VLSI Mask Optimization: From Shallow To Deep Learning

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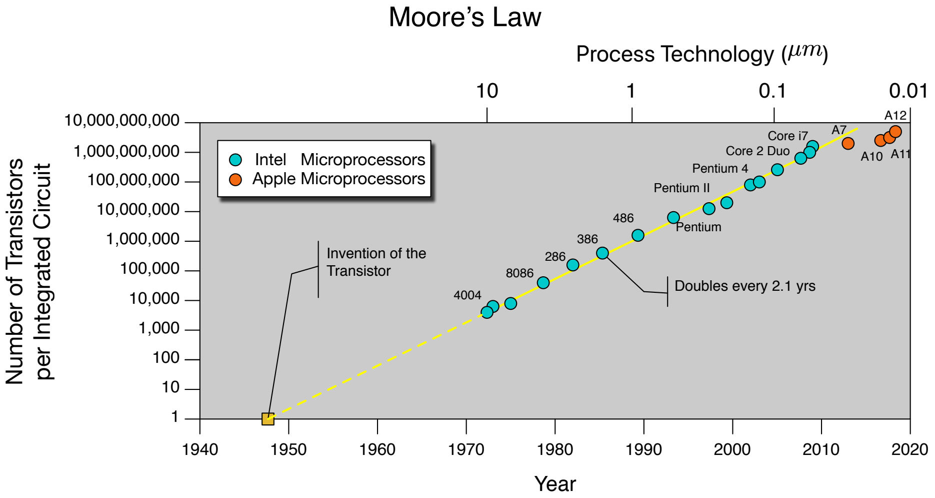
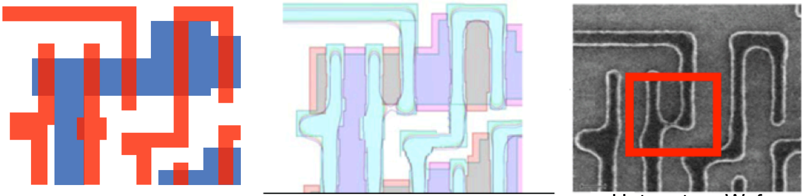
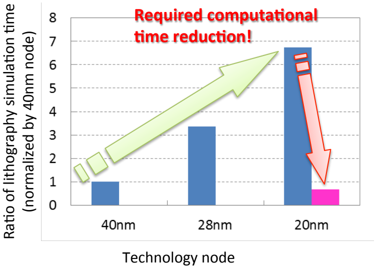
Moore’s Law to Extreme Scaling



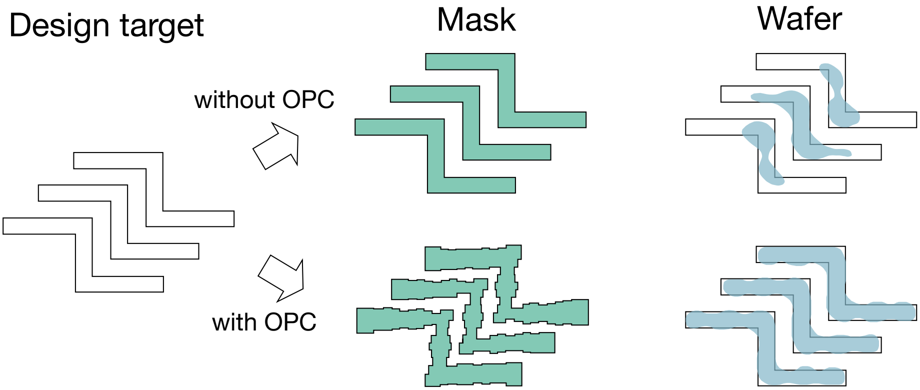
Challenge 1: Failure (Hotspot) Detection





- RET: OPC, SRAF, MPL
- Still hotspot: low fidelity patterns
- Simulations: extremely CPU intensive

Challenge 2: Optical Proximity Correction (OPC)



Why Deep Learning?

