Input Responsiveness: Using Canary Inputs to Dynamically Steer Approximation

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CSE COMPUTER SCIENCE AND ENGINEERING UNIVERSITY OF MICHIGAN

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Approximate Computing

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- Trade small losses in accuracy for big gains in performance/energy

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- Trade small losses in accuracy for big gains in performance/energy
- Why approximation?
  - Machine learning, data mining, image, video and sound processing, statistics, graphics
  - Loose constraints on output quality, growing computational demands

Approximation Runtime Systems

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- Central question — *how to approximate?*

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  - How to parameterize approximation
  - Where in the application to approximate

The Importance of Input

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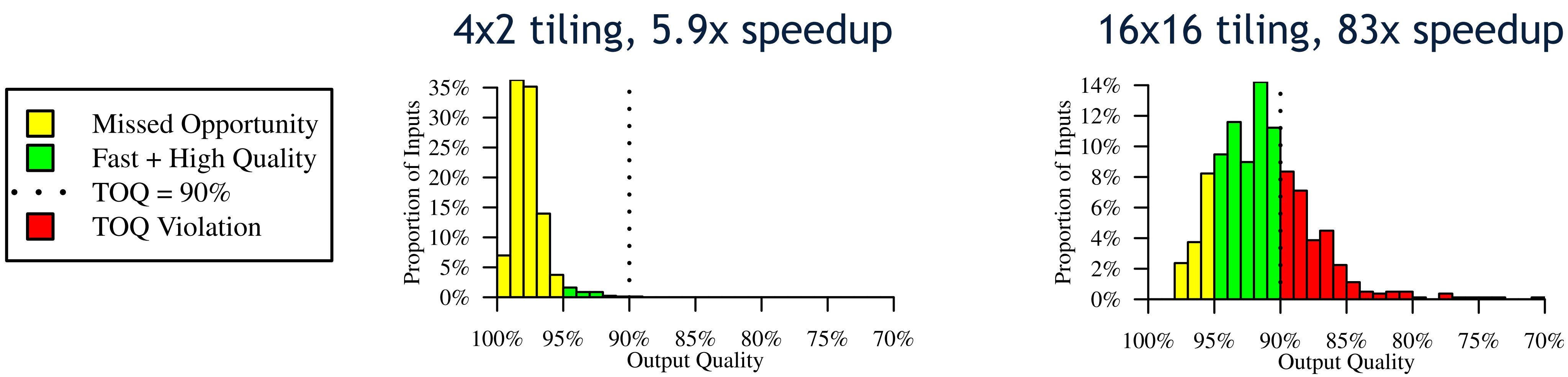

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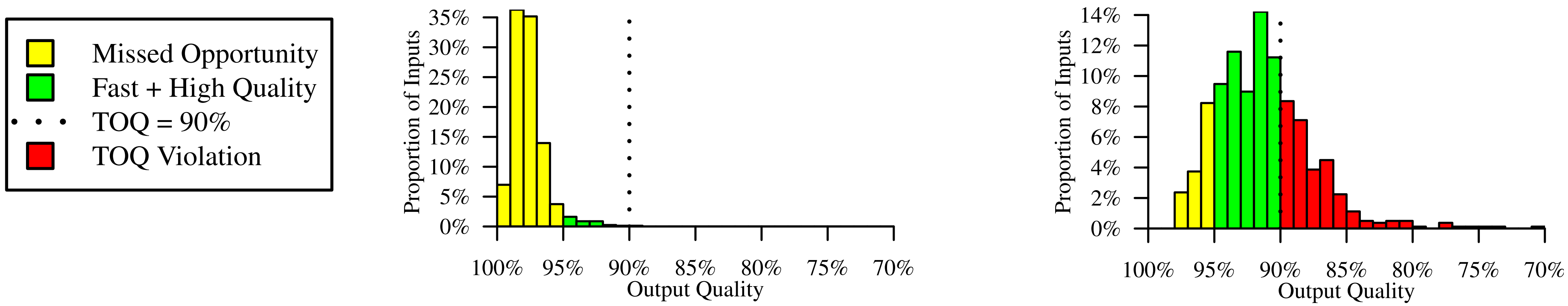
4x2 tiling, 5.9x speedup　　　16x16 tiling, 83x speedup



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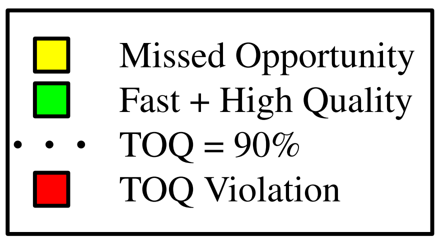

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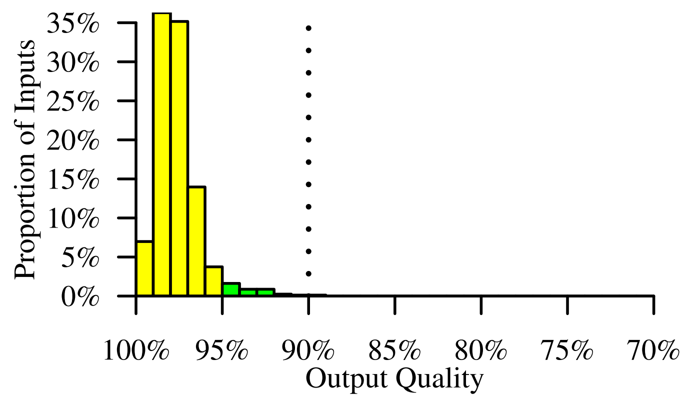

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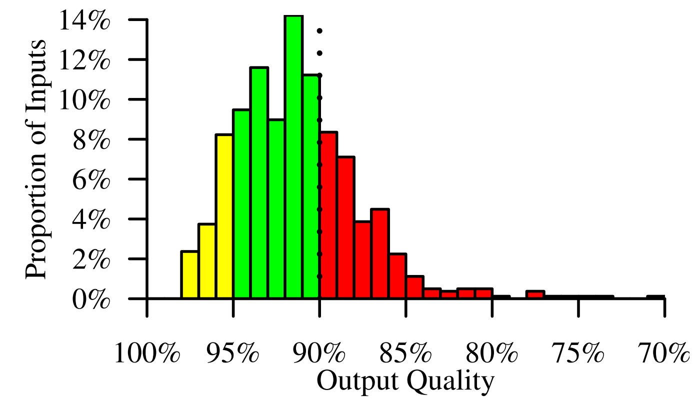

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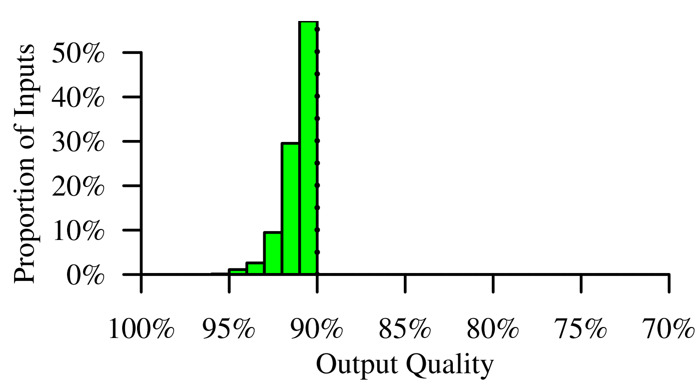
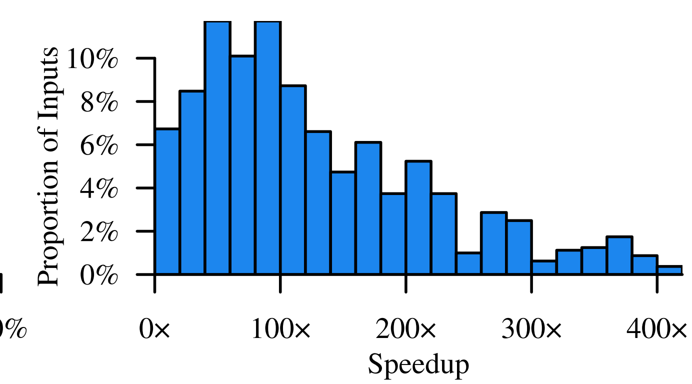
High output quality



61x speedup



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- **Goal** — end-to-end runtime system to choose *how to approximate*, customized for each input
  - Maximize performance given an accuracy target

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- **Goal** — end-to-end runtime system to choose *how to approximate*, customized for each input
  - Maximize performance given an accuracy target
- **Challenges**
  - Choose highly effective approximation per input
  - Choose it quickly!

Input Responsive Approximation (IRA)

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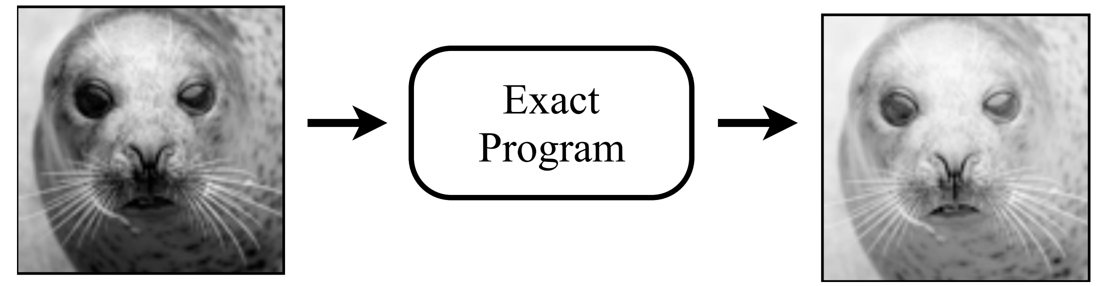
exact execution



Full Input

Exact Solution

Input Responsive Approximation (IRA)

- Create a small *canary input* from full input

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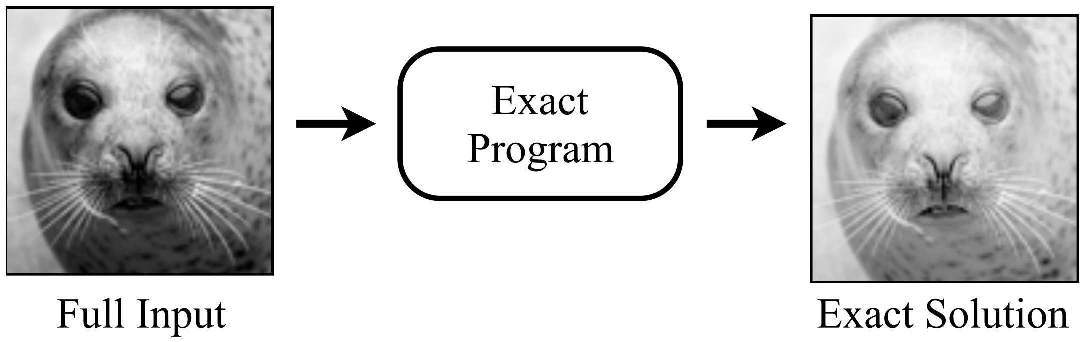

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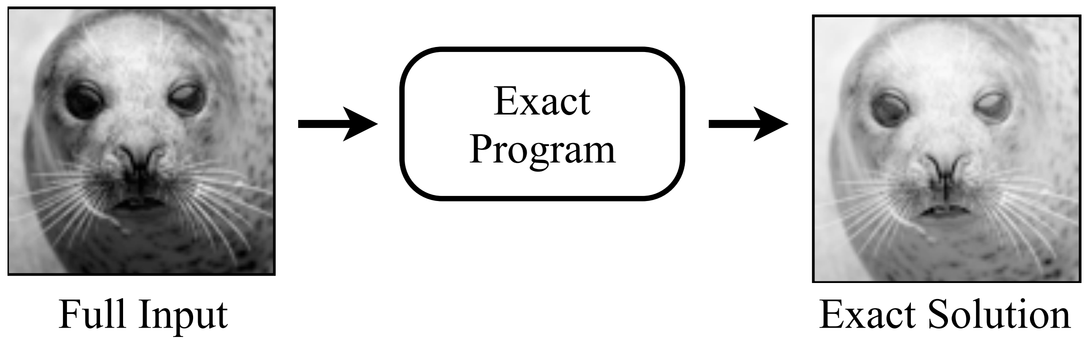
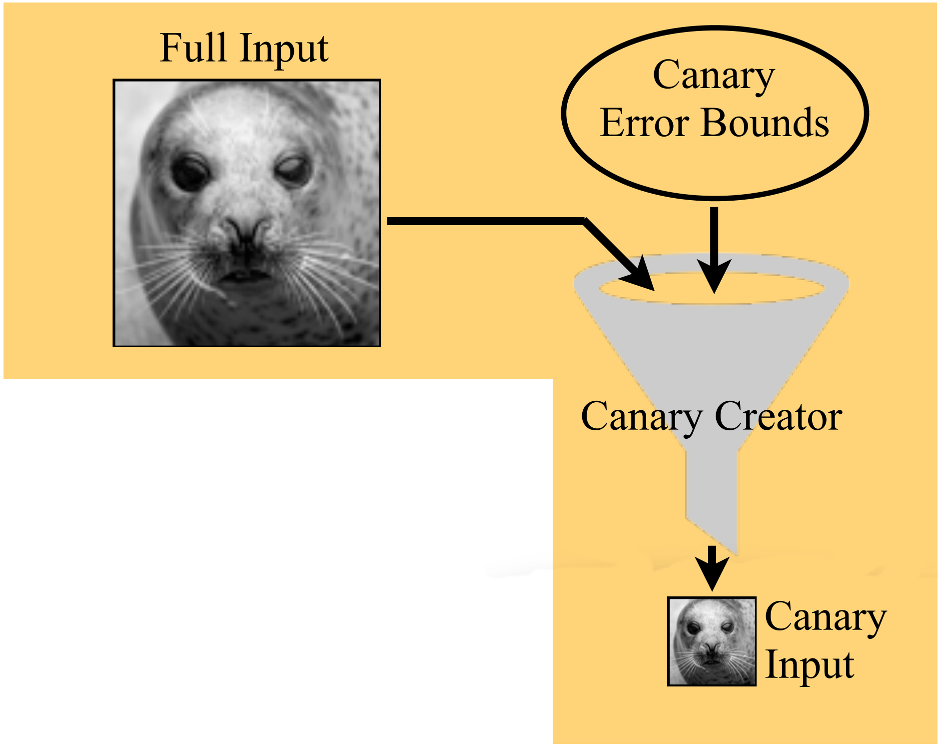


approximation with IRA



Input Responsive Approximation (IRA)

- Create a small *canary input* from full input
- Choose an approximation using canary

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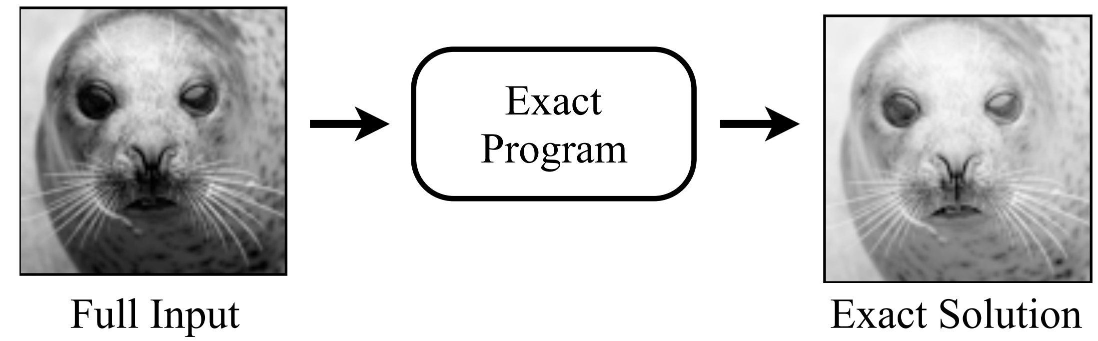

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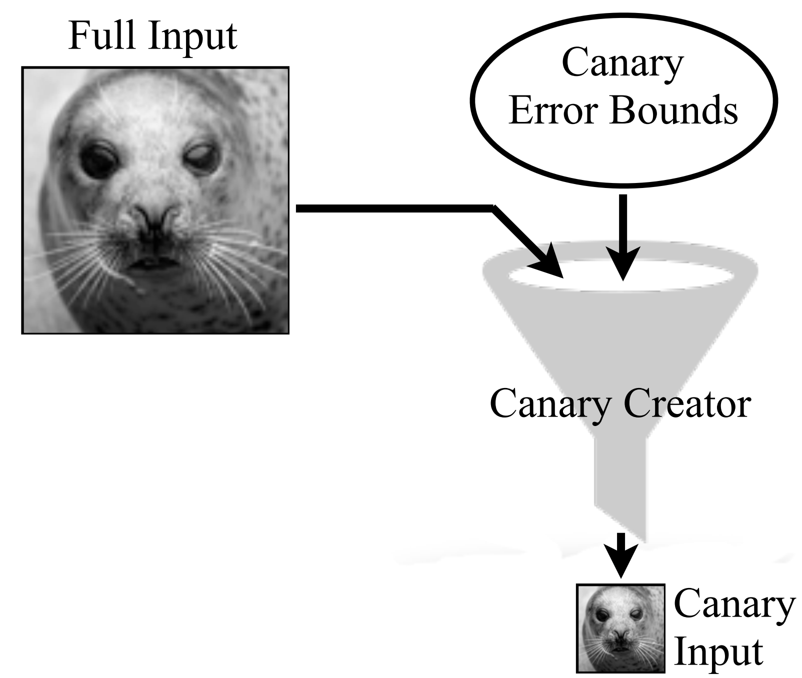

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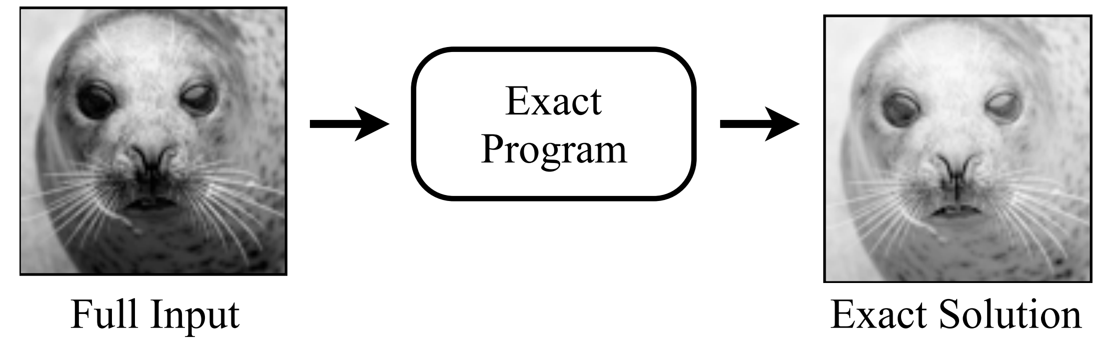

