CAD Tool Design Space Exploration via Bayesian Optimization

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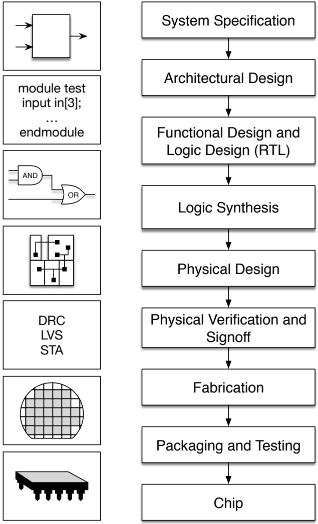
Design Flow



- It's really a long journey;
- Each step is more complicated as the technology node advances;
- Huge effort is needed to achieve the desired design quality.

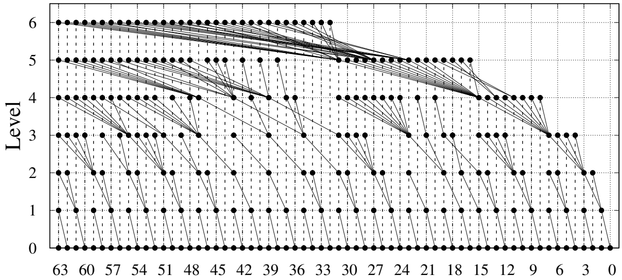
Case Study: Adder Design

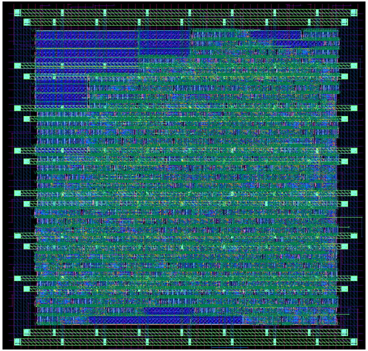
Binary Adder

- Primary building blocks in the datapath logic of a microprocessor.
- A fundamental problem in VLSI industry for last several decades.

Anything else we can do?

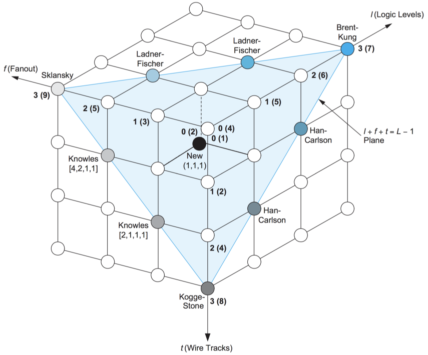
Gaps Between Design Stages





- Logic synthesis v.s. physical synthesis
- Constraints mapping between two synthesis stages is difficult.

Design Space – Front-End



Parallel Prefix Adders

→ Flexible delay-power trade-off

Regular Adders

→ Sub-optimal

Custom Adders

→ High TAT

Design Space – Back-End

- Tool settings. Huge space for different options.

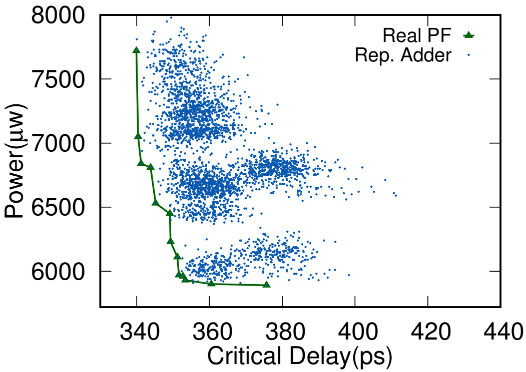
Table 2-4 set_route_options Command Options

Option	Valid values	Description
Global routing options (Global Routing tab in the GUI)		
`-groute_skew_control` ("Skew control" check box in the GUI)	`true` | `false`	Enables (true) or disables (false) skew control during global routing. The default is `false`.
`-groute_skew_weight` ("Skew control Weight" box in the GUI)	*int* (must be between 1 and 10)	Specifies the weight associated with skew control. The default is 5.
`-groute_timing_driven` ("Timing driven" check box in the GUI)	`true` | `false`	Enables (true) or disables (false) timing-driven global routing. The default is `false`.
`-groute_timing_driven_weight` ("Timing driven Weight" box in the GUI)	*int* (must be between 1 and 7)	Specifies the weight associated with timing-driven global routing. The default is 4.
`-groute_congestion_weight` ("Congestion weight" box in the GUI)	*int* (must be between 1 and 12)	Specifies the weight associated with congestion-driven global routing. The default is 4.
`-groute_clock_routing` ("Clock routing" radio buttons in the GUI)	`normal` | `comb` | `balanced`	Specifies the global-routing clock topology. The default is `balanced`.
`-groute_incremental` (Incremental check box in the GUI)	`true` | `false`	Enables (true) or disables (false) incremental global routing. The default is `false`.