- **Feature Crafting v.s. Feature Learning**
  Although prior knowledge is considered during manually feature design, information loss is inevitable.
  Feature learned from mass dataset is more reliable.
- **Scalability**
  With shrinking down circuit feature size, mask layout becomes more complicated.
  Deep learning has the potential to handle ultra-large-scale instances while traditional machine learning may suffer from performance degradation.
- **Mature Libraries**

TensorFlow™ Caffe2 PYTORCH

Outline

Hotspot Detection via Machine Learning

OPC via Machine Learning

Heterogeneous OPC

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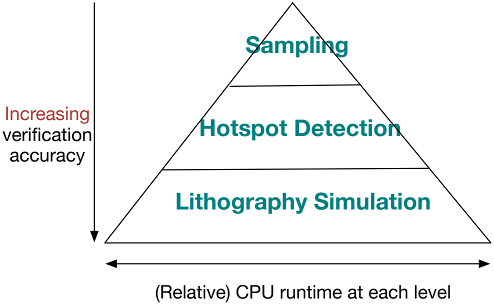
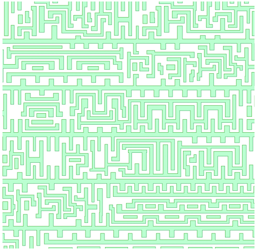
Heterogeneous OPC

Hotspot Detection Hierarchy

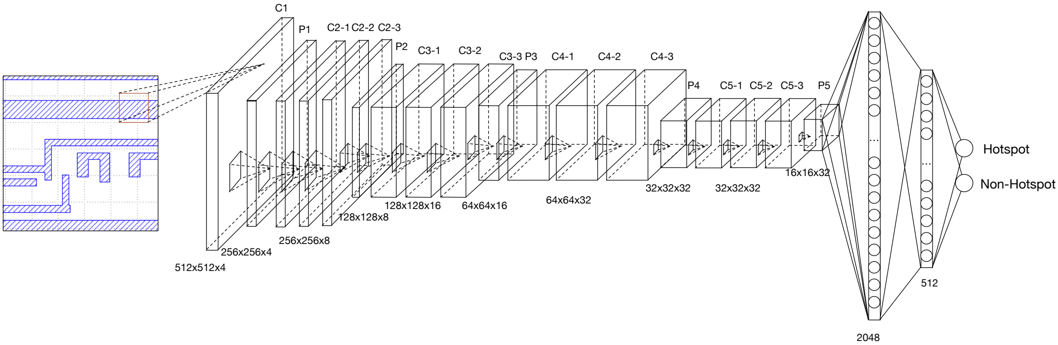




- **Sampling** (DRC Checking):
  scan and rule check each region
- **Hotspot Detection**:
  verify the sampled regions and report potential hotspots
- **Lithography Simulation**:
  final verification on the reported hotspots

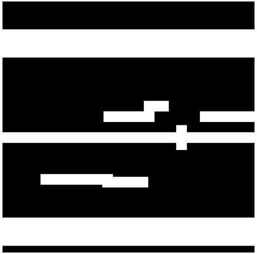
Early Study of DNN-based Hotspot Detector∗

- Total 21 layers with 13 convolution layers and 5 pooling layers.
- A ReLU is applied after each convolution layer.

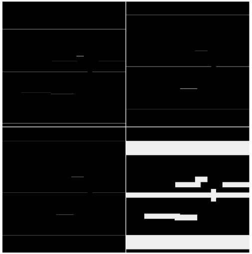


∗Haoyu Yang, Luyang Luo, et al. (2017). "Imbalance aware lithography hotspot detection: a deep learning approach". In: *JM3* 16.3, p. 033504.

