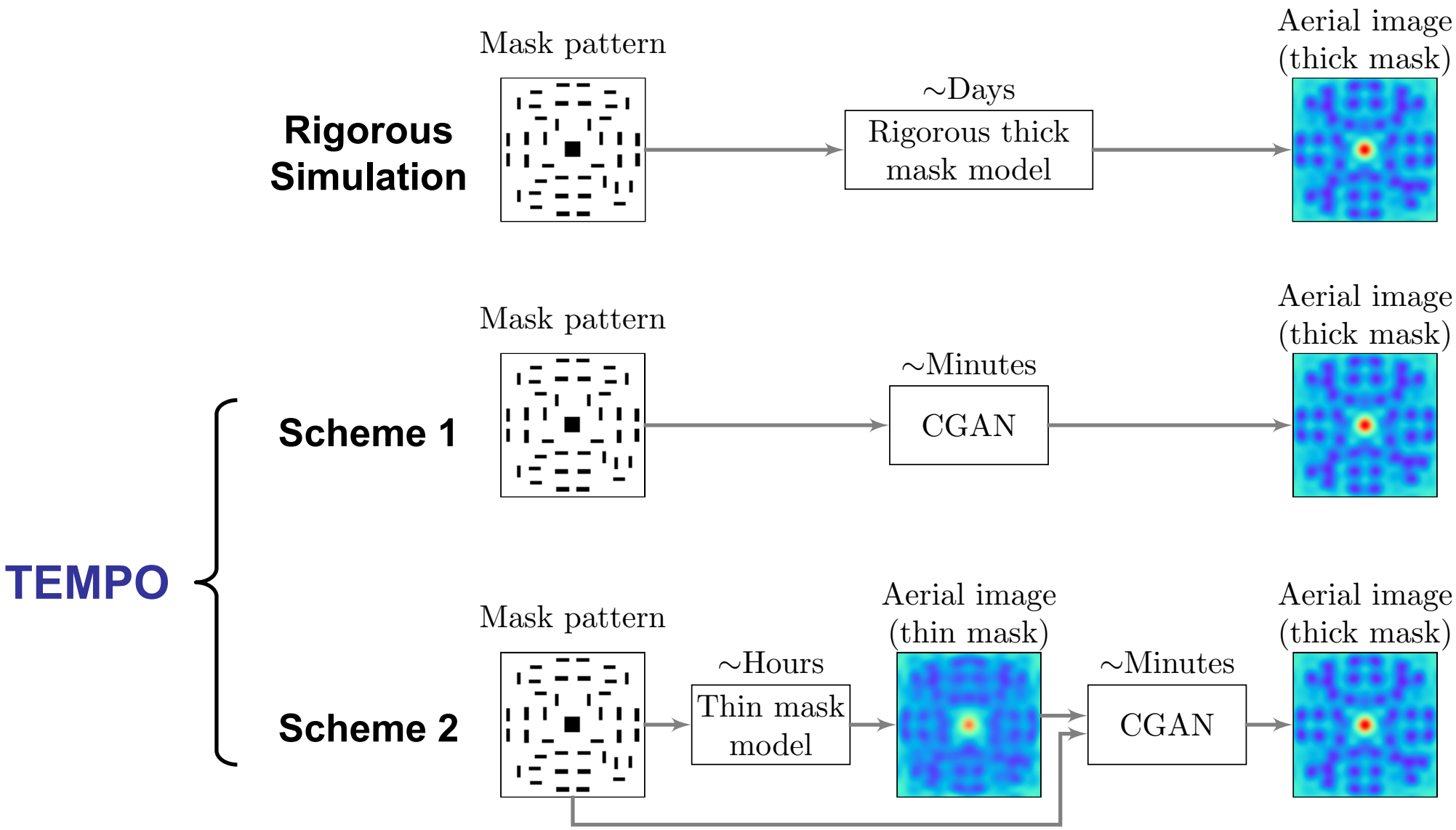
Can We Further Improve Accuracy?