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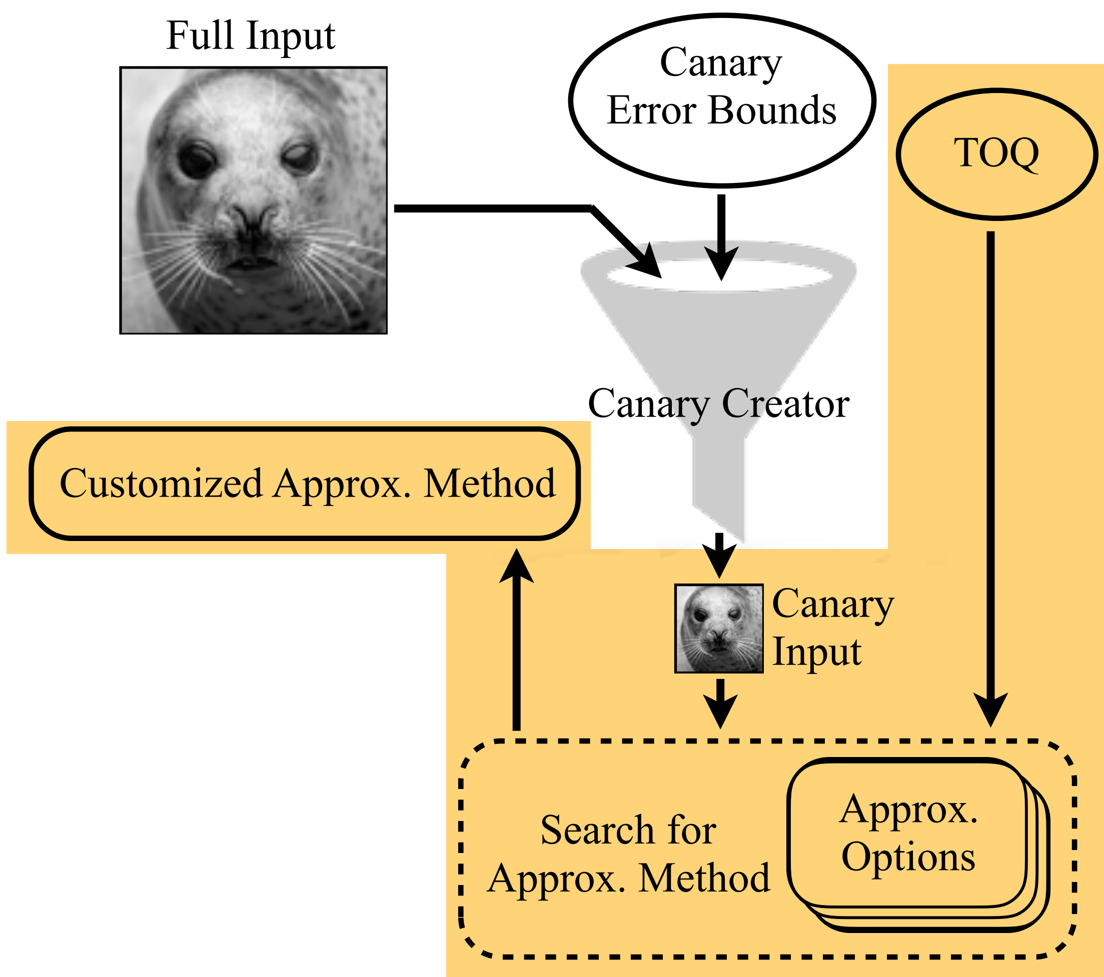
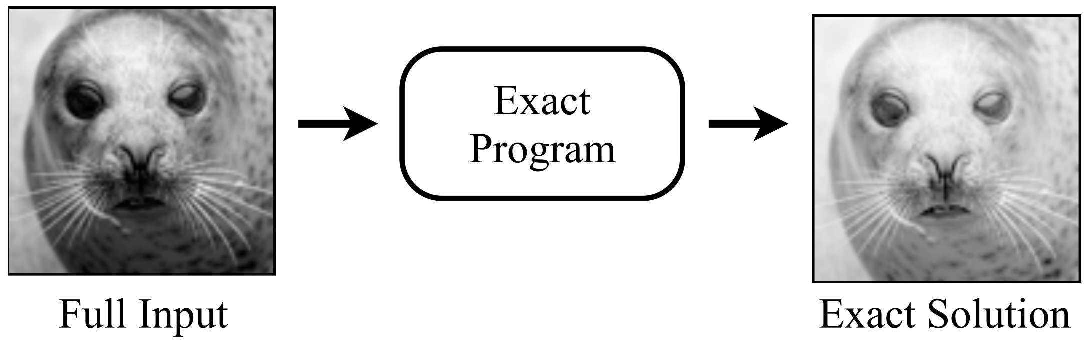


Input Responsive Approximation (IRA)

- Create a small *canary input* from full input
- Choose an approximation using canary
- Compute approximate solution on full input

exact execution



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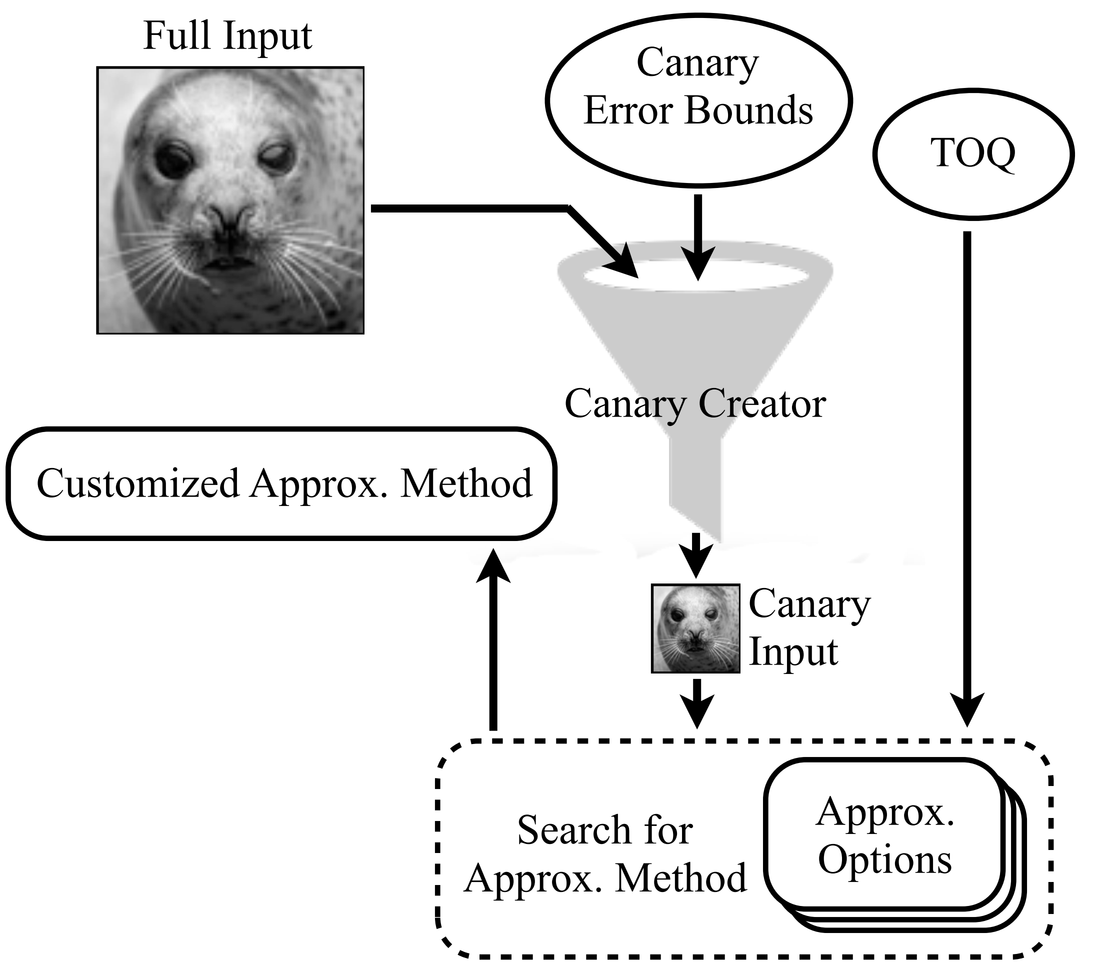

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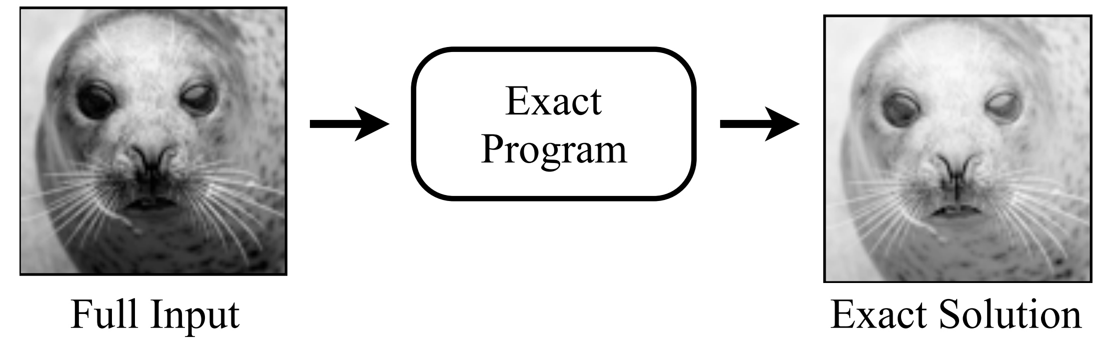

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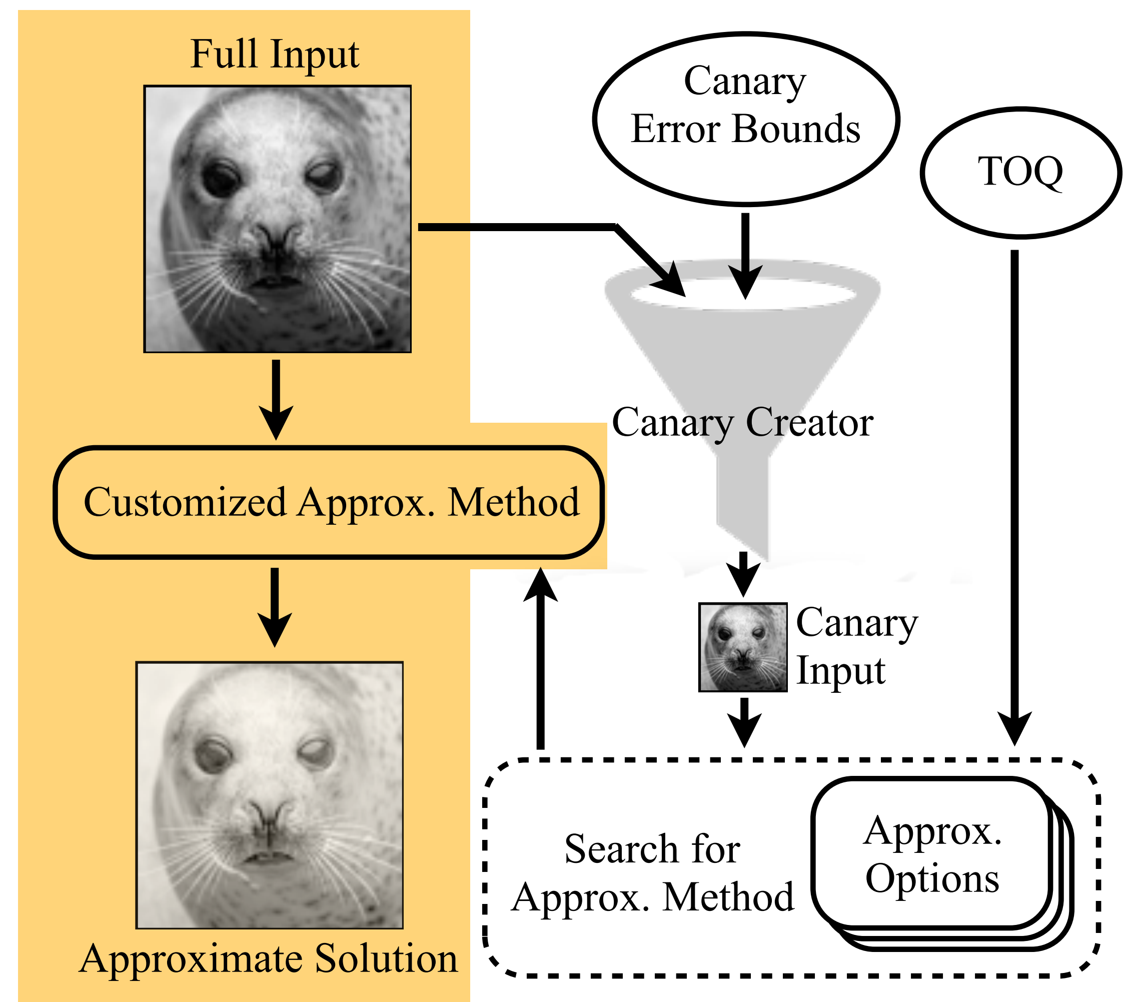

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Goals of Canary Creation in IRA

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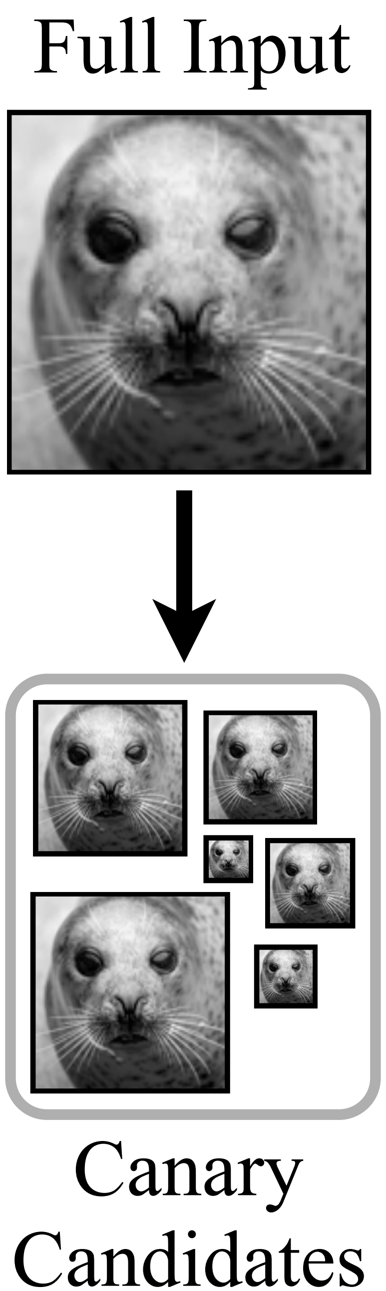
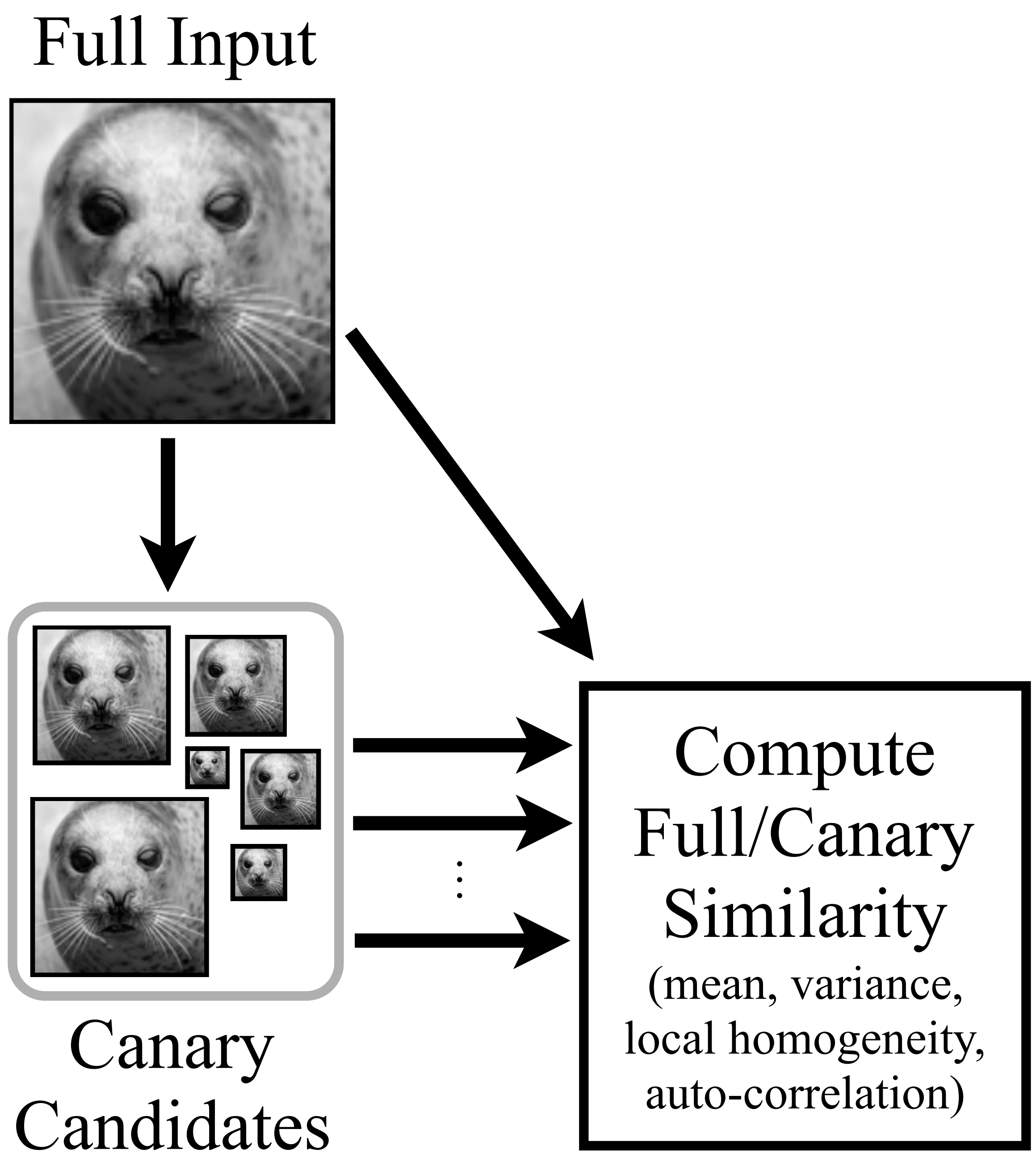
- **Similarity** – sufficient similarity to full input
- **Inexpensive Computation** – create it quickly
- **Size Reduction**
    - Computational complexity often depends on input size
    - Canary should be as small as possible