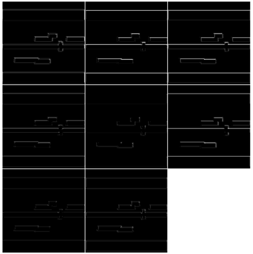
What Does Deep Learning Learn?



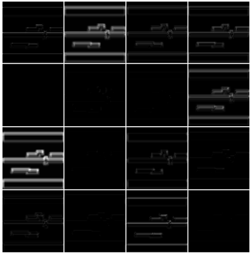
Origin



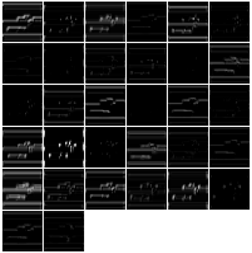
Pool1



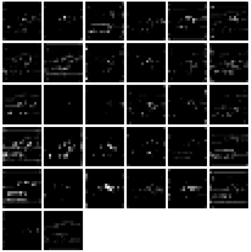
Pool2



Pool3

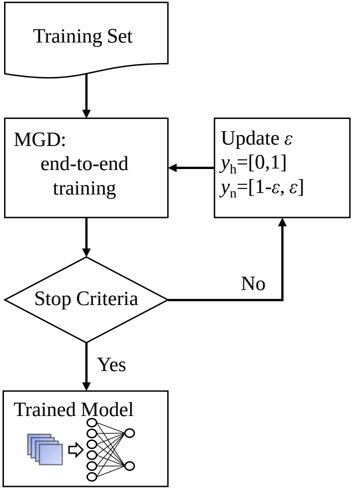


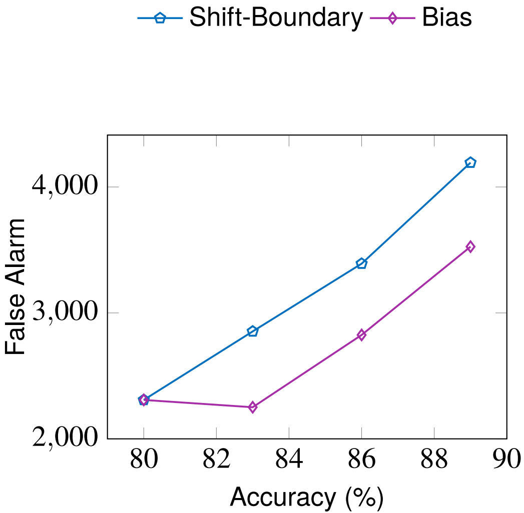
Pool4



Pool5

The Biased Learning Algorithm [DAC'17]†





†Haoyu Yang, Jing Su, et al. (2017). "Layout Hotspot Detection with Feature Tensor Generation and Deep Biased Learning". In: *Proc. DAC*, 62:1–62:6.

Optimizing AUC [ASPDAC'19]‡

The AUC objective:

$$\mathcal{L}_\Phi(f) = \frac{1}{N_+N_-}\sum_{i=1}^{N_+}\sum_{j=1}^{N_-}\Phi\left(f\left(\mathbf{x}_i^+\right) - f\left(\mathbf{x}_j^-\right)\right).$$

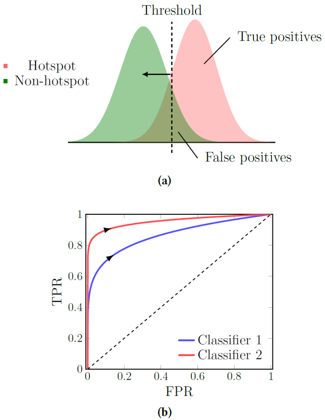
Approximation candidates:

PSL $\Phi_{\mathrm{PSL}}(z) = (1-z)^2$

PHL $\Phi_{\mathrm{PHL}}(z) = \max(1-z, 0)$

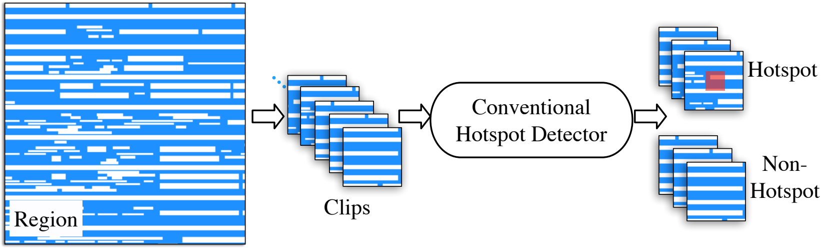
PLL $\Phi_{\mathrm{PLL}}(z) = \log(1+\exp(-\beta z))$

R $\Phi_{\mathrm{R}*}(z) = \begin{cases} -(z-\gamma)^p, & \text{if } z > \gamma \\ 0, & \text{otherwise} \end{cases}$



‡Wei Ye et al. (2019). "LithoROC: lithography hotspot detection with explicit ROC optimization". In: *Proc. ASPDAC*, pp. 292–298.

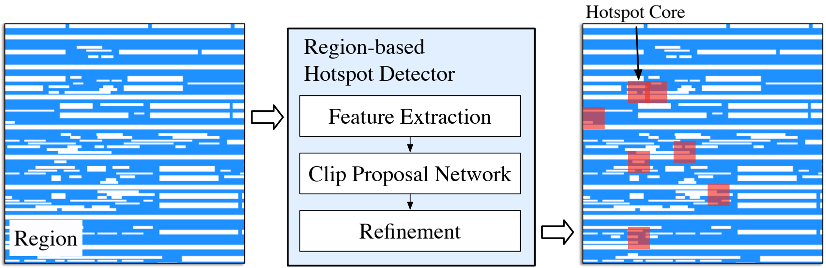
Conventional Clip based Solution



- A binary classification problem.
- Scan over whole region.
- Single stage detector.

- Scanning is time consuming and single stage is not robust to false alarm.

Region based approach [DAC'19]



- Learning what and where is hotspot at same time.
- Classification Problem -> Classification & Regression Problem.

Ran Chen et al. (2019). "Faster Region-based Hotspot Detection". In: *Proc. DAC*, 146:1–146:6.

Outline

Hotspot Detection via Machine Learning

OPC via Machine Learning

Heterogeneous OPC

OPC Previous Work

Classic OPC

- Model/Rule-based OPC

  [Cobb+,SPIE'02][Kuang+,DATE'15]
  [Awad+,DAC'16][Su+,ICCAD'16]

  1. Fragmentation of shape edges;
  2. Move fragments for better printability.

- Inverse Lithography

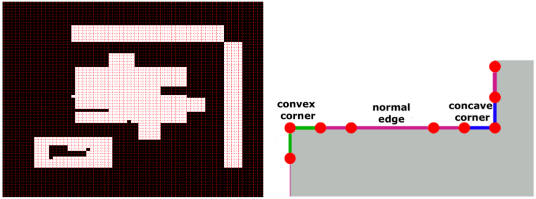
  [Pang+,SPIE'05][Gao+,DAC'14]
  [Poonawala+,TIP'07][Ma+,ICCAD'17]

  1. Efficient model that maps mask to aerial image;
  2. Continuously update mask through descending the gradient of contour error.

Machine Learning OPC

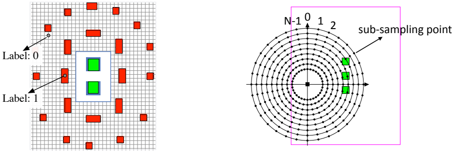
[Matsunawa+,JM3'16][Choi+,SPIE'16]
[Xu+,ISPD'16][Shim+,APCCAS'16]