Option	Valid values	Description
Track assignment options (Track Assign tab in the GUI)		
`-track_assign_timing_driven` ("Timing driven" check box in the GUI)	`true` | `false`	Enables (true) or disables (false) timing-driven track assignment. The default is `false`.
`-track_assign_timing_driven_weight` ("Timing driven" Weight box in the GUI)	*int* (must be between 1 and 10)	Specifies the weight associated with timing-driven track assignment. The default is 1.
Detail routing options (Detail Routing tab in the GUI)		
`-droute_connect_tie_off` ("Connect tie off" check box in the GUI)	`true` | `false`	Enables (true) or disables (false) connection of tie-off nets during detail routing. The default is `true`.
`-droute_connect_open_nets` ("Connect open nets" check box in the GUI)	`true` | `false`	Enables (true) or disables (false) connection of open nets during detail routing. The default is `true`.
`-droute_reroute_user_wires` ("Reroute user wires" check box in the GUI)	`true` | `false`	Specifies whether the router can reroute user-created wires. The default is `false`.
`-droute_CTS_nets` ("Change CTS nets" radio buttons in the GUI)	`normal` | `minor_change_only`	Specifies whether only minor changes can be made to clock nets. The default is `minor_change_only`.
`-droute_single_row_column_via_array` ("Single row column via array" radio buttons in the GUI)	`center` | `optimize`	Specifies how to handle via arrays that consist of a single row and single column. The default is `center`.

Source: ICC documentation

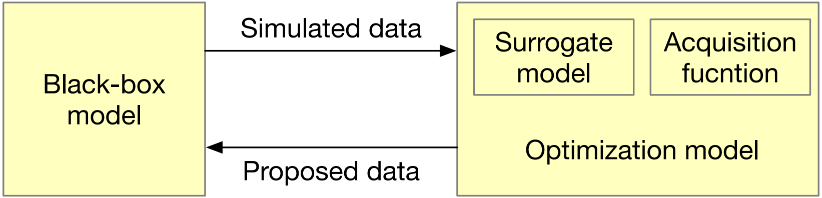
Design Space Exploration



- Search for the Pareto-optimal designs;
- None of the objective metrics, such as area, power or delay, can be improved without worsening at least one of the others.

Bayesian Optimization

- Good candidate to optimize functions that take a long time to evaluate.
- Can tolerate stochastic noise in function evaluations.



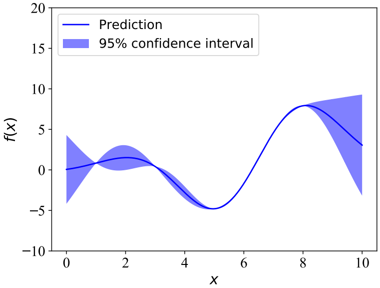
- Acquisition function serves as a utility measurement to select the next point for evaluation;
- Surrogate model is adaptively refined to approximate the latent function.

Gaussian Process Regression

- Gaussian process regression is a Bayesian statistical approach for modeling unknown functions.

- Prior: $f \sim GP(0, k(\cdot,\cdot))$
- Posterior:

$$\begin{cases} m(\mathbf{x}) = k(\mathbf{x},\mathbf{X})^\top (k(\mathbf{X},\mathbf{X}) + \sigma^2\mathbf{I})^{-1}\mathbf{Y}, \\ \sigma^2(\mathbf{x}) = k(\mathbf{x},\mathbf{x}) - k(\mathbf{x},\mathbf{X})^\top (k(\mathbf{X},\mathbf{X}) + \sigma^2\mathbf{I})^{-1} k(\mathbf{x},\mathbf{X}), \end{cases}$$



Acquisition Function

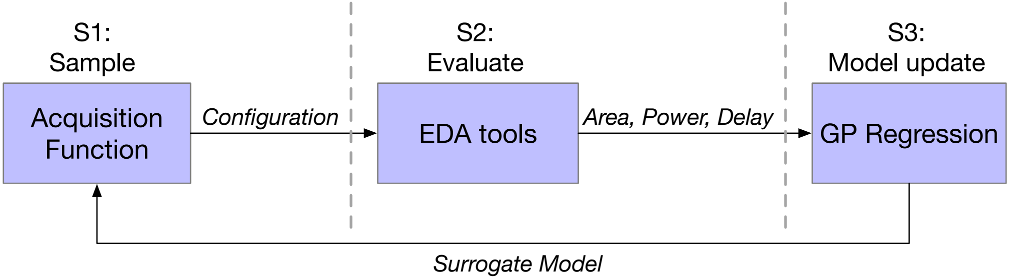
Lower Confidence Bound (LCB)