Full Input


Full Input
Canary
Candidates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Compute
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(mean, variance,
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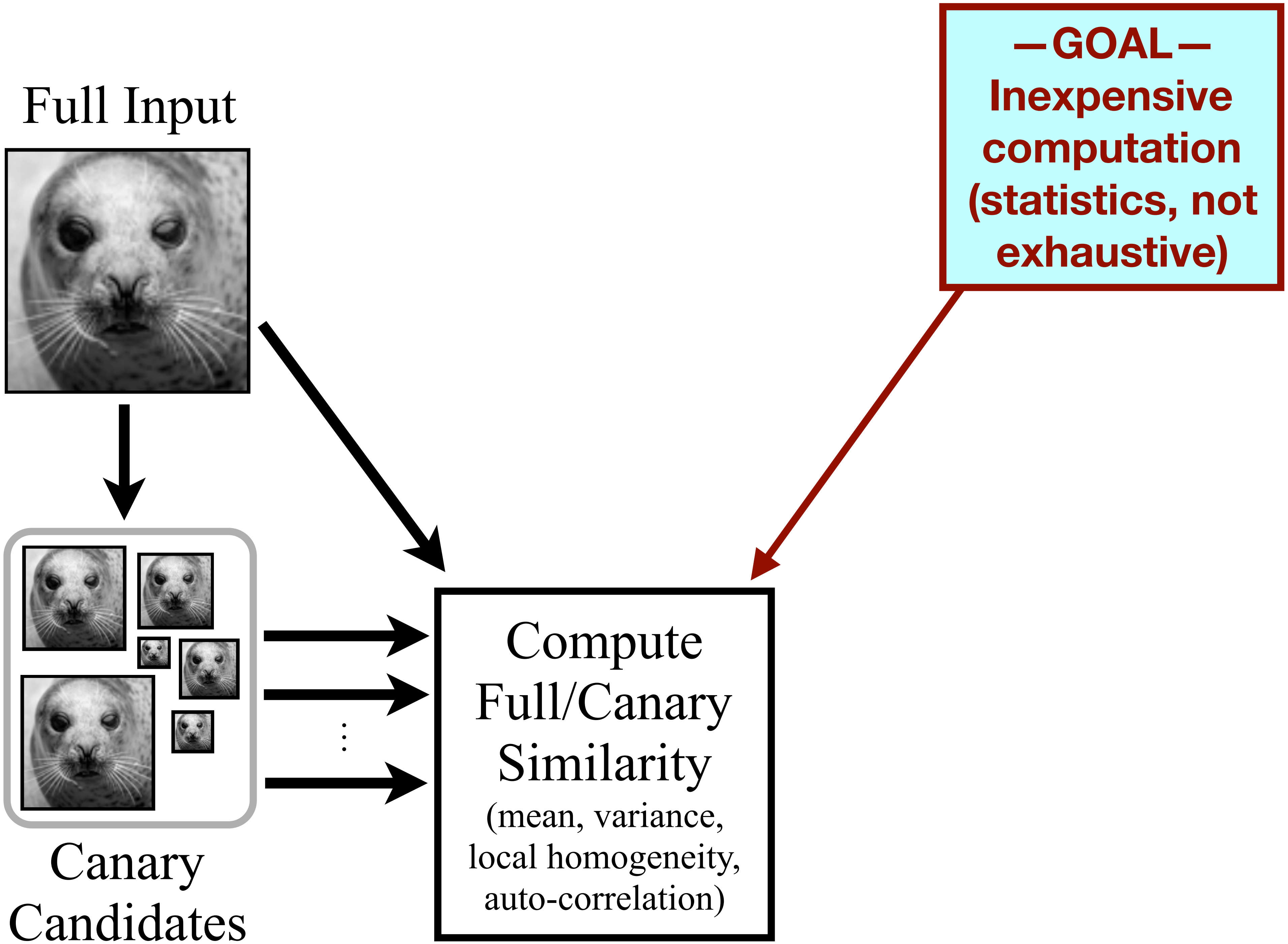
—GOAL—
Inexpensive computation (statistics, not exhaustive)
Full Input
Canary Candidates
Compute Full/Canary Similarity
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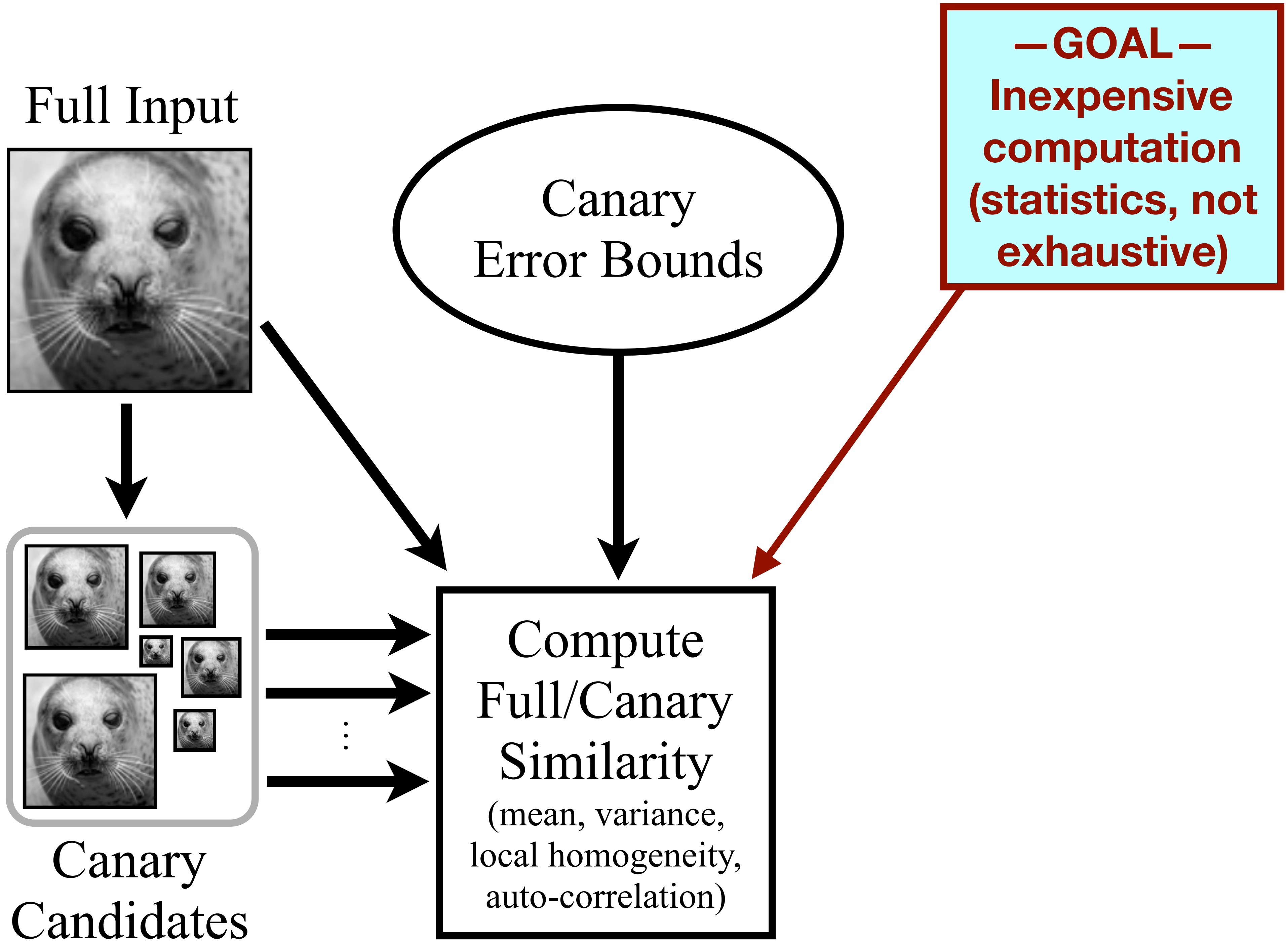
Full Input
Canary Error Bounds
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Inexpensive computation (statistics, not exhaustive)
Canary Candidates
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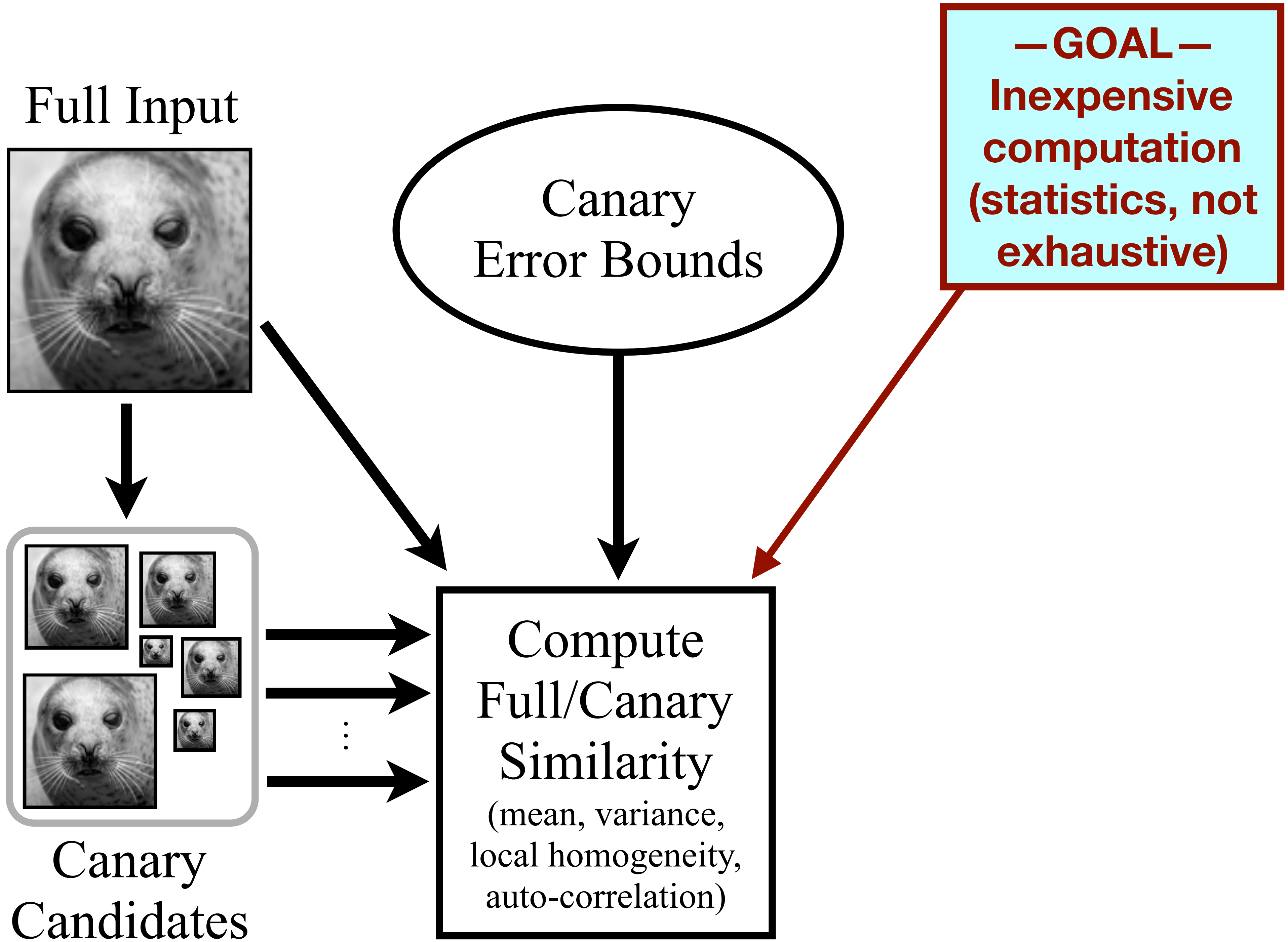
	Mean	Variance	Local Homogeneity	Autocorrelation
Description	Mean μ of input elements	Variance σ^2 of input elements	Proportion Λ of elements represented by λ in canary $\notin [\lambda - \sigma z_{1-\alpha/2}, \lambda + \sigma z_{1-\alpha/2}]$	Correlation ρ among pairs of input elements (y_j, y_{j+1})
Null Hypothesis (H_0) **Alt. Hypothesis** (H_A)	$H_0 : \overline{\mu_i} = \mu_0$ $H_A : \overline{\mu_i} \neq \mu_0$	$H_0 : \overline{\sigma_i}^2 = \sigma_0^2$ $H_A : \overline{\sigma_i}^2 \neq \sigma_0^2$	$H_0 : \overline{\Lambda_i} \leq 0.1$ $H_A : \overline{\Lambda_i} > 0.1$	$H_0 : \overline{\rho_i} = \rho_0$ $H_A : \overline{\rho_i} \neq \rho_0$
Test Statistic (t_i)	$t_i = \frac{\mu_0 - \overline{\mu_i}}{\overline{\sigma_i}\sqrt{n}}$	$t_i = \frac{\overline{\sigma_i}^2}{\sigma_0^2}$	$t_i = \frac{\sqrt{n}\,\lvert\overline{\Lambda_i} - 0.1\rvert}{\sqrt{0.1(1-0.1)}}$	$t_i = \frac{ln\left(\frac{(1+\rho_0)(1-\overline{\rho_i})}{(1-\rho_0)(1+\overline{\rho_i})}\right)}{2\sqrt{n-3}}$
p-value (p_i)	$p_i = 2P(Z > t_i)$	$p_i = 2P(F_{n-1,n-1} > t_i)$	$p_i = 2P(Z > t_i)$	$p_i = 2P(Z > t_i)$
Sample Size (n)	$n = 2(z_{1-\alpha/2k}$ $+ z_{1-\beta/k})^2$	Formula yields no simple form; see Cohen [14] for details.	$g(x) = \sqrt{x(1-x)}$ $n = 0.1^{-2}(g(0.1)z_{1-\alpha/2k} + g(\overline{\Lambda_i})z_{1-\beta/k})^2$	$n = \frac{4(z_{1-\alpha/2k} + z_{1-\beta/k})^2}{ln((1+\rho_0)/(1-\rho_0))^2}$
Acceptability Test	*Holm-Bonferroni method:* sort p-values $p_1, p_2, \ldots p_k$ to obtain sorted p-values $p_{(1)}, p_{(2)}, \ldots p_{(k)}$. Find the minimum index m such that $p_{(m)} > \frac{\alpha}{k+1-m}$, then reject all canaries $C_{(i)}$ where $i \geq m$.			
Definitions	α: the desired bound on the probability of committing any Type I errors (false negative), β: the desired bound on Type II errors (false positive) k: the number of canary candidates, C_i: the ith canary candidate, $\overline{x_i}$: the sample statistic x for canary C_i, x_0: the sample statistic x for the full input Z: the standard normal distribution, z_y: the quantile function at y of Z, $F_{b,c}$: the F-distribution with degrees of freedom b and c			



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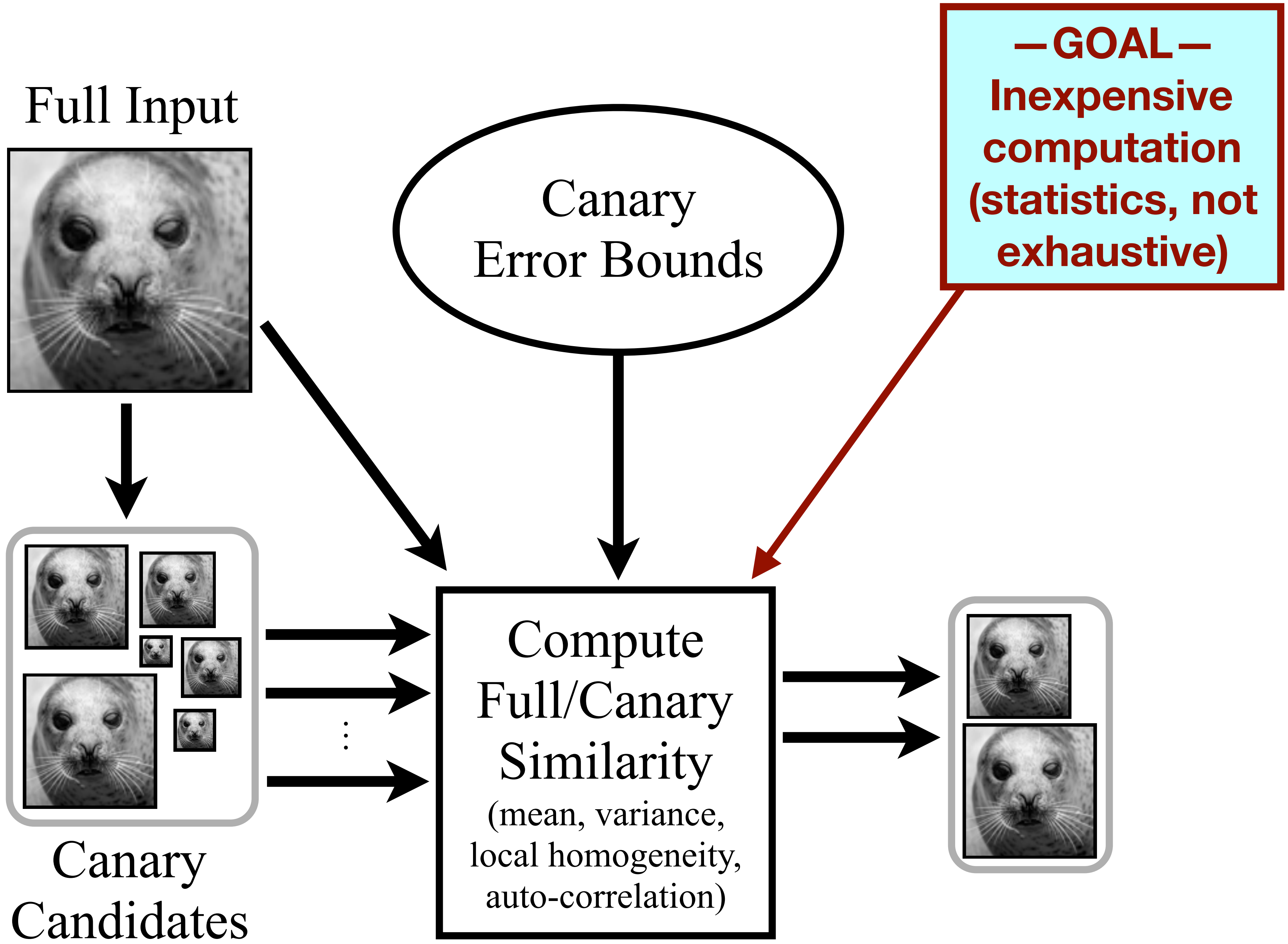