1. Edge fragmentation;
2. Feature extraction;
3. Model training.

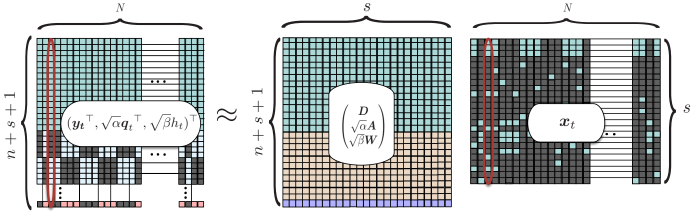


Machine Learning-based SRAF Insertion

SRAF Insertion with Machine Learning [ISPD'16]¶



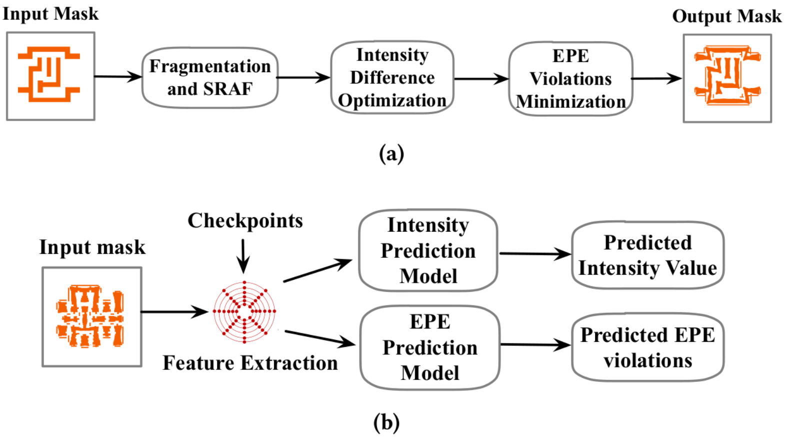
Tackling Robustness with Dictionary Learning [ASPDAC'19]‖



¶Xiaoqing Xu et al. (2016). "A machine learning based framework for sub-resolution assist feature generation". In: *Proc. ISPD*, pp. 161–168.

‖Hao Geng et al. (2019). "SRAF Insertion via Supervised Dictionary Learning". In: *Proc. ASPDAC*, pp. 406–411.

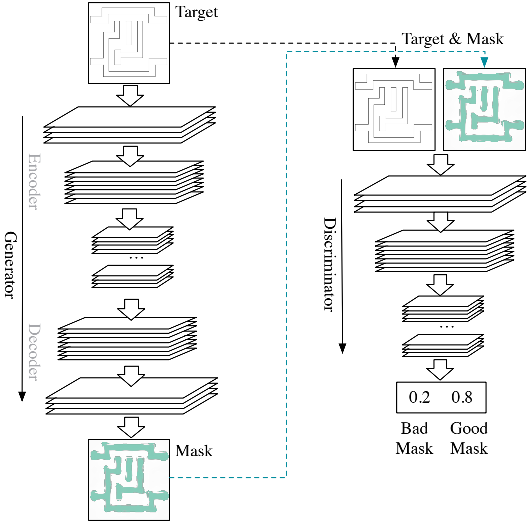
Machine Learning Assists Model-based OPC [ASPDAC'19]**



- Replace lithography simulation (slow) with machine learning-based EPE predictor (fast) in OPC iterations.

**Bentian Jiang et al. (2019). "A fast machine learning-based mask printability predictor for OPC acceleration". In: *Proc. ASPDAC*, pp. 412–419.

GAN-OPC [DAC'18]††



- Better starting points for legacy OPC engine and reduce iteration count.

††Haoyu Yang, Shuhe Li, et al. (2018). "GAN-OPC: Mask Optimization with Lithography-guided Generative Adversarial Nets". In: *Proc. DAC*, 131:1–131:6.