- $\mathrm{LCB}(\boldsymbol{x}) = m(\boldsymbol{x}) - \beta\sigma(\boldsymbol{x})$;
- $m(x)$ indicates the “exploitation” and $\sigma(x)$ indicates the “exploration”;
- β is a parameter that balances the exploitation and exploration.

Expected Improvement (EI)

- $\mathrm{EI}(\boldsymbol{x}) = \sigma(\boldsymbol{x})(\lambda\Phi(\lambda) + \phi(\lambda))$, where $\lambda = \frac{\tau - \xi - \mu(\boldsymbol{x})}{\sigma(\boldsymbol{x})}$
- The expected improvement function favors the optimal region with high probability and the promising area with high uncertainty estimation.

Overall Flow

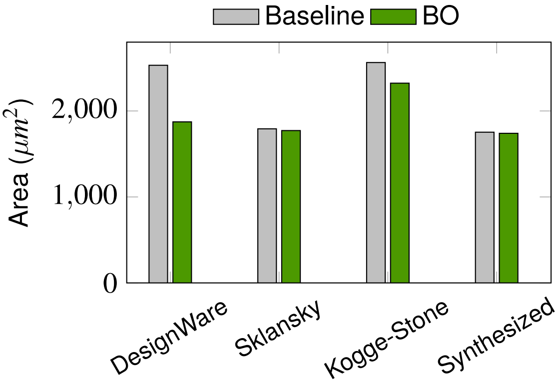


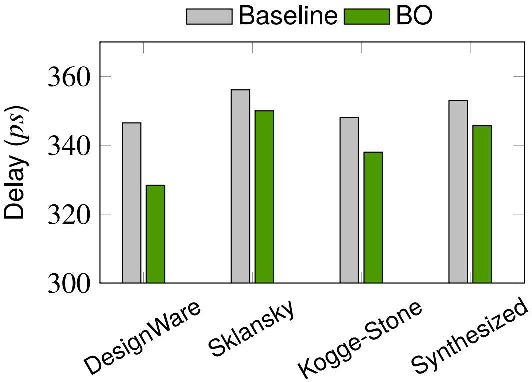
Experimental Configurations

- Design:
  - DesignWare library,
  - Regular: Sklansky, Kogge-Stone,
  - Synthesized prefix adder [Ma+, TCAD'2019].
- Flow:
  - Cell library: 32nm SAED;
  - Tools: DC 2014 & ICC 2017.
- Design space:
  - Parameters in timing constraints, placement utilization, power options, etc.

BO vs. Industrial Setting

- DSE with single objective
- Baseline: a set of complete scripts for adder synthesis from industrial.