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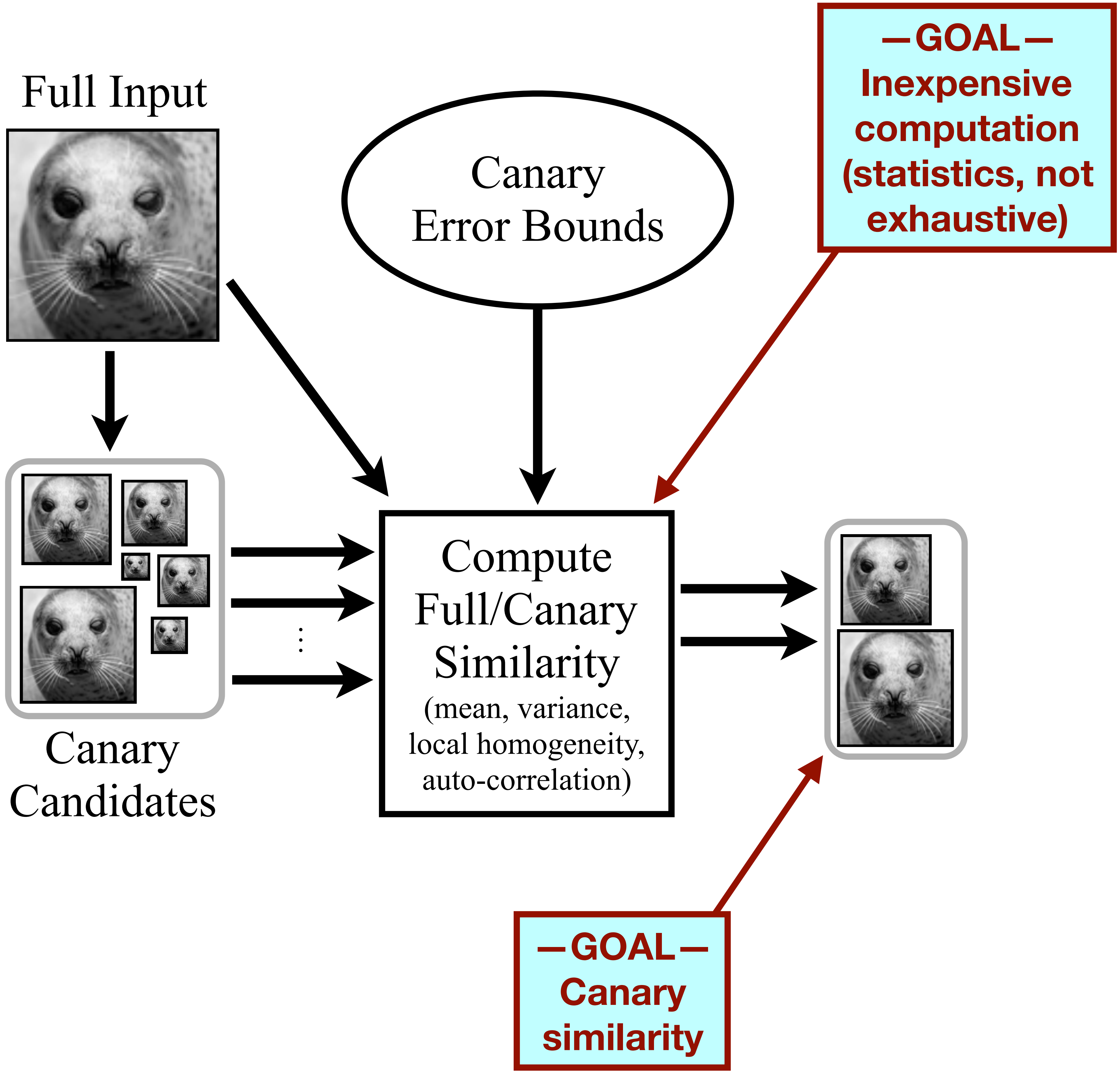
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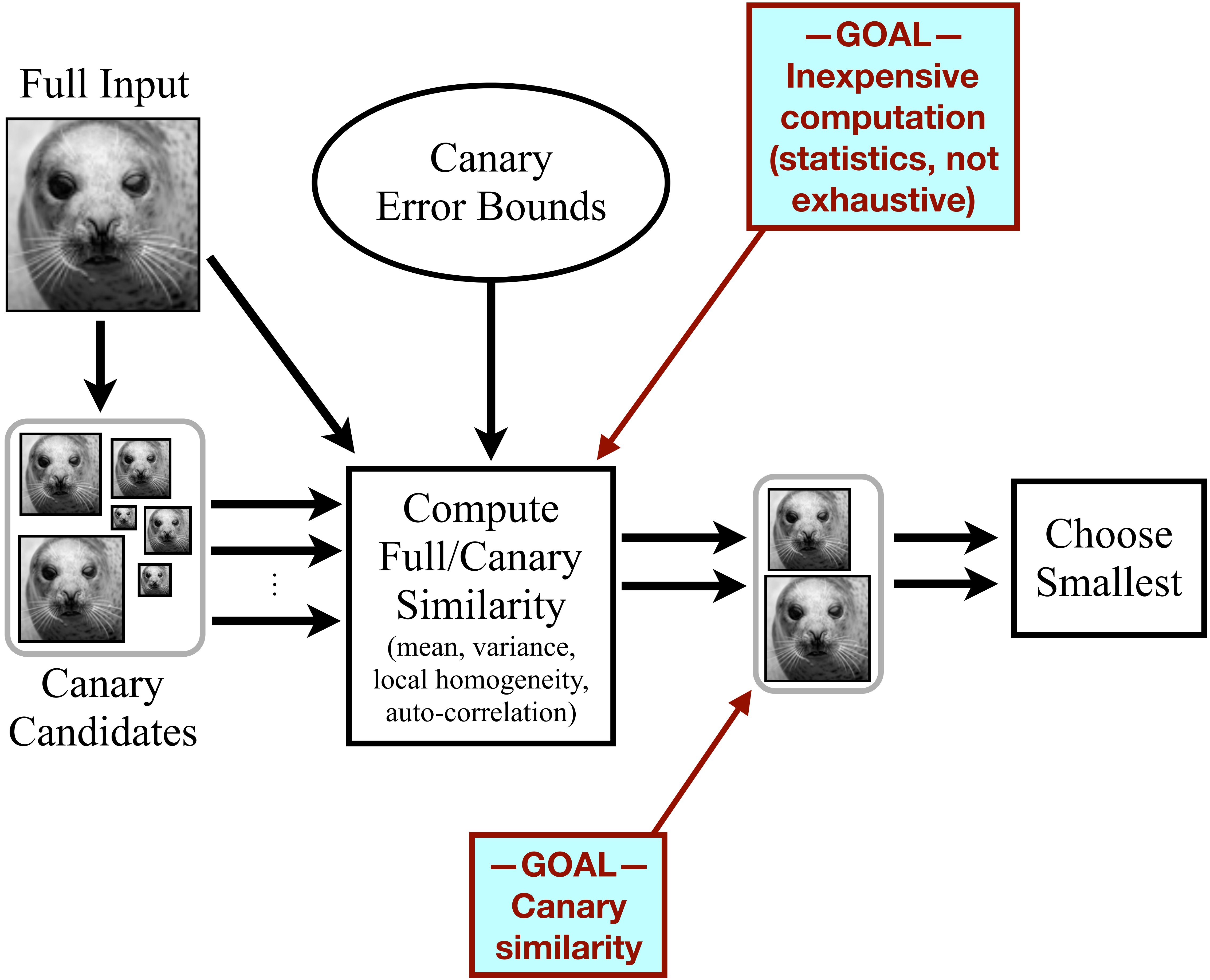
Canary similarity



Full Input
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Inexpensive computation (statistics, not exhaustive)
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Choose Smallest
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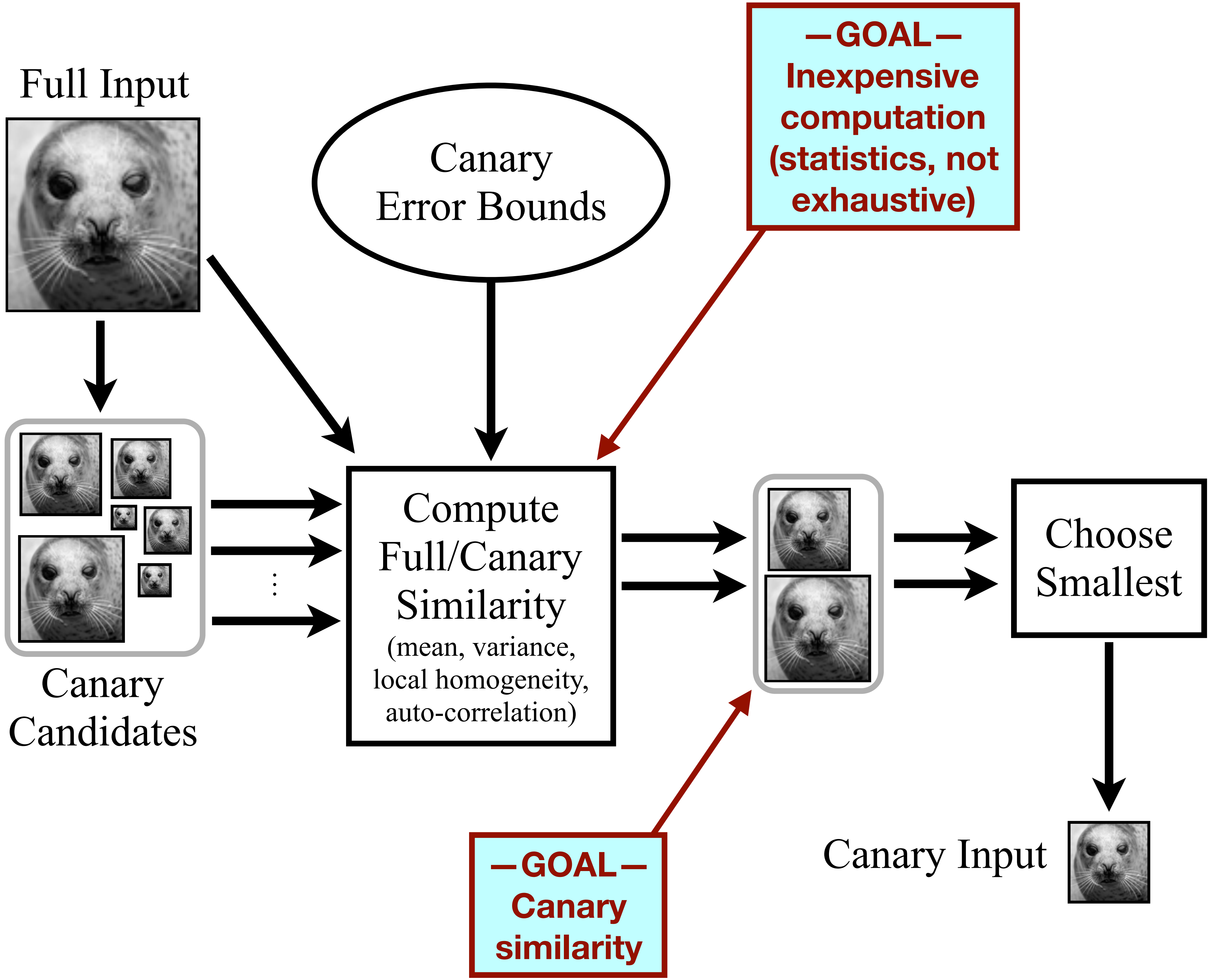
Canary similarity



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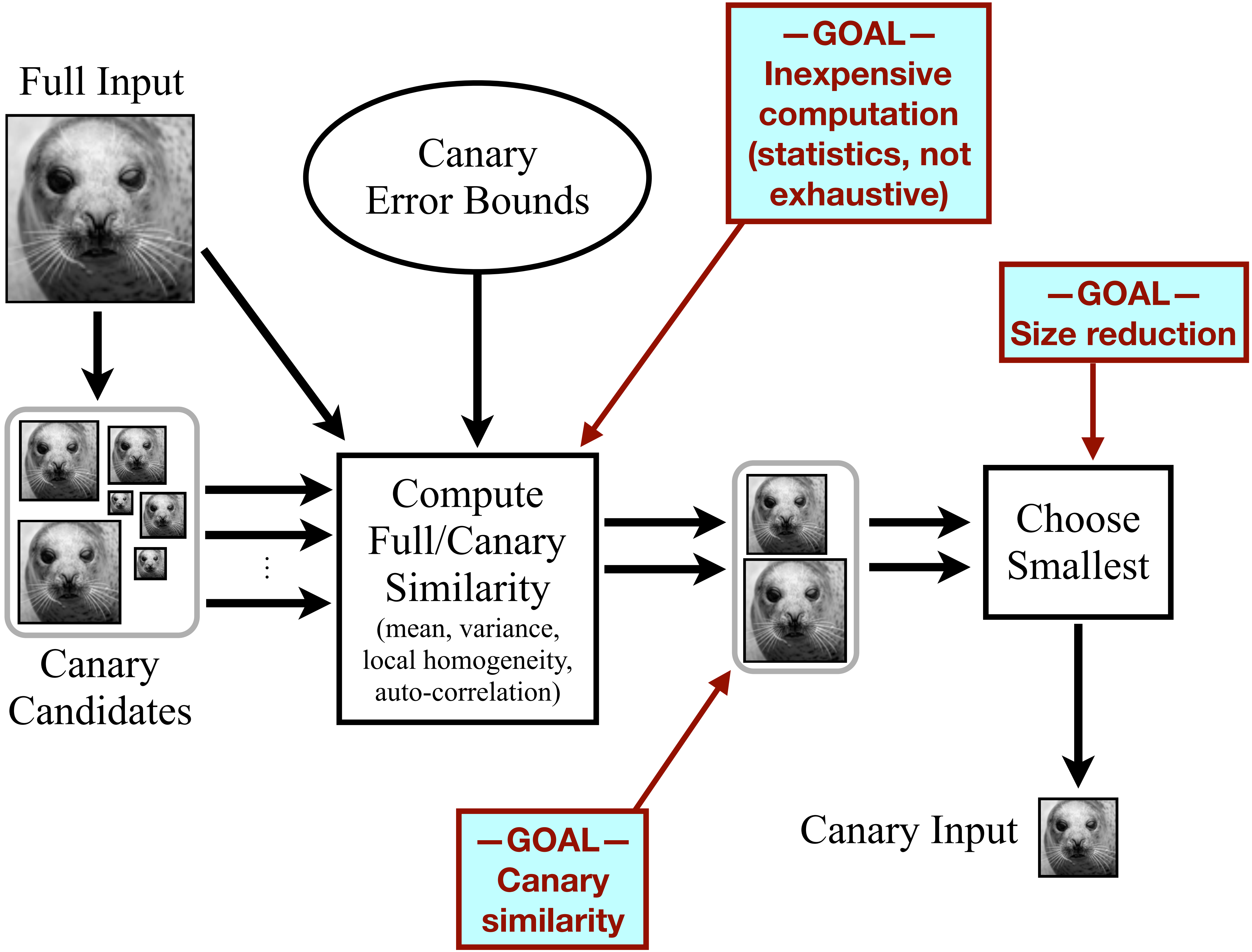
Canary Input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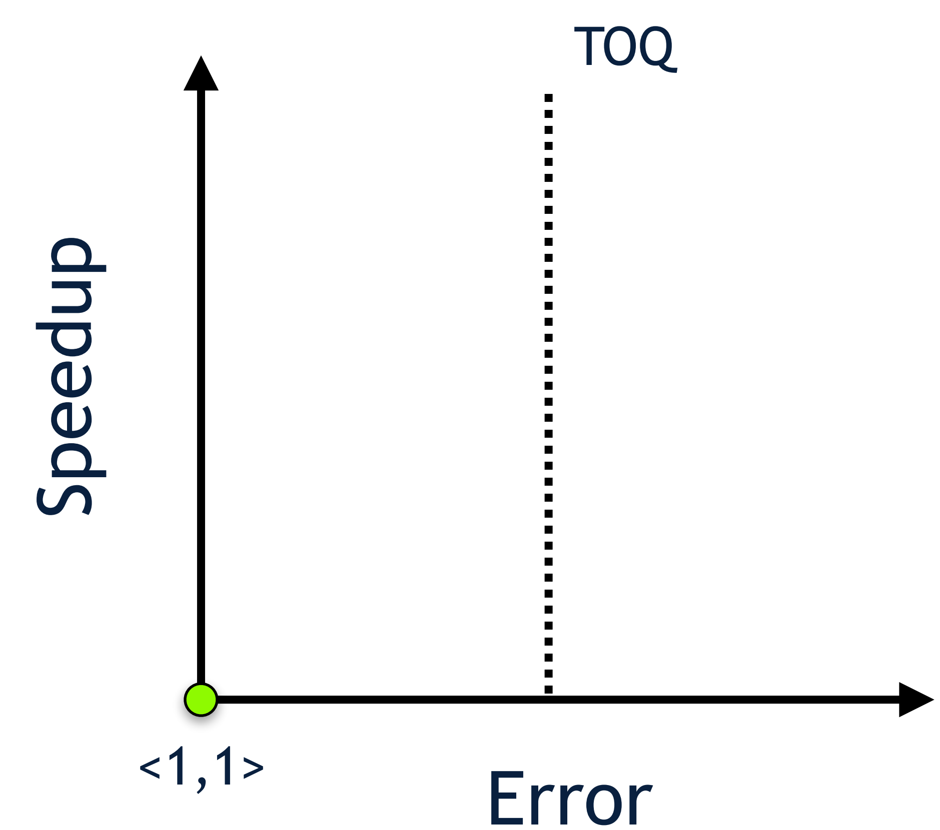
Canary-driven Search



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Encoding of approximation parameters (2 code regions)