- Thin mask simulation can provide guidance
- Thin mask simulation is relatively fast





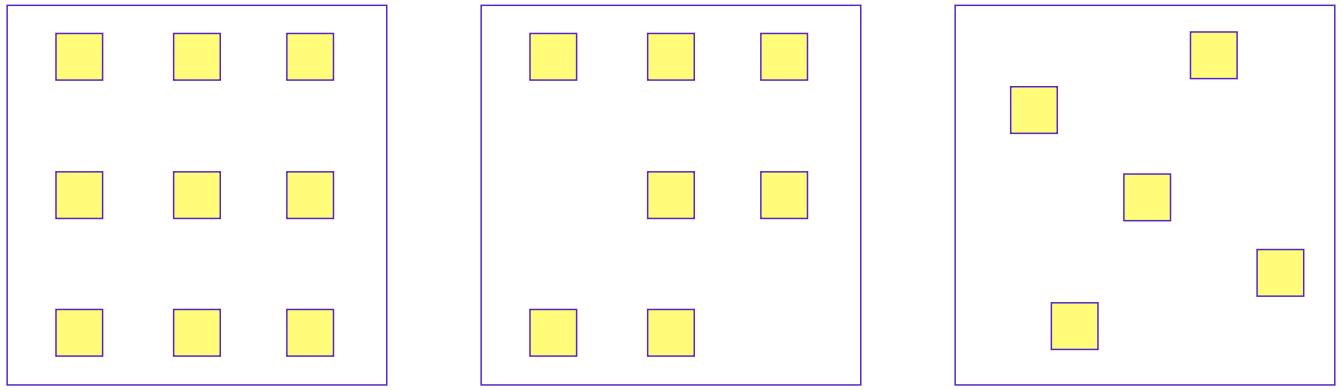
TEMPO Overall Flow



Runtime for 1000 mask clips

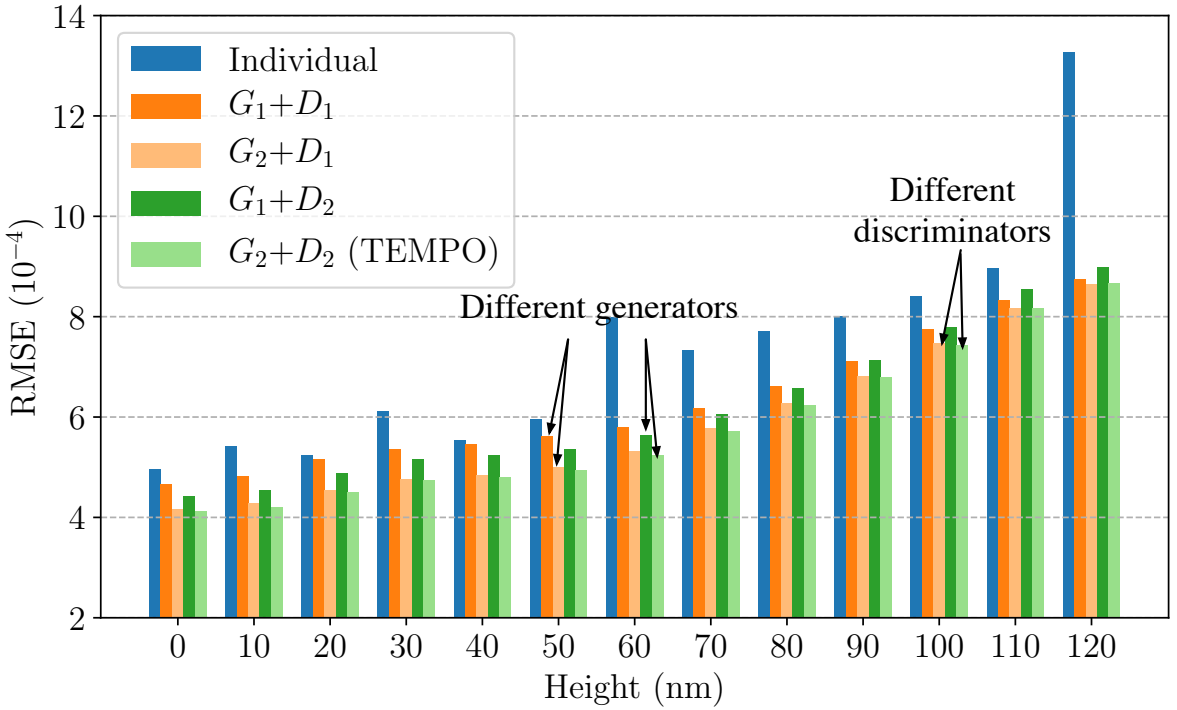
Experimental Setup

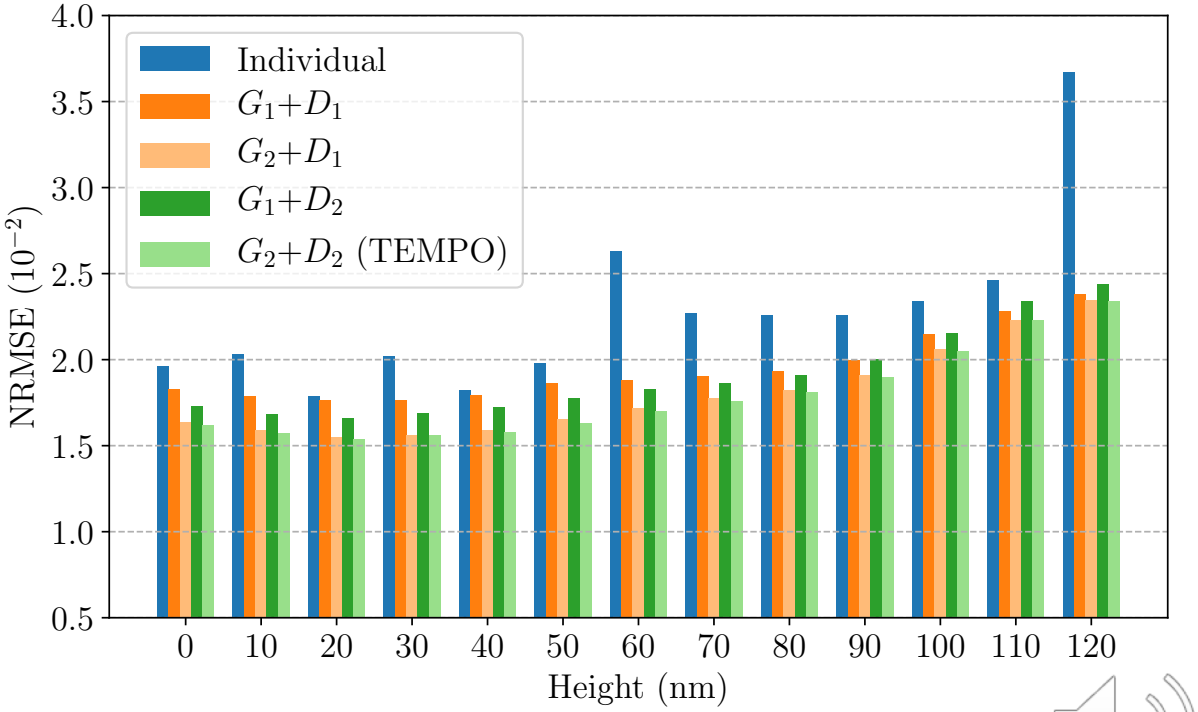
- Python 2.7 + Tensorflow 1.4.1
- GPU: Nvidia TITAN Xp
- SRAF, OPC: Mentor Graphics Calibre
- Aerial image by rigorous simulation: Synopsys S-Litho
- 966 mask clips at 10nm node
  - Different types of contact arrays [Lin+, TCAD'18]
  - 75% for training, 25% for test