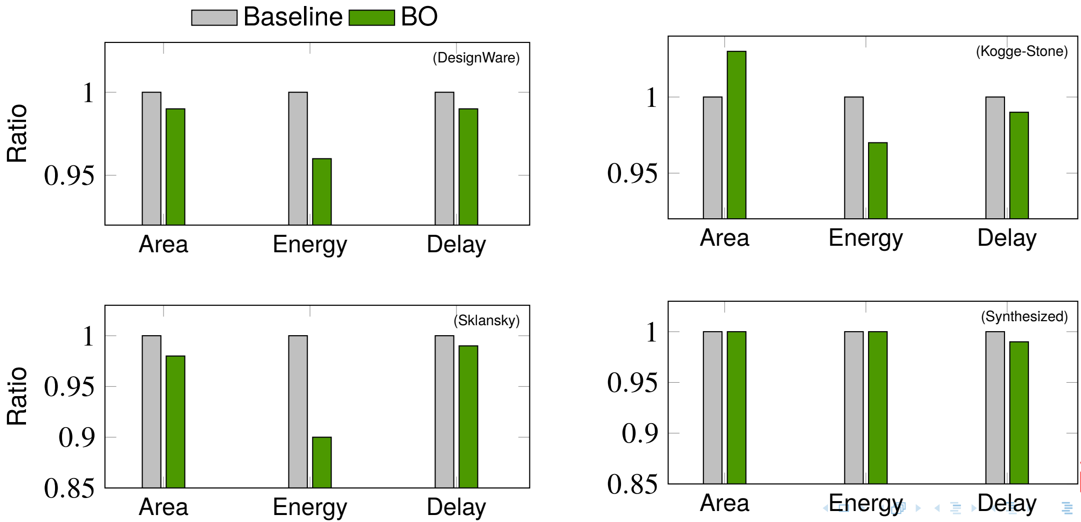




MLCAD

BO vs. Industrial Setting

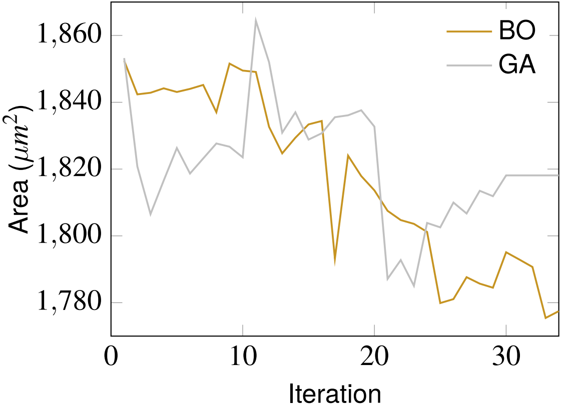
- DSE with multiple objectives using scalarization

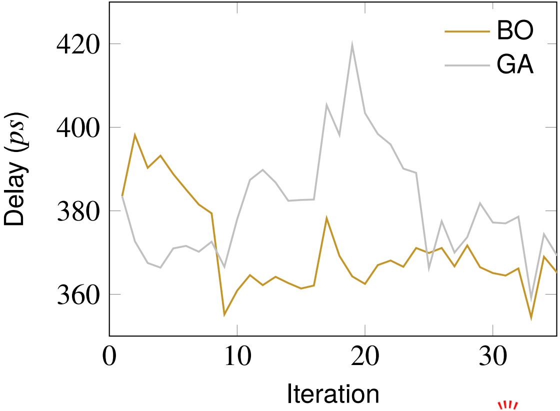


MLCAD

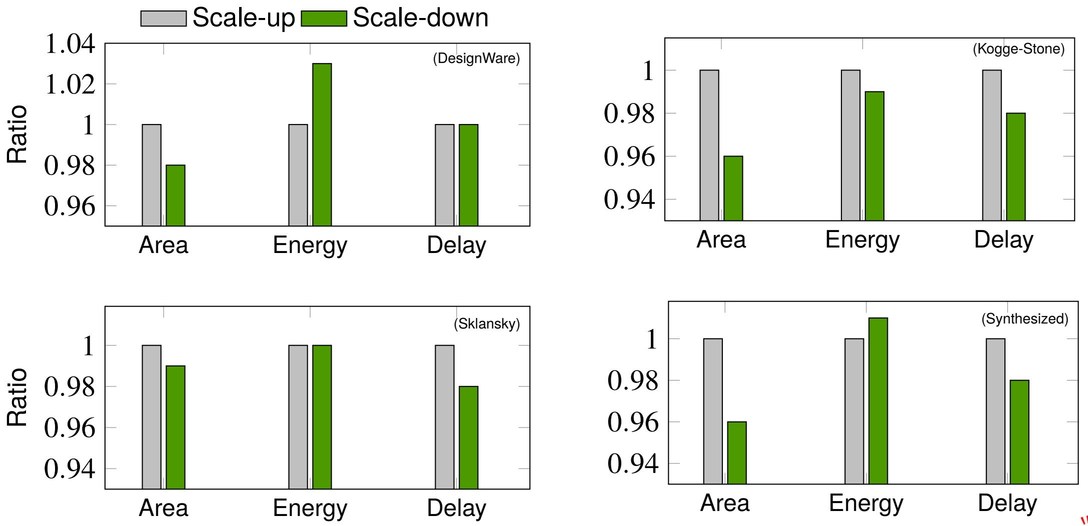
BO vs. Heuristic Search

- Evolutionary algorithms are widely applied in black-box function optimization;
- Genetic algorithm (GA) is not as stable as Bayesian optimization.





Scaling Trick



Discussion & Conclusion

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- A machine learning approach for better design;
- Adapt BO for multi-objective optimization to simultaneously minimize PPA values;
- BO substantially outperforms typical evolutionary algorithms.

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Further Improvement

- A unified design space for exploration.
  - ☹ Currently the design spaces of front-end and back-end are separated.
- A more elegant way to handle multi-objective optimization.
  - ☹ Scalarization requires tuning effort and data processing tricks.

Thank You