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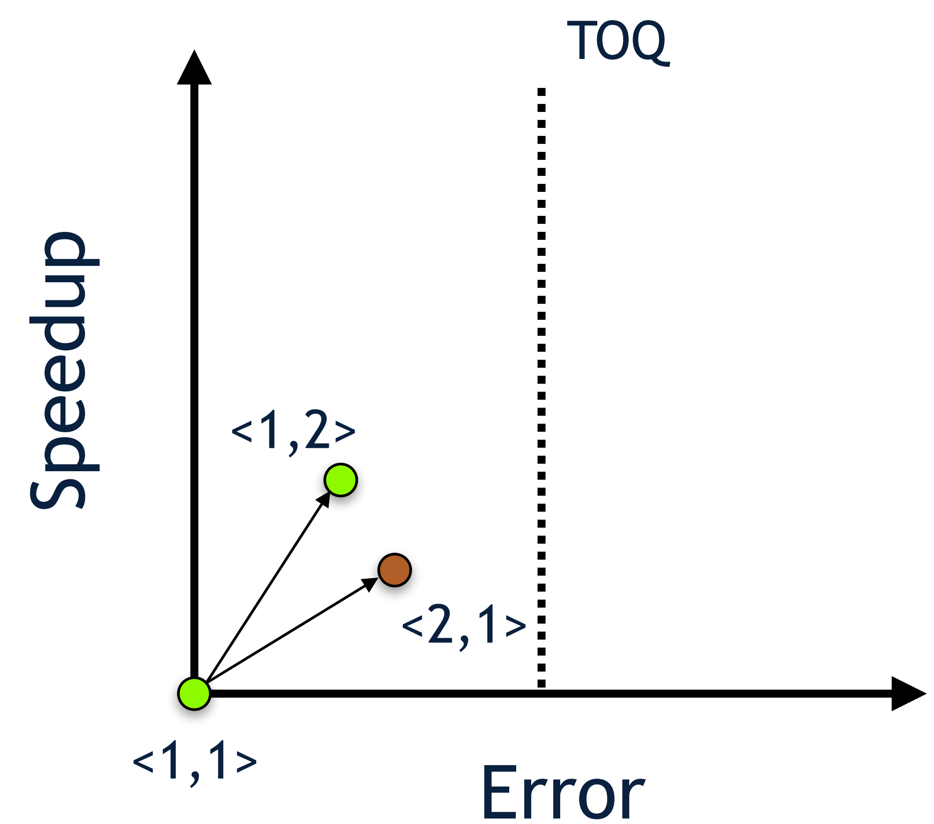

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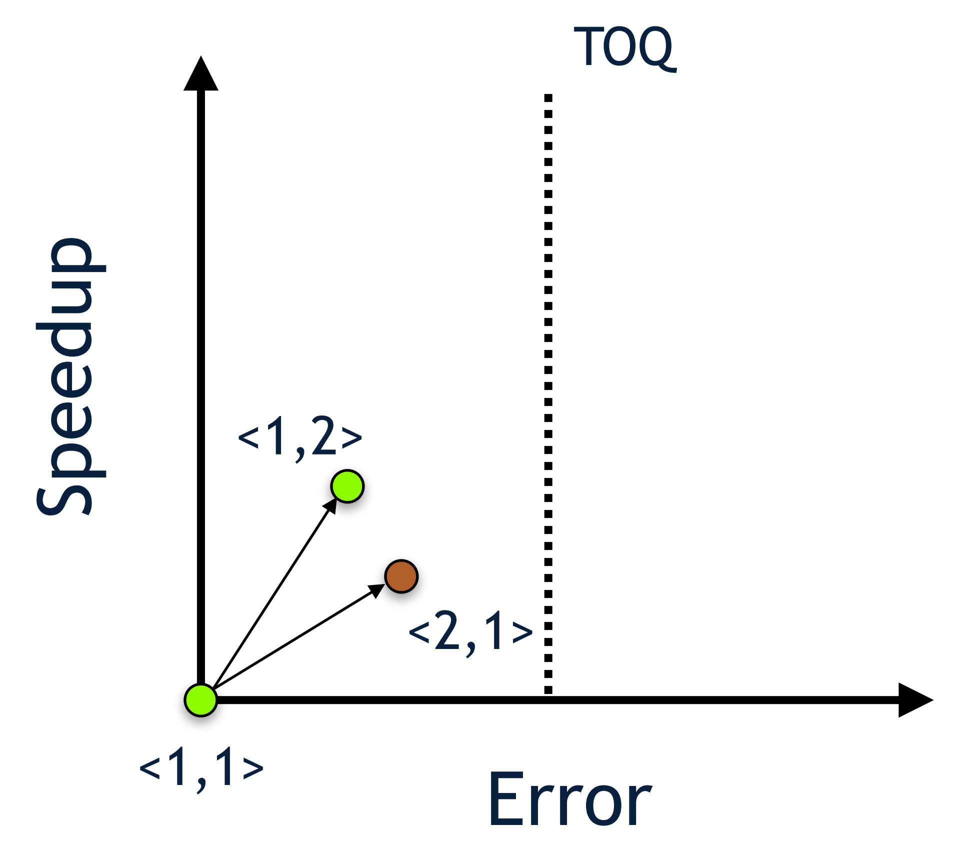

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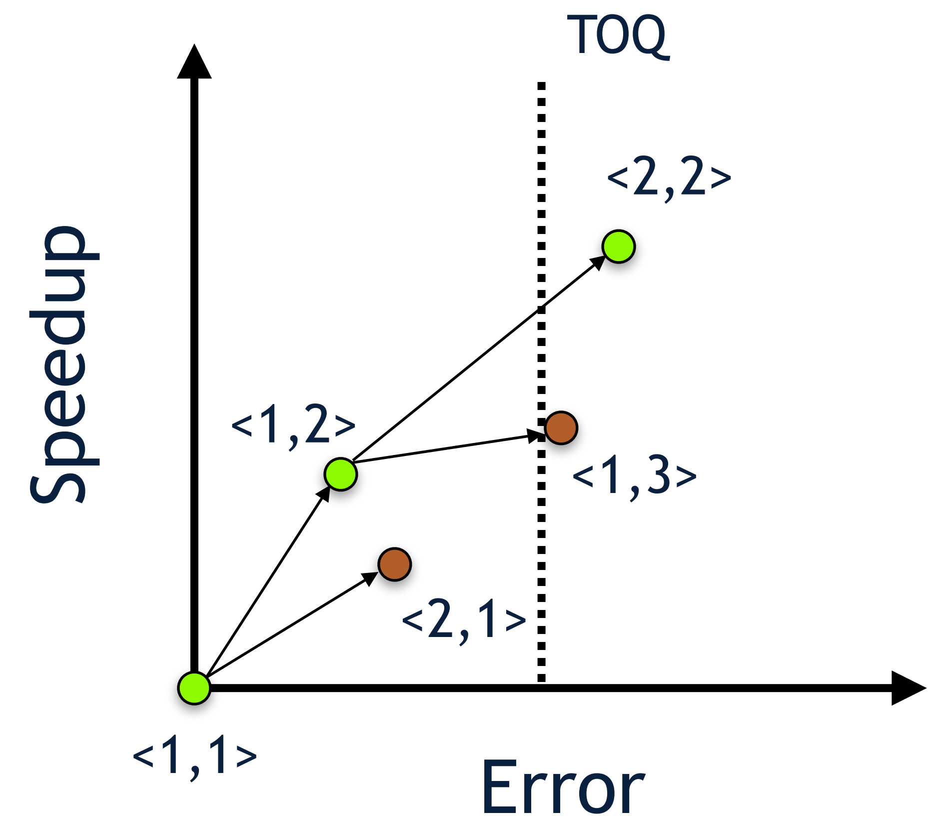

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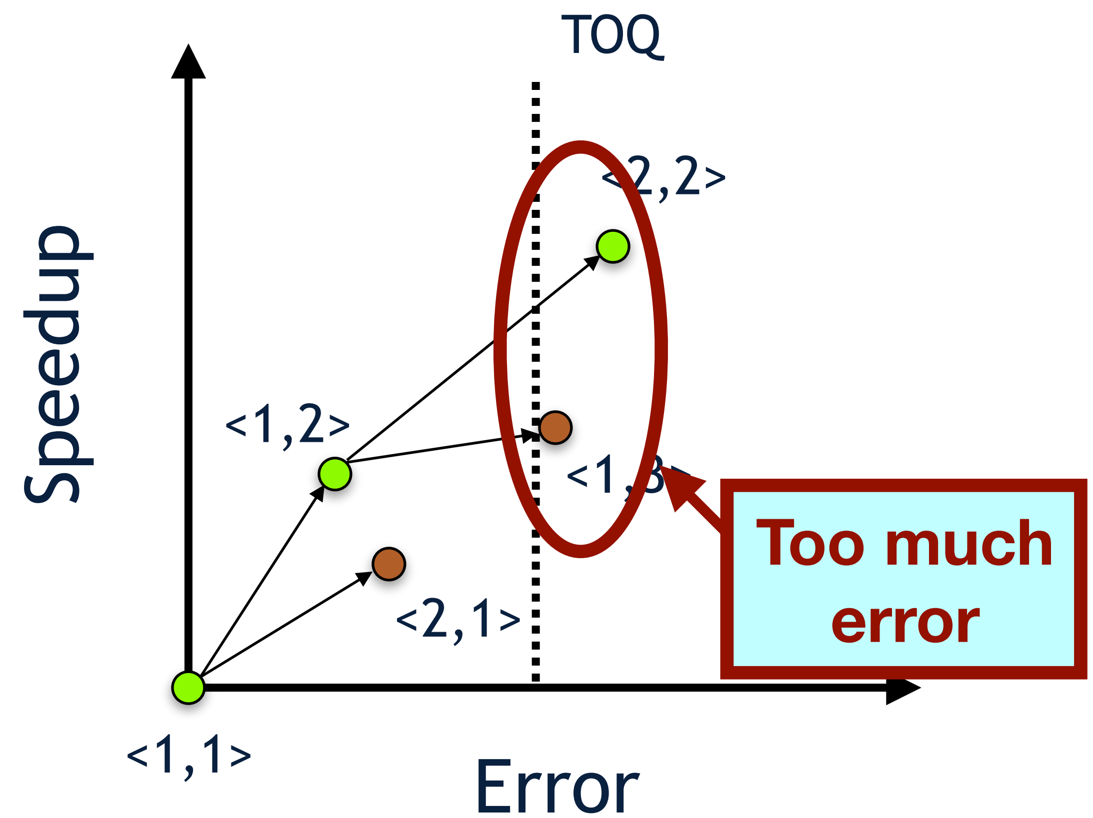

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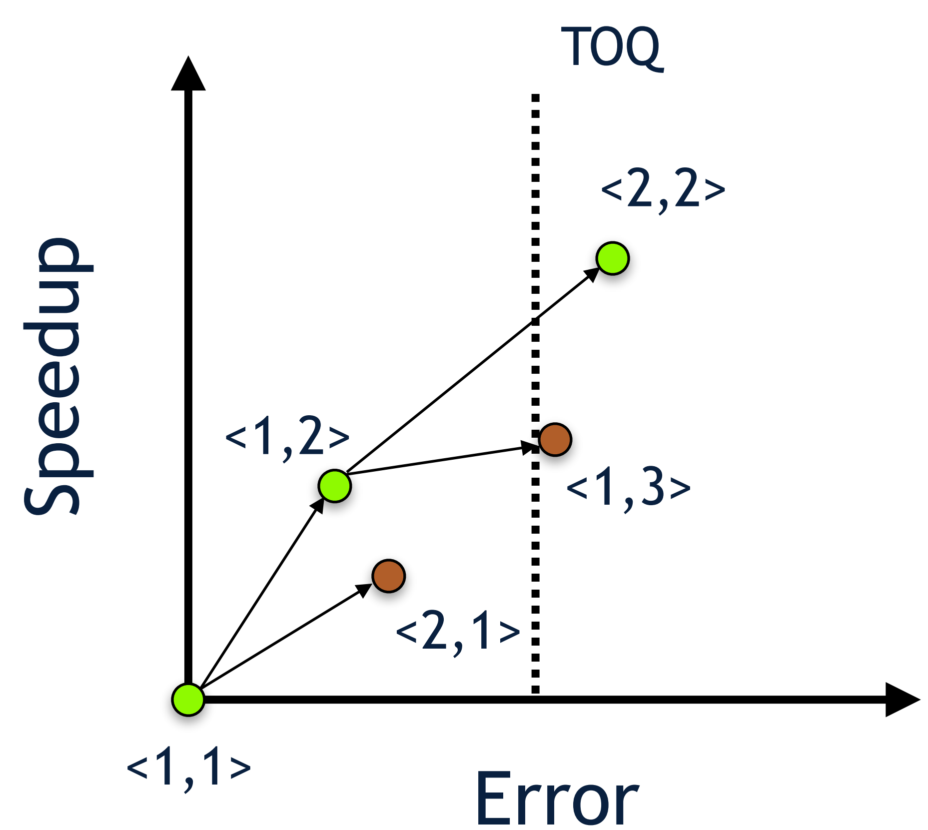

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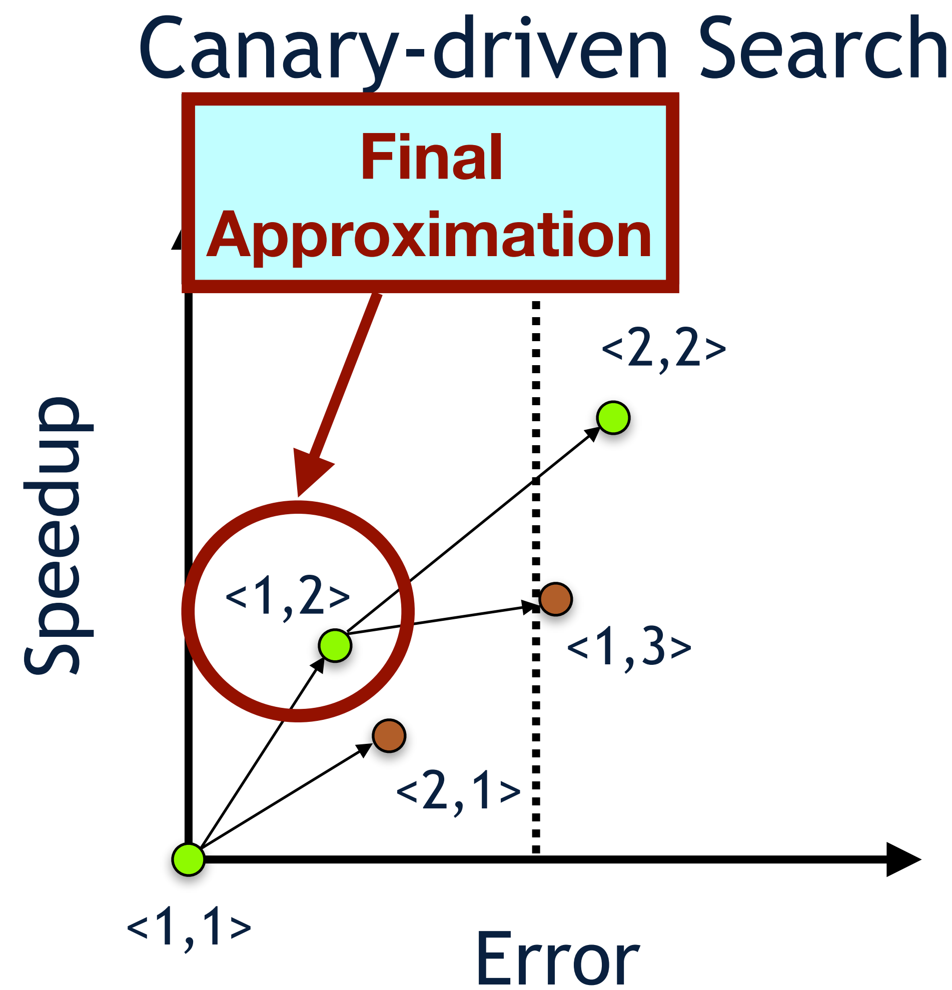

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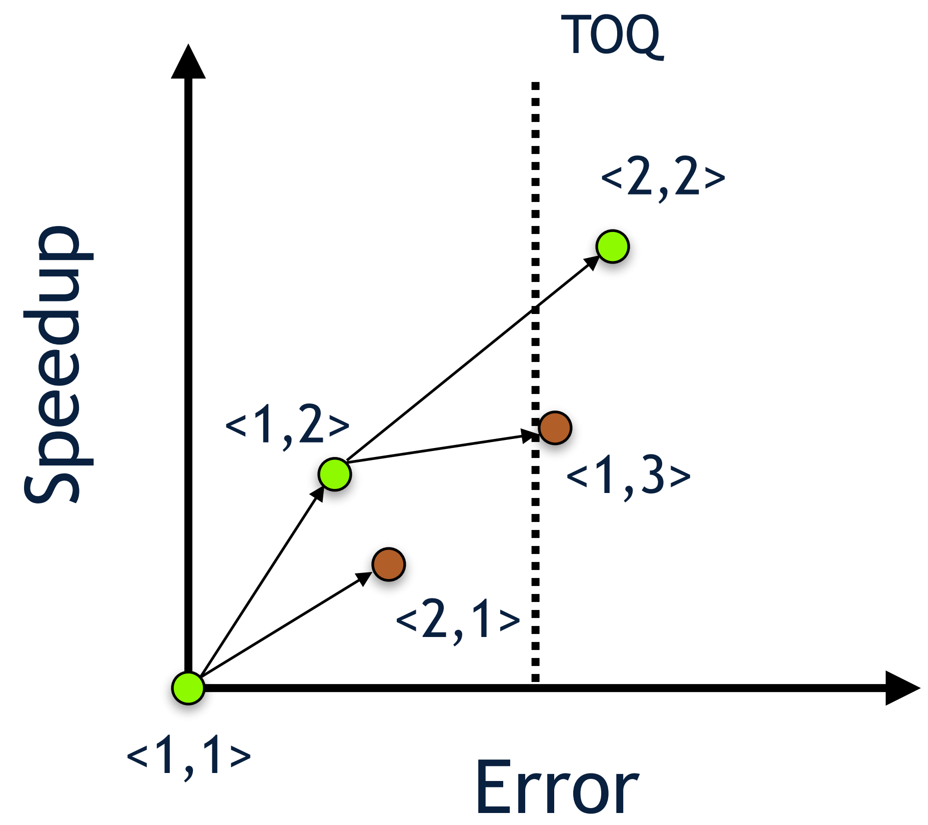