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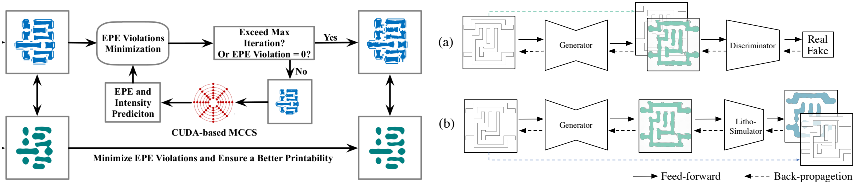
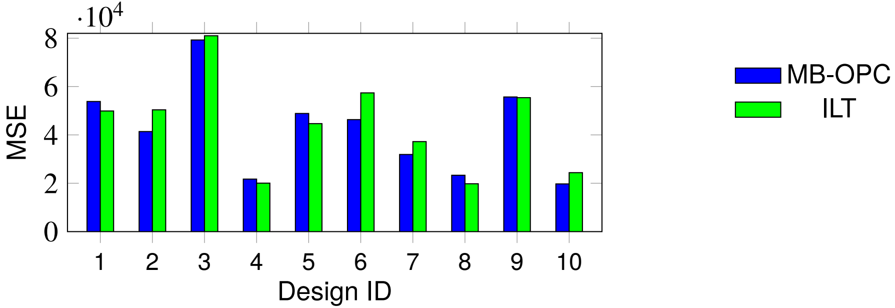
An Observation of Previous OPC Solutions

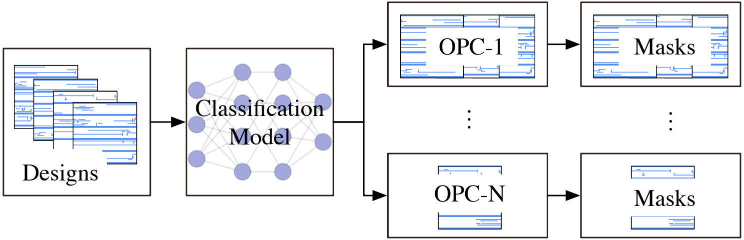
Machine learning solutions rely on legacy OPC engines



Legacy OPC engines exhibit different performance on different designs



A Design of Heterogeneous OPC Framework

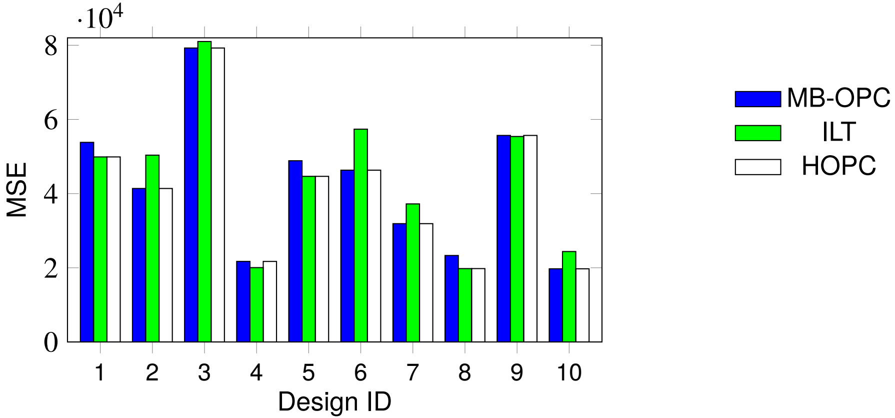


We design a classification model that can determine the best OPC engine for a given design at trivial cost.

Training on Artificial Designs

- Training data comes from GAN-OPC and is labeled according to results of MB-OPC and ILT.
- Test on 10 designs from ICCAD 2013 CAD Contest.

Experimental Results



Several Benefits

- Does not require extremely high prediction accuracy of the classification model.
- Take advantages of different OPC solutions on different designs.

Conclusion and Discussion

So Far:

- Recent progress of deterministic machine learning model for hotspot detection
- State-of-the-art machine learning solutions for OPC and SRAF insertion
- A heterogeneous OPC framework guided by a classification engine

Future:

- Manufacturability issues.
- Classification challenge when more than two OPC engines are available.