Experimental Results

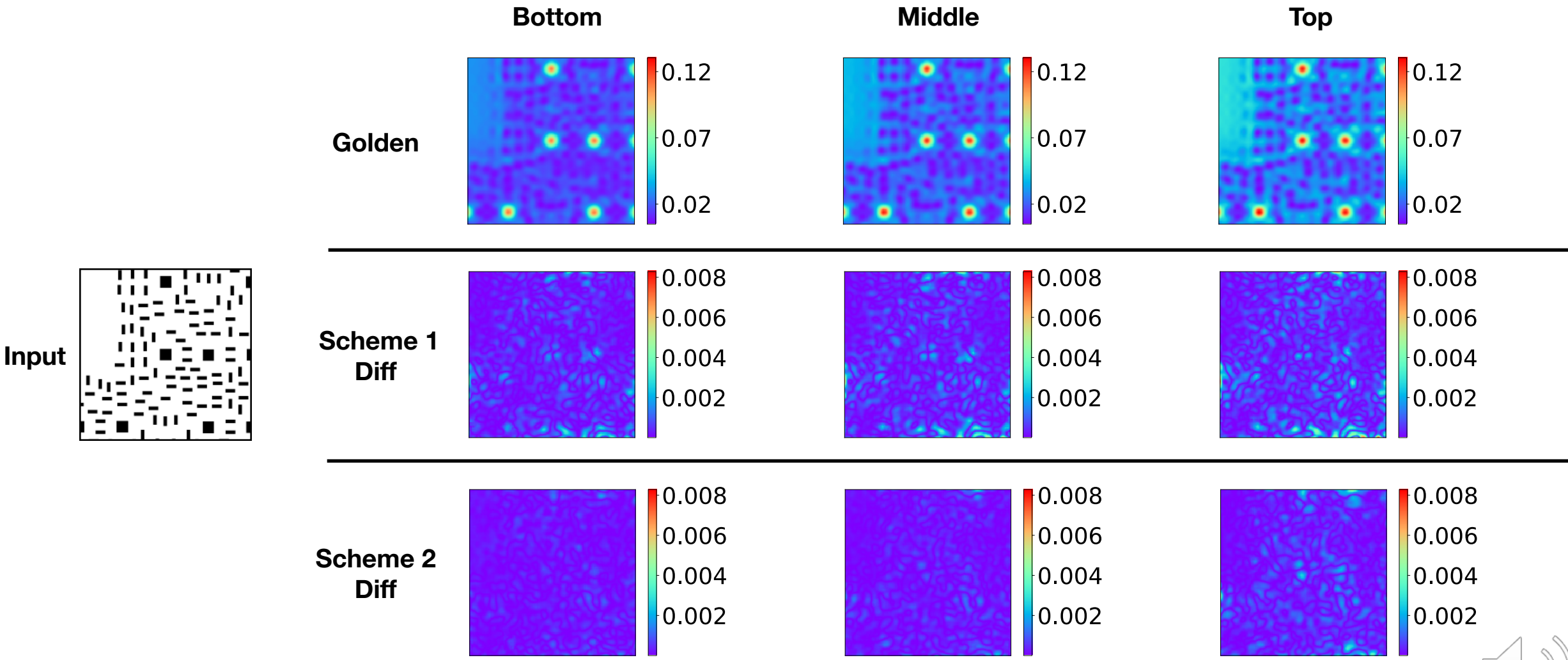
- Across-height information sharing benefits performance
- Latent space encoding in generator gives better accuracy
- Ordinal encoding in discriminator further improves accuracy