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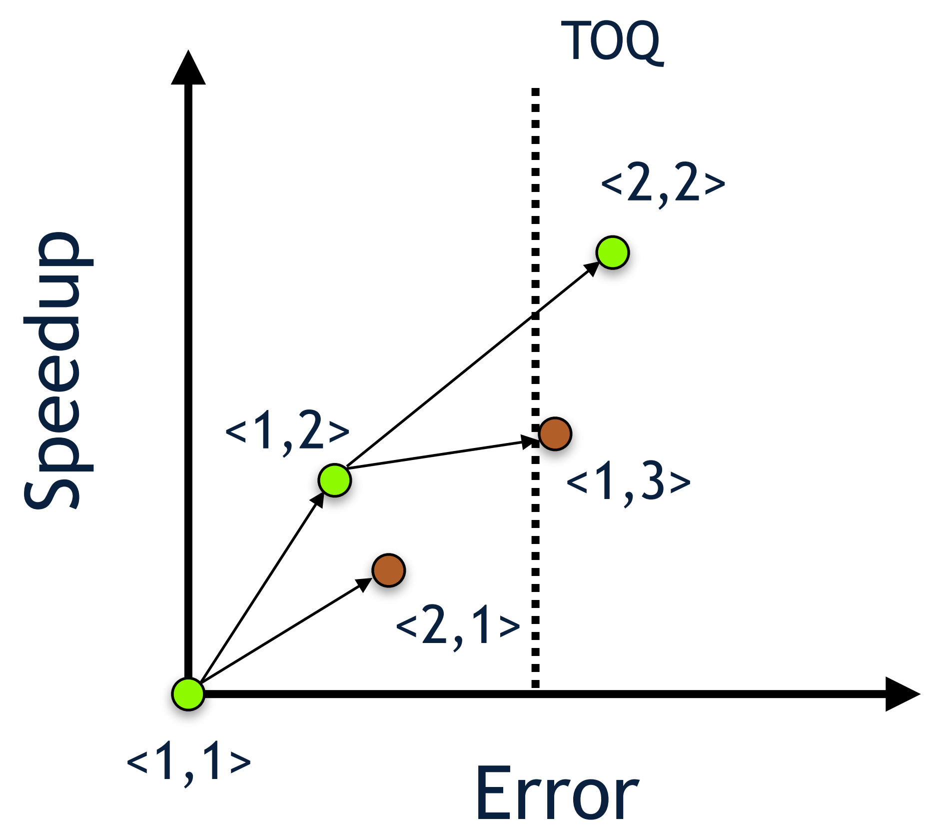
- Use the resulting approximation on full input

Canary-driven Search



Evaluation

Experimental Setup

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- 13 applications
  - Approximation opportunities per application — 1-5
  - Inputs per application — 2-800

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- Canary similarity metric — variance

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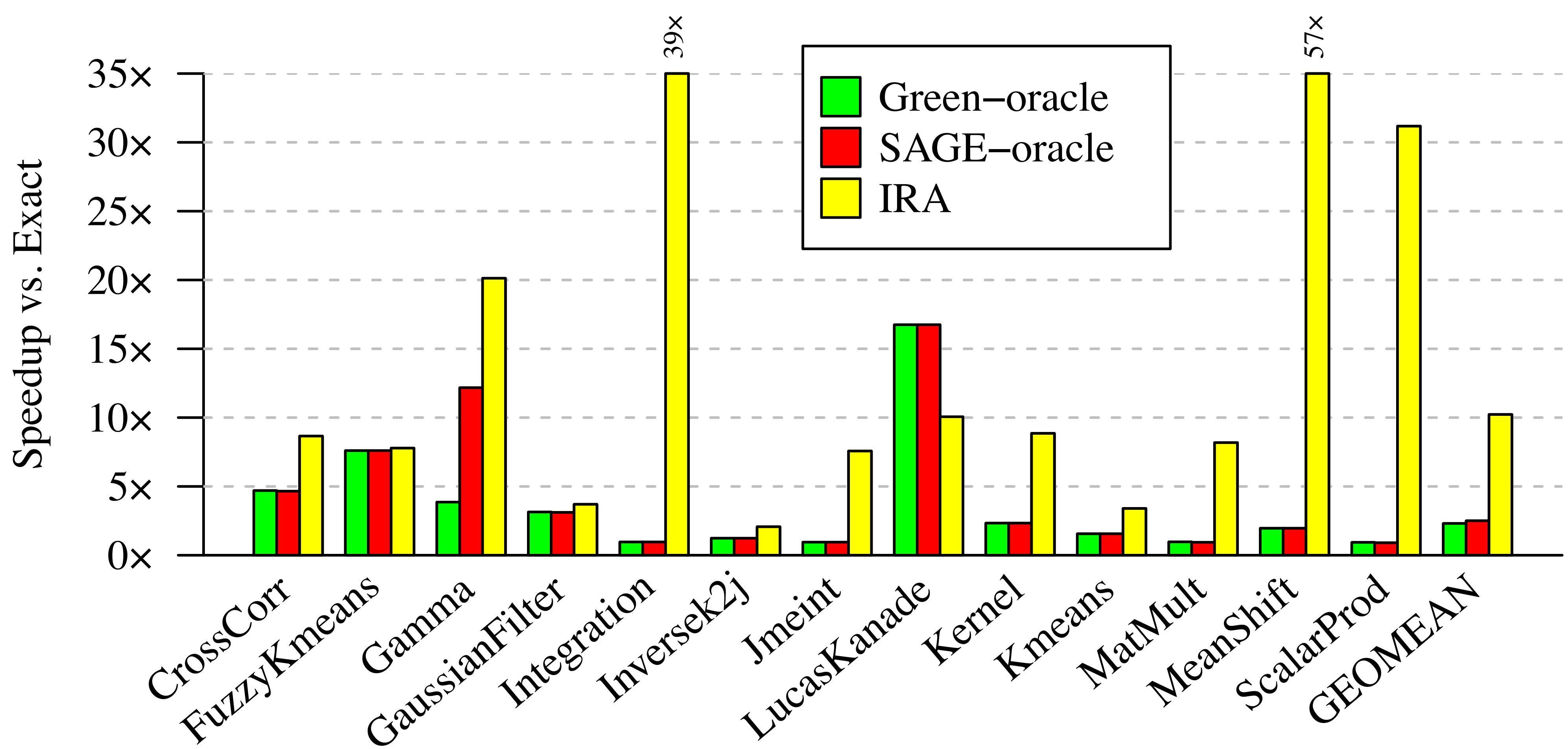
  - Loop perforation, tiling, algorithm choice, numerical approximation
- Canary similarity metric — variance
- Target output quality (TOQ) — 90%

Speedup — IRA vs. Prior Work

- Calibration — compare exact result to approximate result every so often
  - Oracle versions of SAGE [MICRO'13] and Green [PLDI'10]



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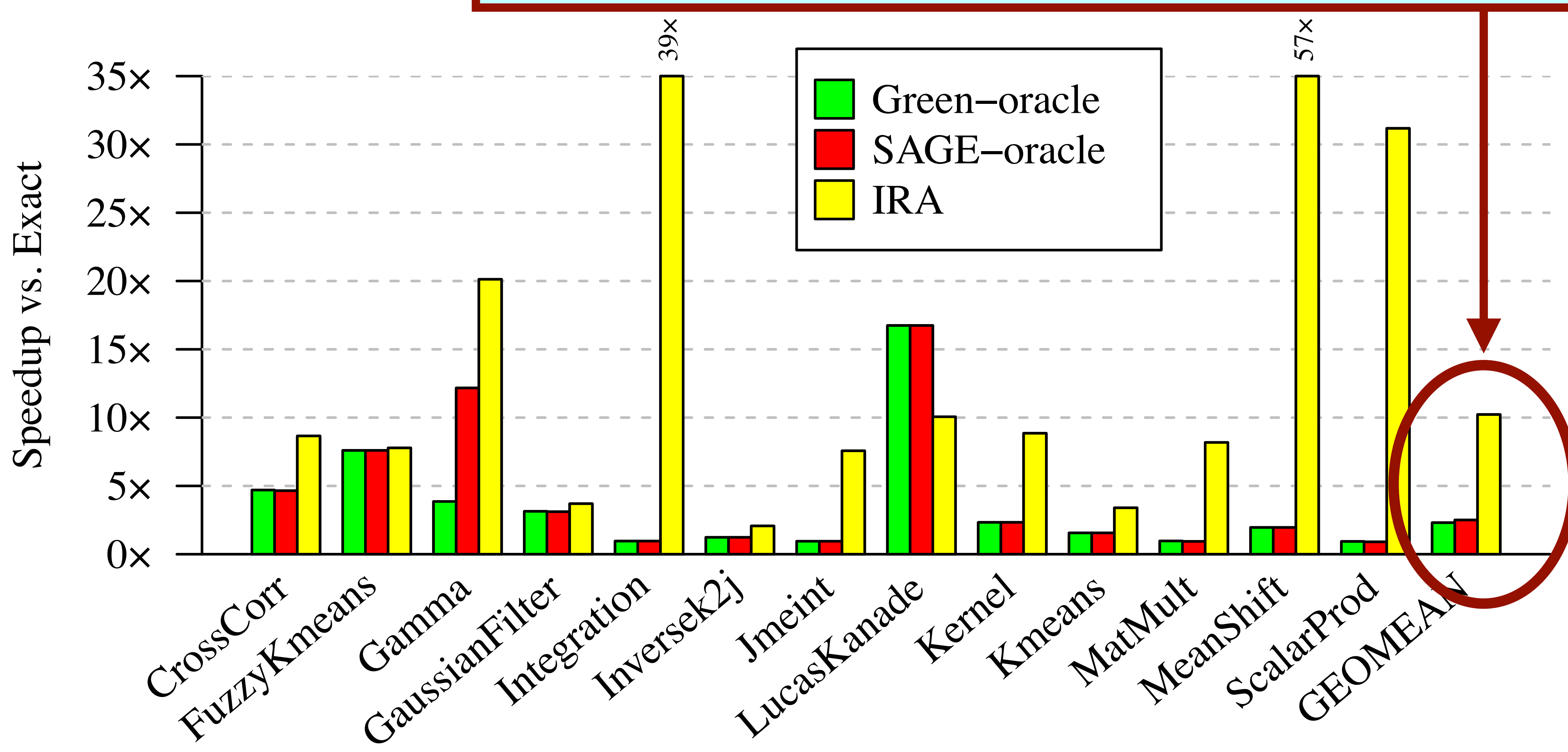
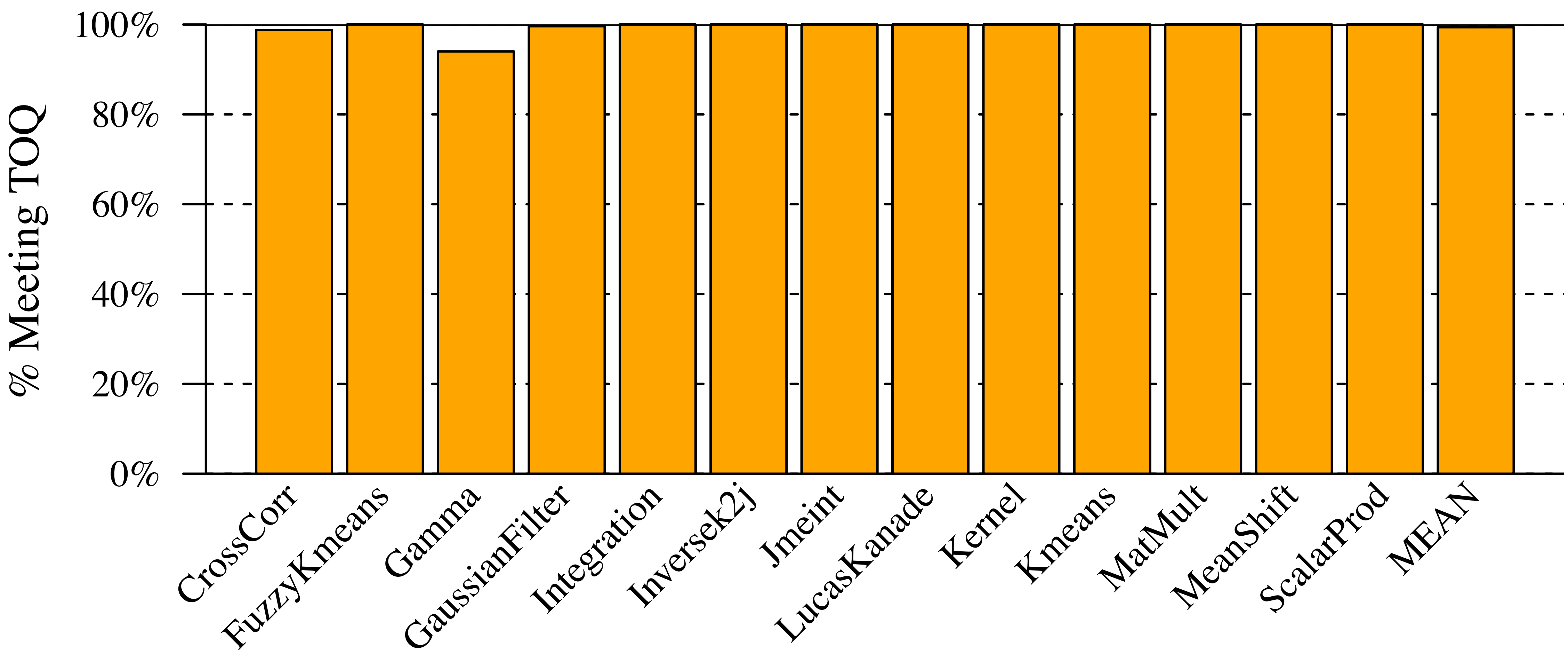
IRA's 10x speedup outperforms oracle calibration by 4x



Accuracy of IRA

- % of outputs meeting TOQ (TOQ=90%)



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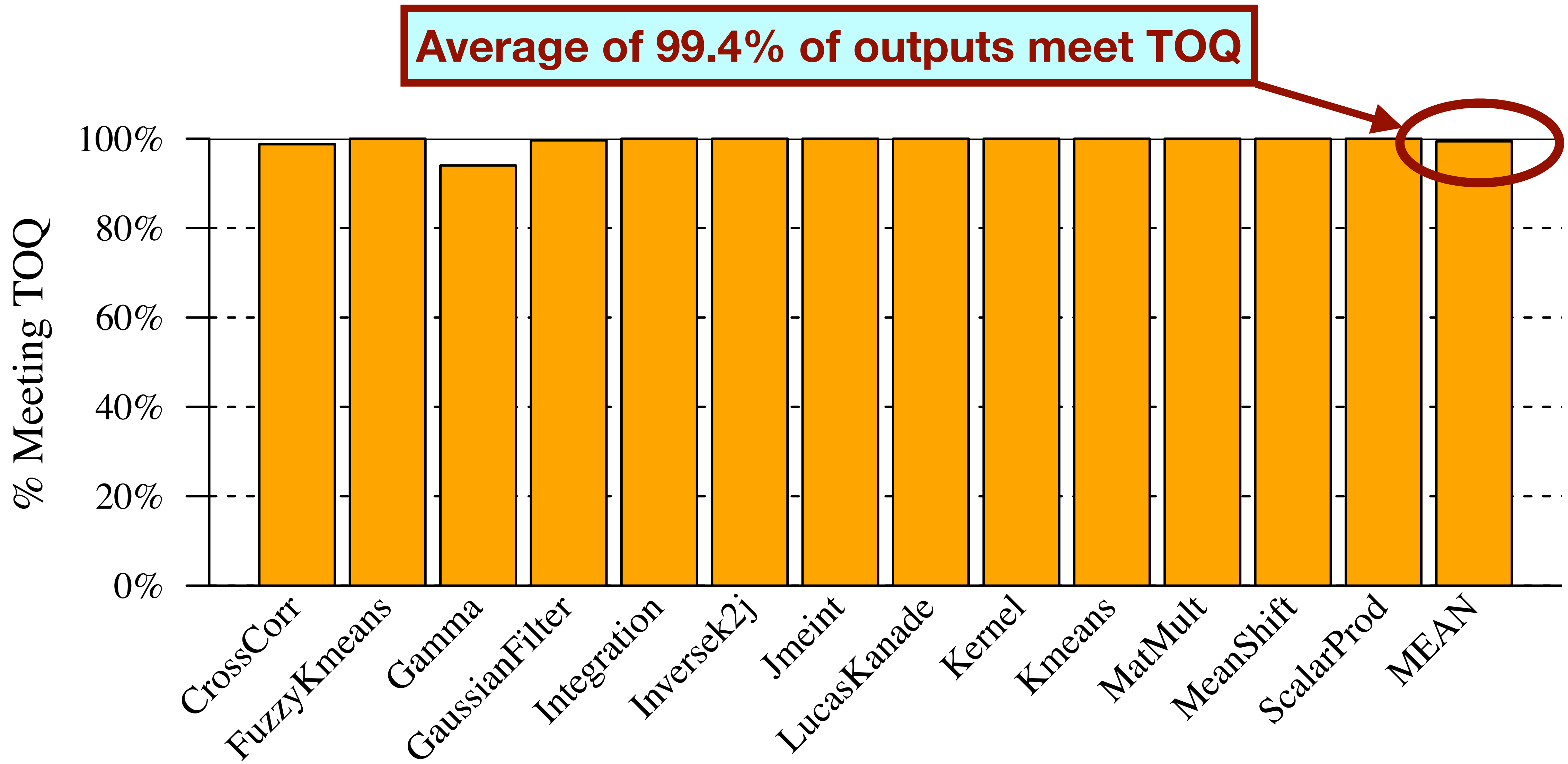
Accuracy of IRA

- % of outputs meeting TOQ (TOQ=90%)



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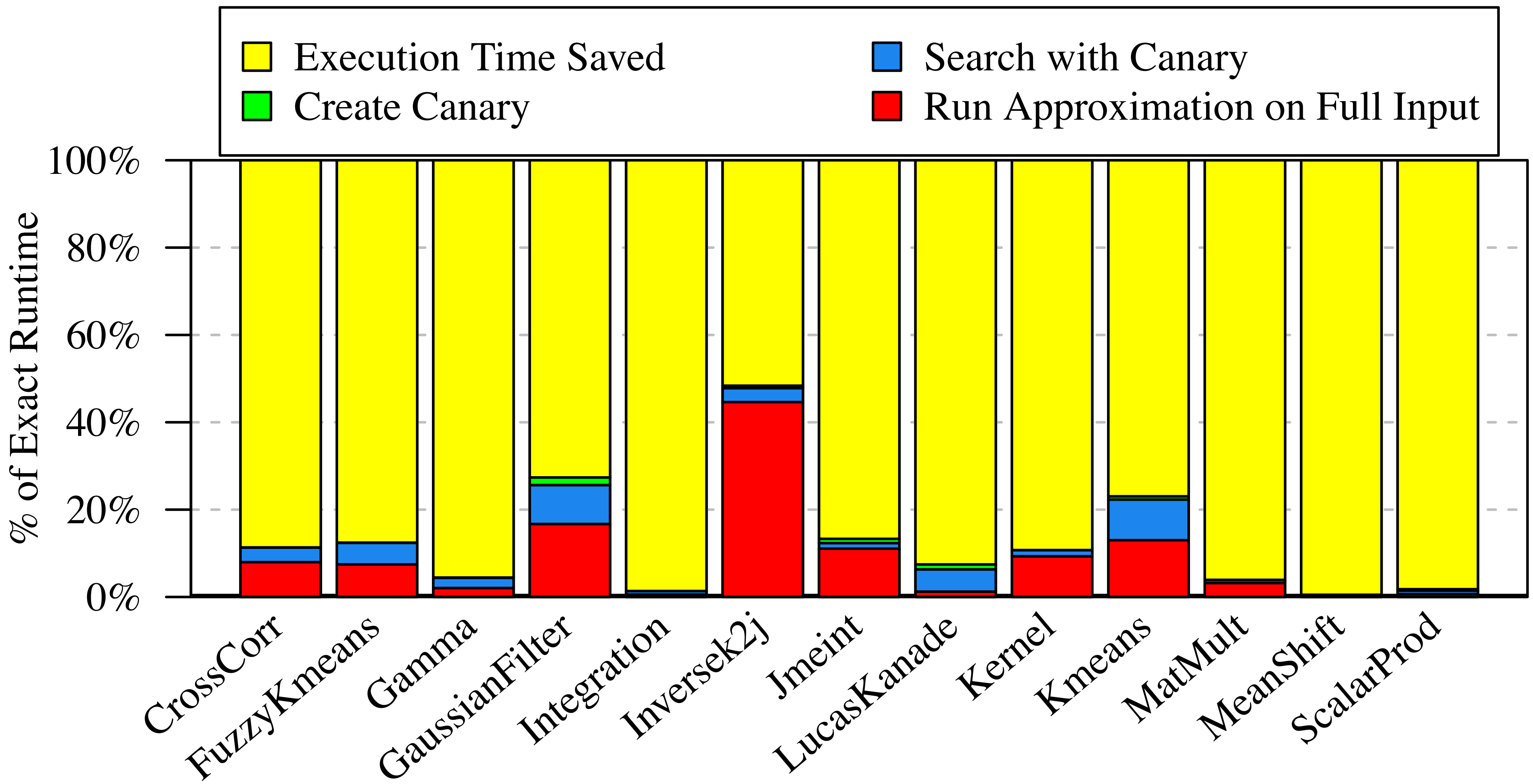
Where is the Time Spent?

- End-to-end execution time broken down



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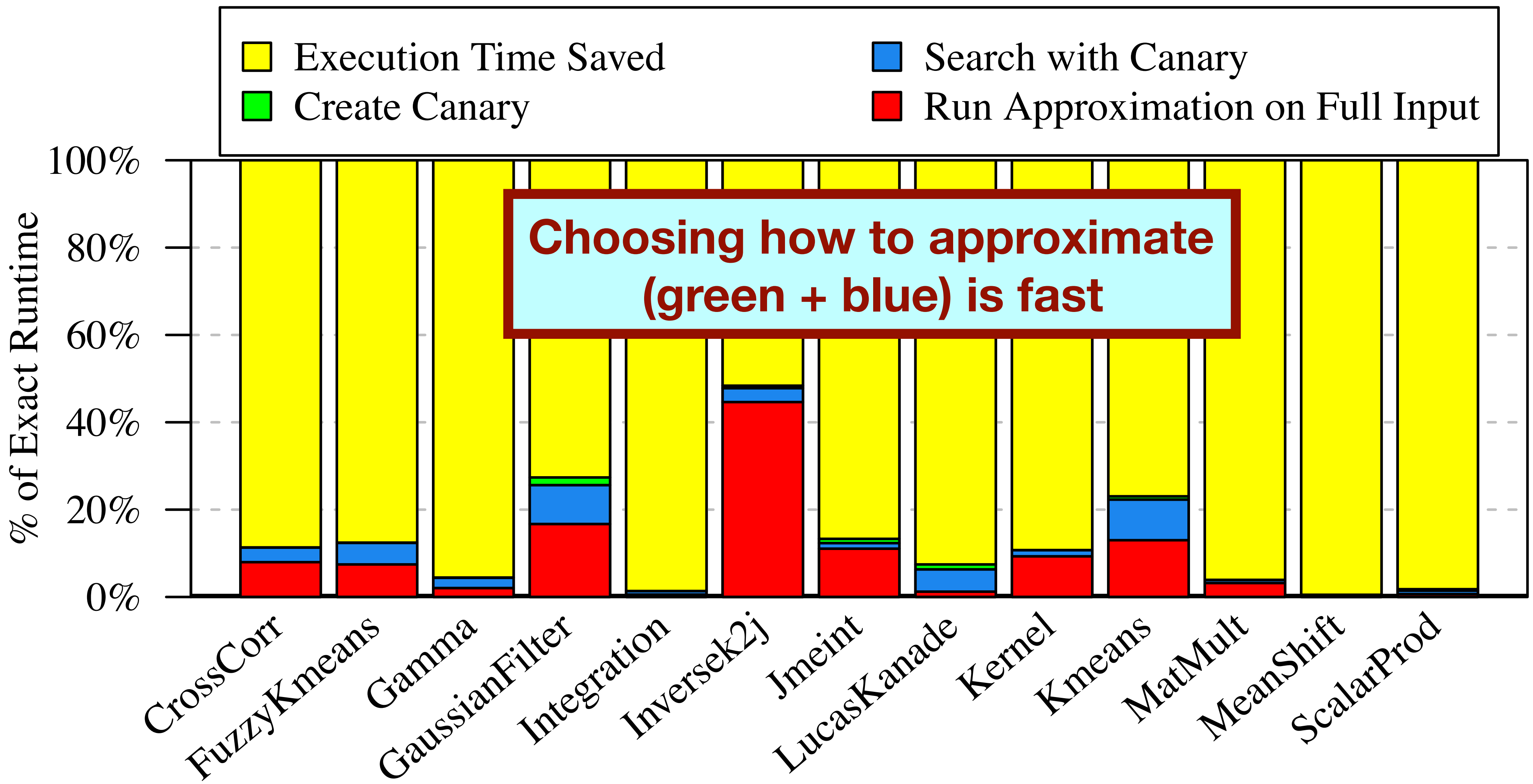
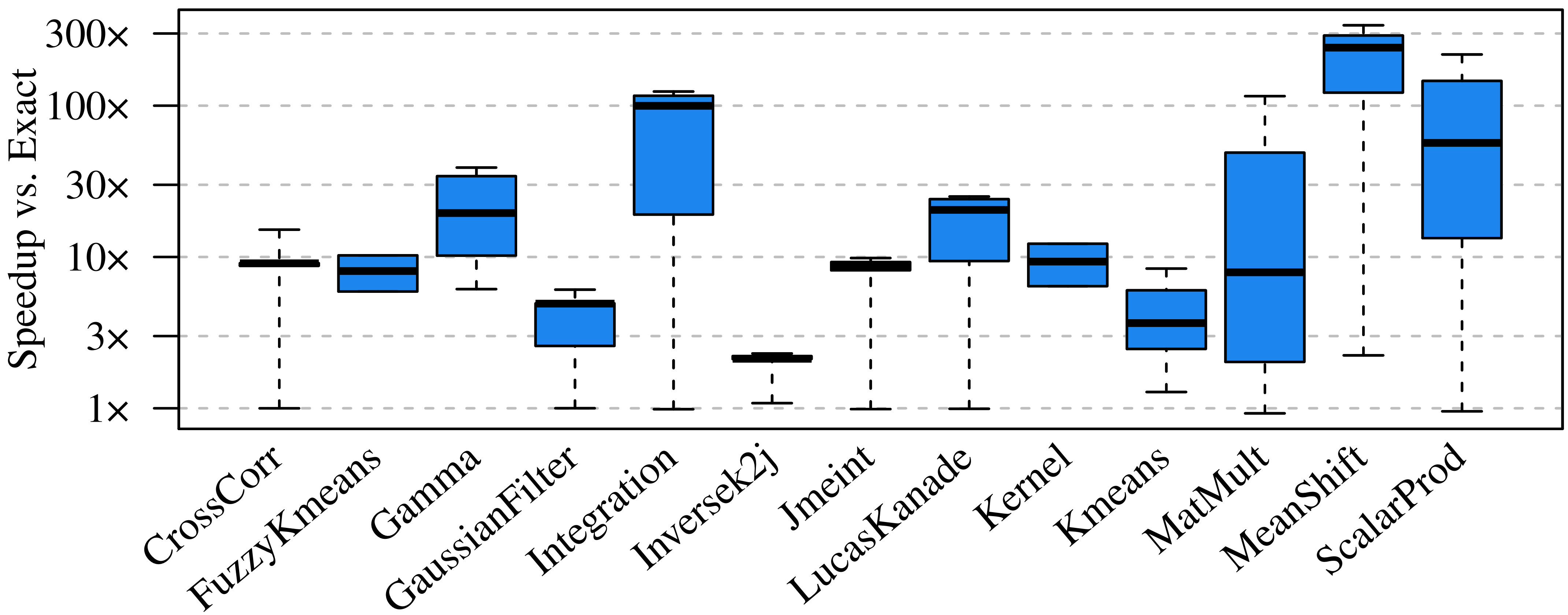


Input Responsiveness

- Wide range of speedups (and approximations) used across different inputs



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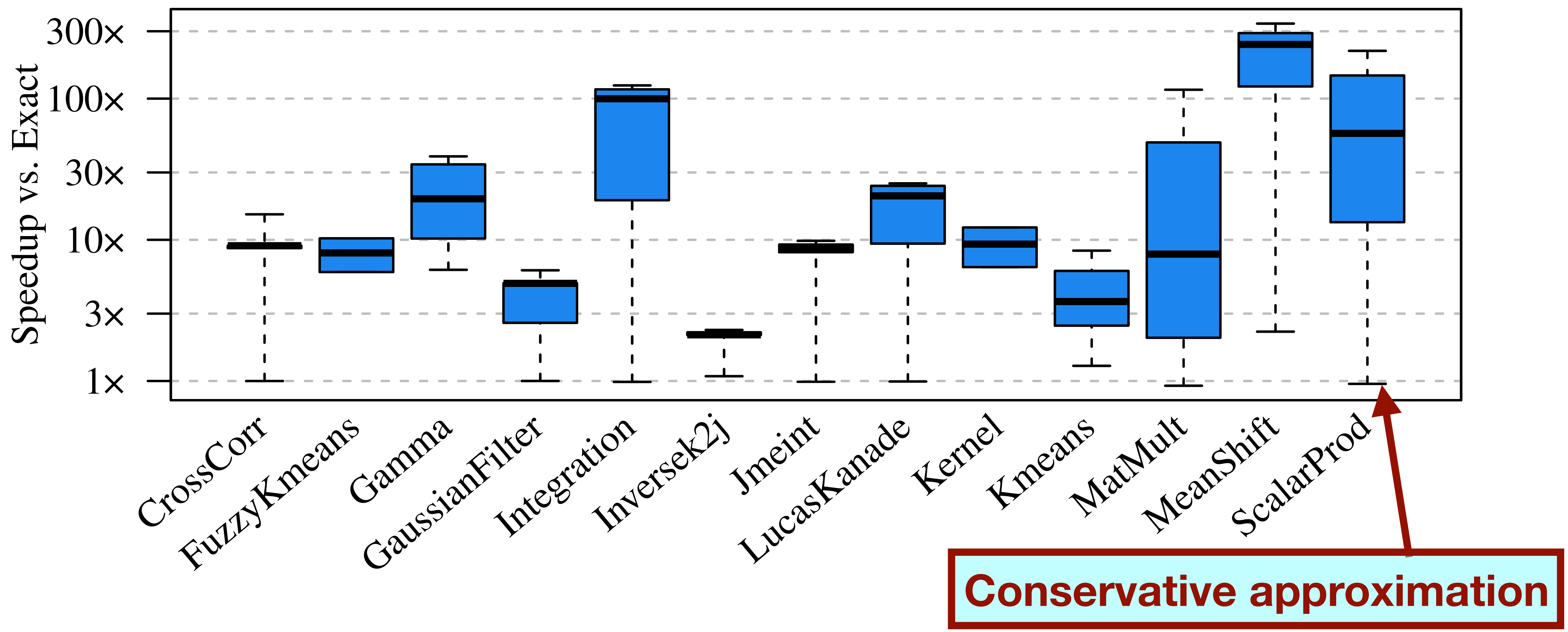

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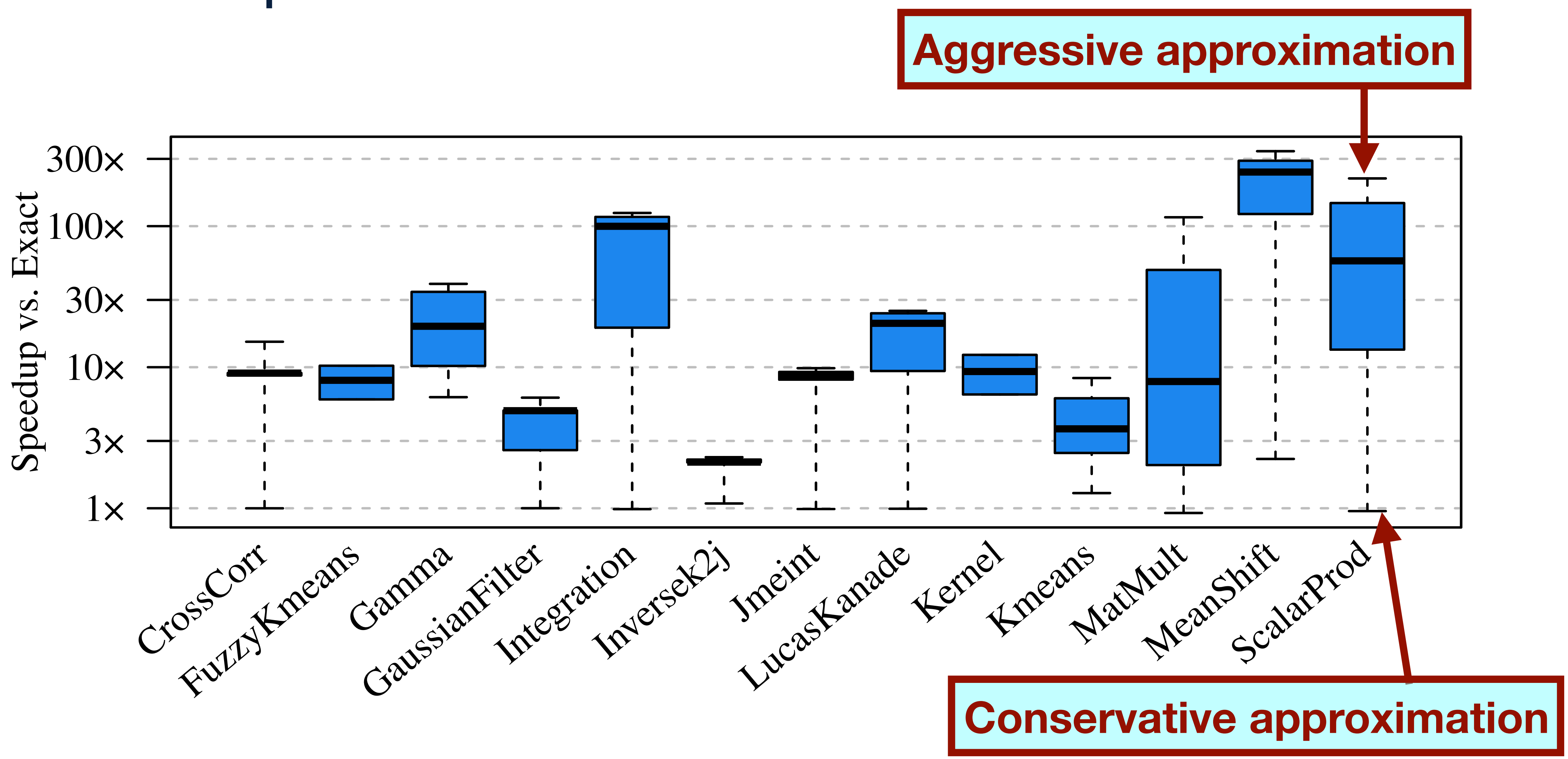

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Conclusion

Conclusion

- Input is a key component in approximation
- IRA — end-to-end system for input responsive approximation
  - Driven by canaries — smaller representations of full input
  - Chooses code regions to approximate and how to parameterize approximation
  - 10x speedup across applications (90% TOQ)
  - Outperforms oracle calibration by ~4x

?

Backup Slides

Canary Inputs

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Canary Inputs

- **Canary** – a smaller program input to model full input behavior
- Why is a canary useful?
  - Characterize full input behavior without the computational expense
  - Customize approximation for each input

Regularly-structured Computation

- **Data-centric** — amount of computation depends on the size of the input
- **Summarizable inputs** — redundancy, pattern, or marginal information in the input data
- E.g., image filters on the following

Why Input Responsiveness?

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- Example: gamma correction, 3 tiling approximations, 800 inputs

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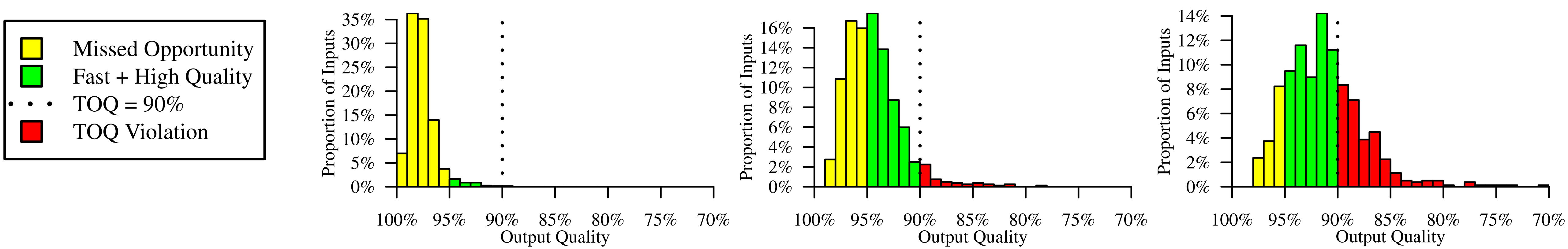
4x2 tiling, 5.9x speedup

8x8 tiling, 22x speedup

16x16 tiling, 83x speedup



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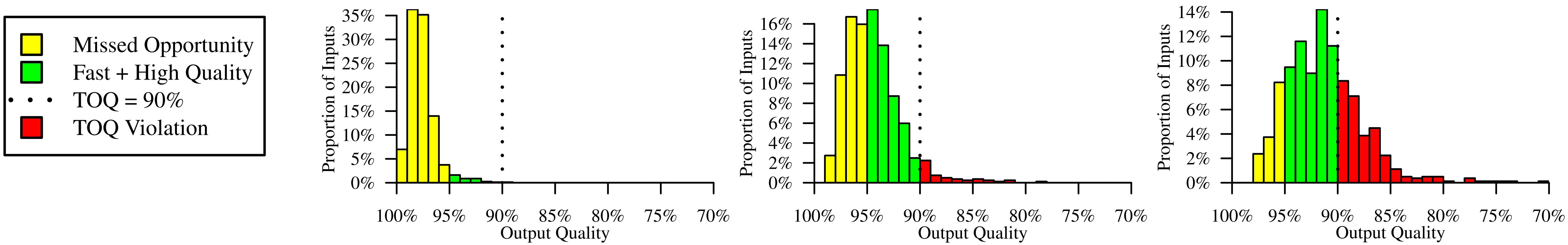

- What if we take full advantage of the differences among inputs?