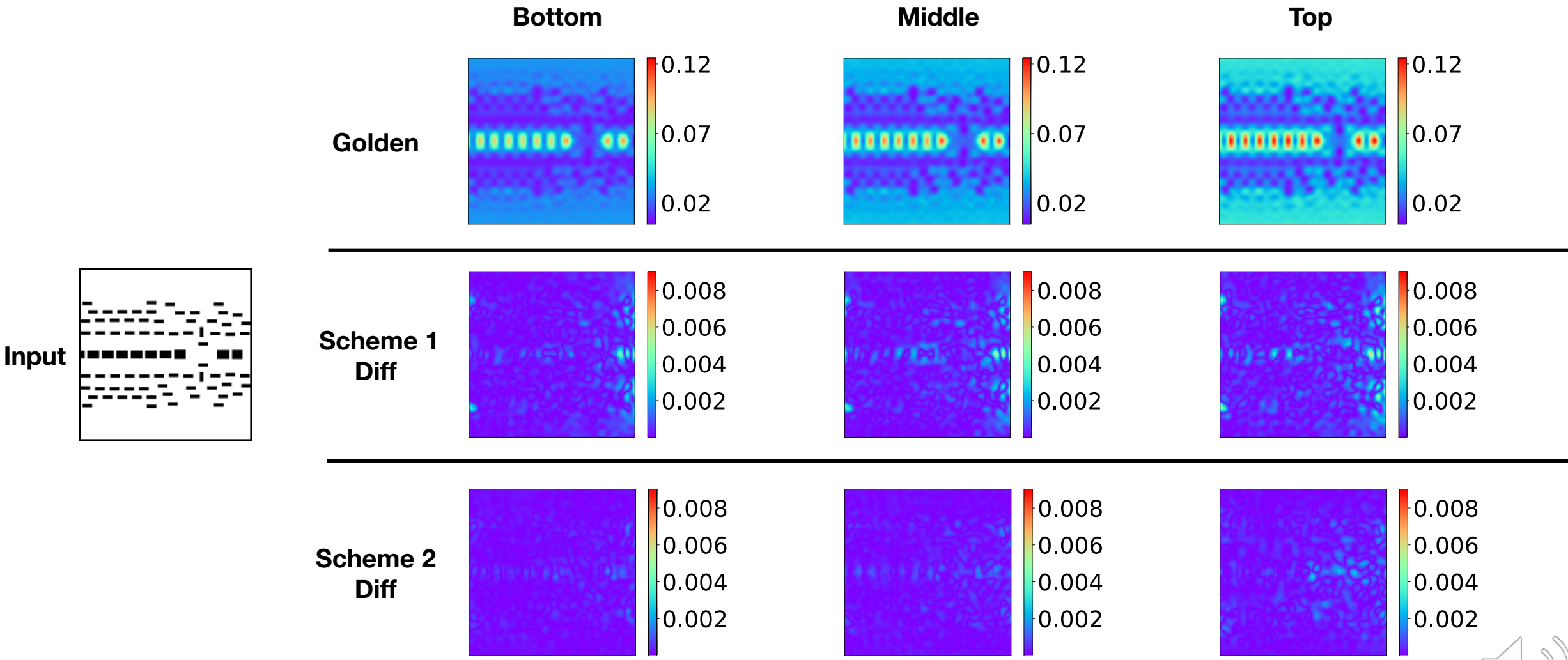


Apply different models in Scheme 2

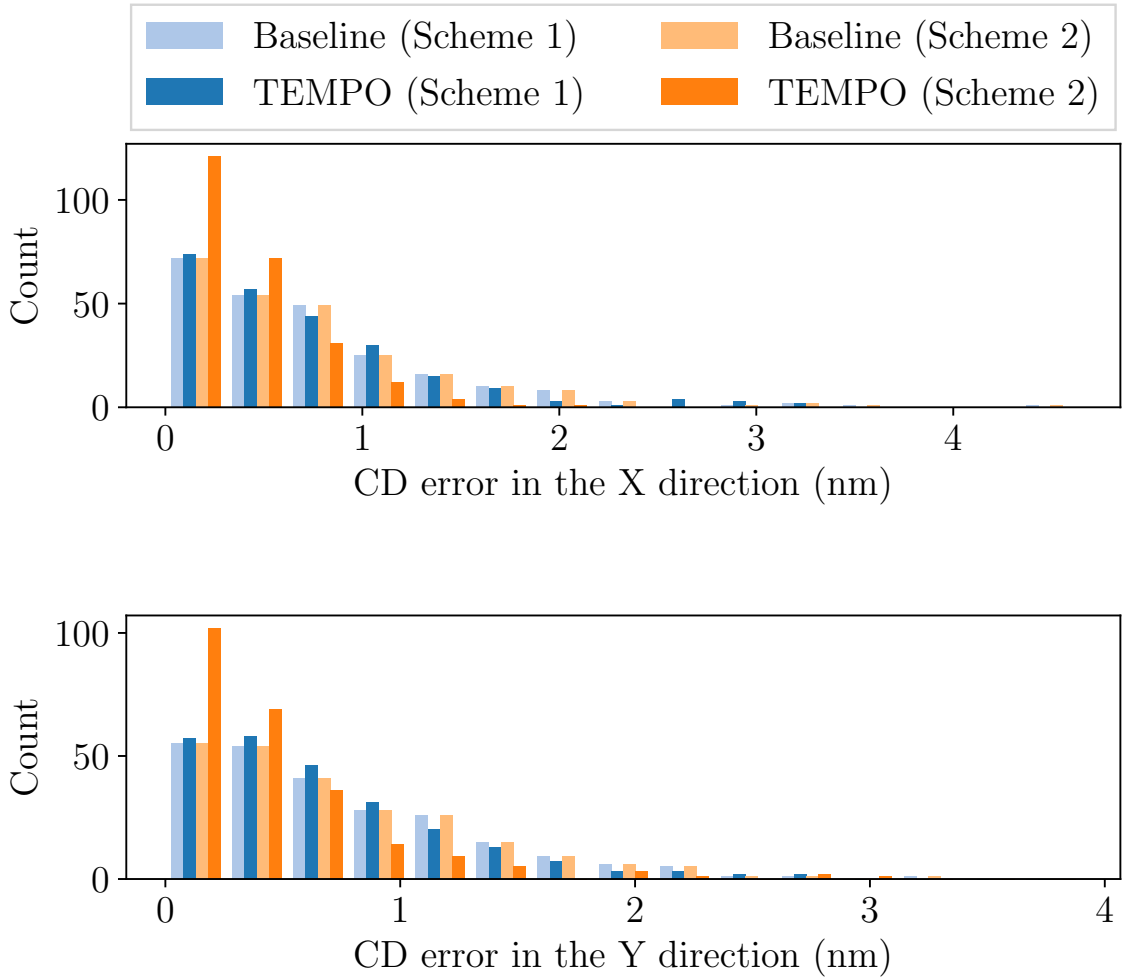
Experimental Results

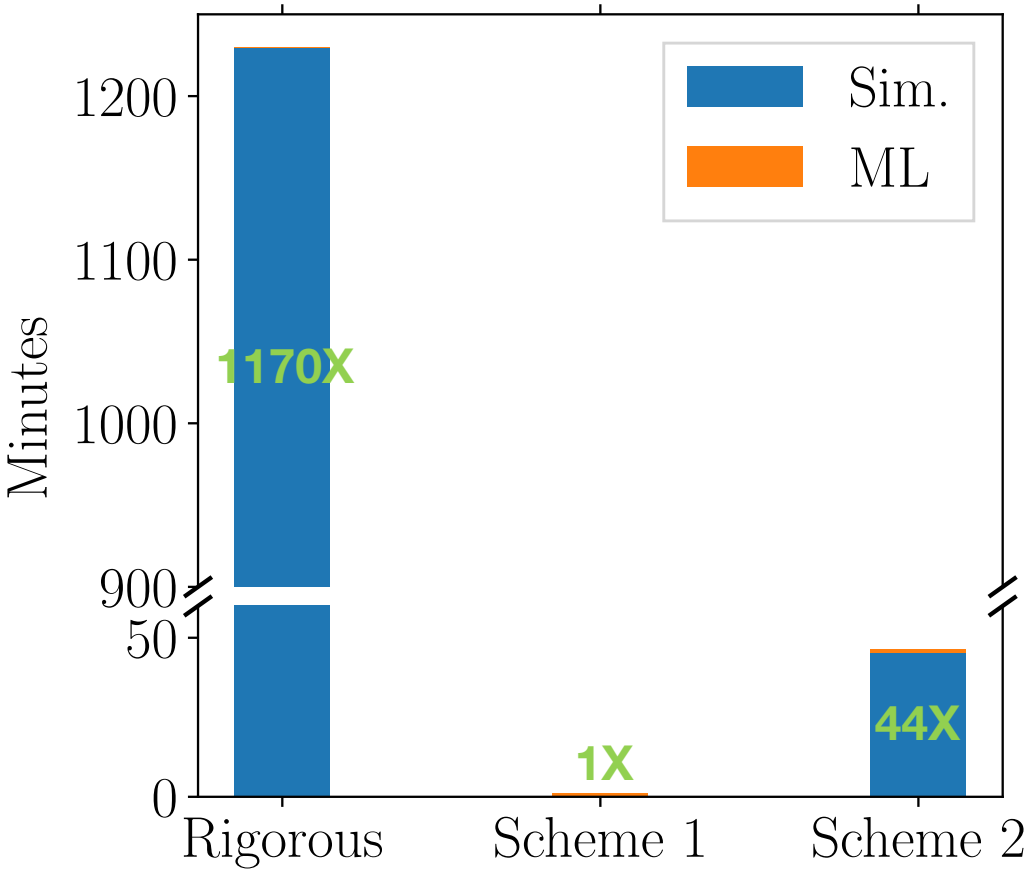


Experimental Results



CD Error and Runtime Comparison





Baseline: the individual model approach

Conclusion

- TEMPO: framework for 3D aerial image generation considering mask topography effects
- One-fits-all CGAN model
  - Novel target domain encoding
  - Compact
  - Superior accuracy: leveraging across-domain information sharing
- Two schemes provide trade-offs between accuracy and efficiency

Thank you!