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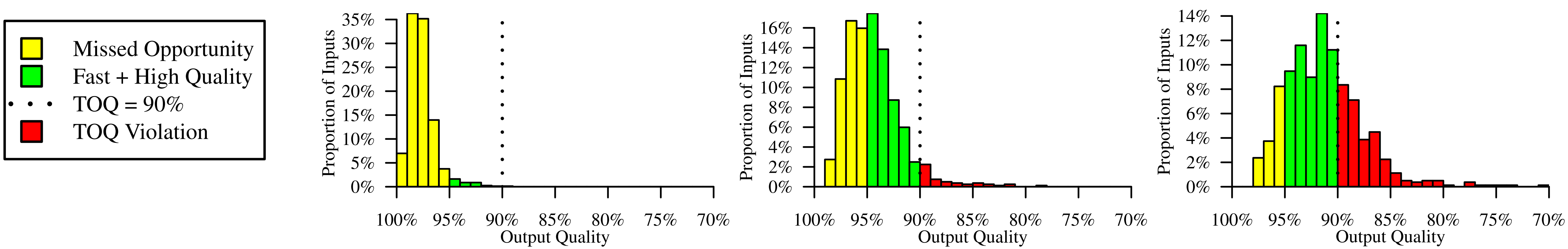
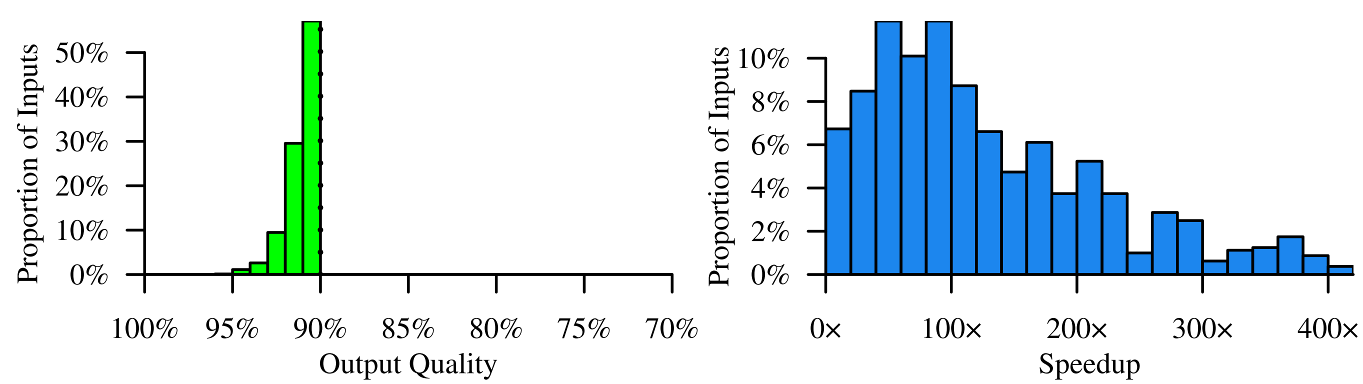
- Example: gamma correction, 3 tiling approximations, 800 inputs

4x2 tiling, 5.9x speedup   8x8 tiling, 22x speedup   16x16 tiling, 83x speedup



- What if we take full advantage of the differences among inputs?

High output quality   61x speedup



Sketch of Canary Creation Approach

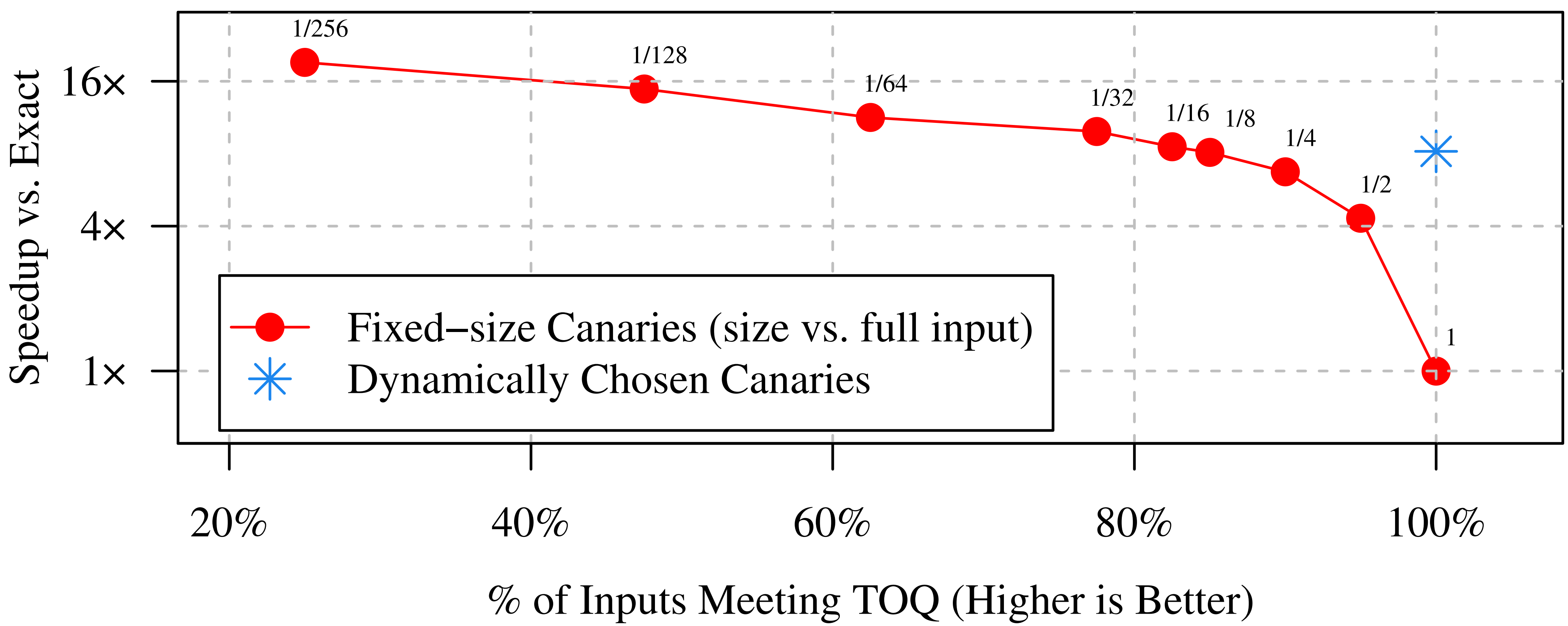
- Create a batch of canary candidates — subsets of full input
- Statistically measure similarity of candidates to full input
  - Hypothesis tests — *is canary candidate X similar to the full input?*
  - Metrics — mean, variance, local homogeneity, auto-correlation
  - Multiple comparisons problem — across all candidates, bound the probability of making a mistake
- Choose the smallest canary that is found to be similar

Addressing Challenges

Challenge	Devised Solution
Similarity to Full Input	Explore 4 definitions of similarity ranging from simple to complex
Computational Expense	Use incomplete measures of similarity (i.e., use statistics)
Significant Size Reduction	Choose smallest from a set of acceptable canaries

Why Dynamically Chosen Canaries?

- Matrix multiplication (40 inputs)



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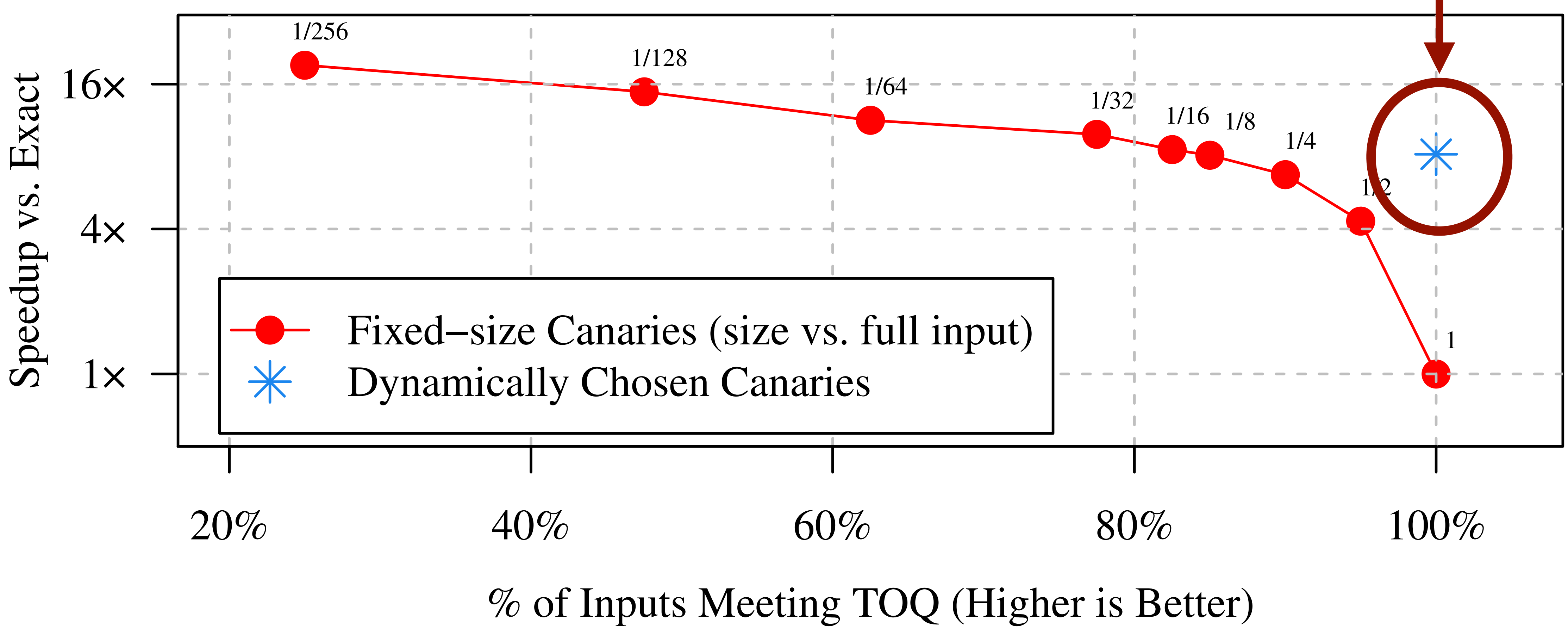
Why Dynamically Chosen Canaries?

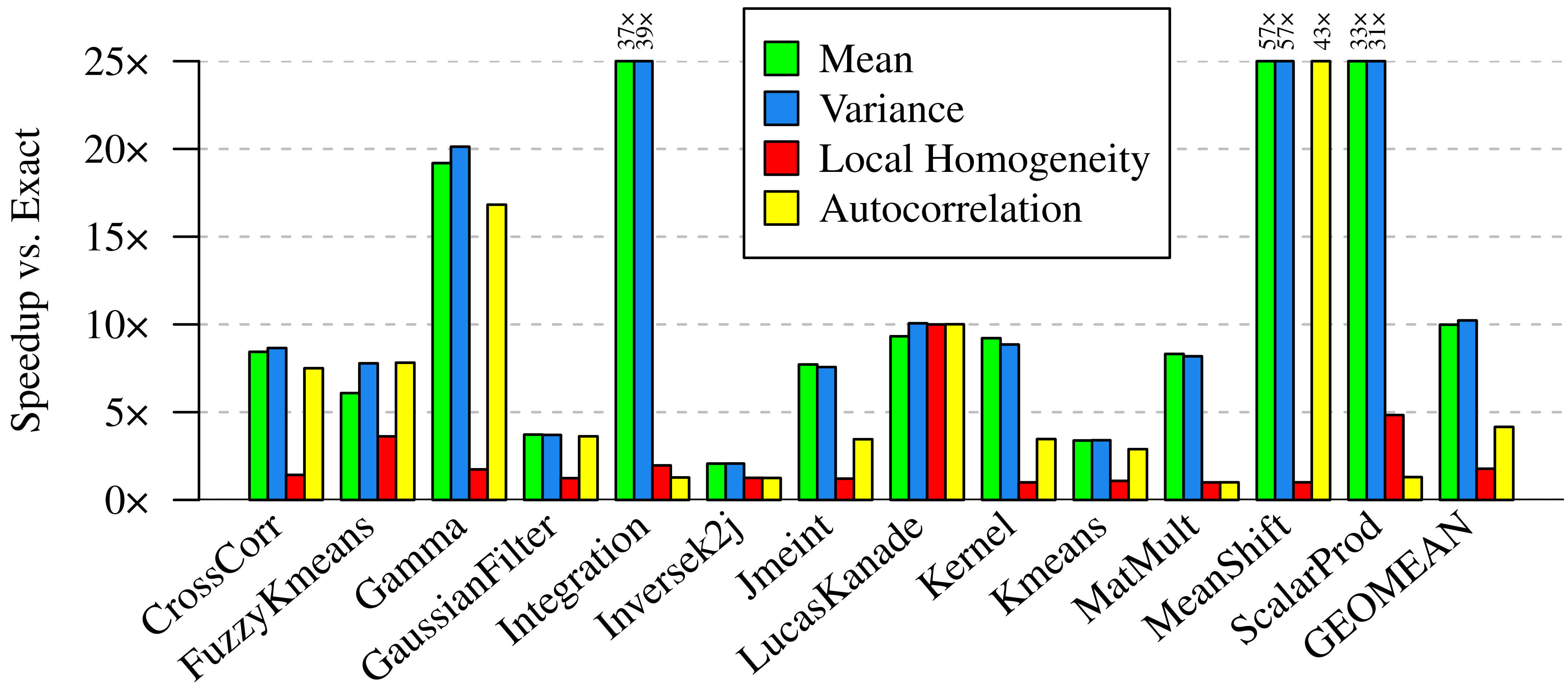
- Matrix multiplication (40 inputs)

Dynamically chosen canaries yield no TOQ violations and 8.2x speedup



Canary Metrics Comparison

- End-to-end IRA speedup across 4 similarity metrics



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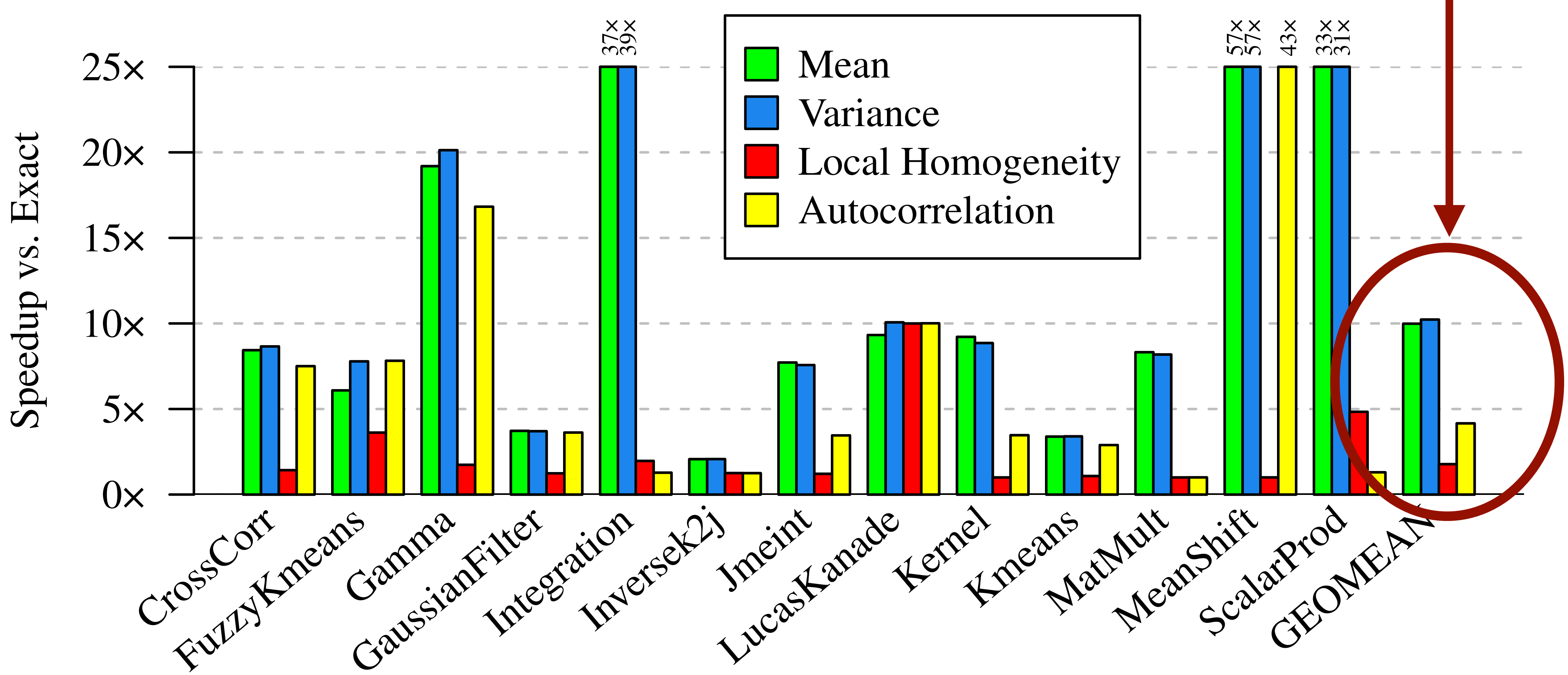
Canary Metrics Comparison

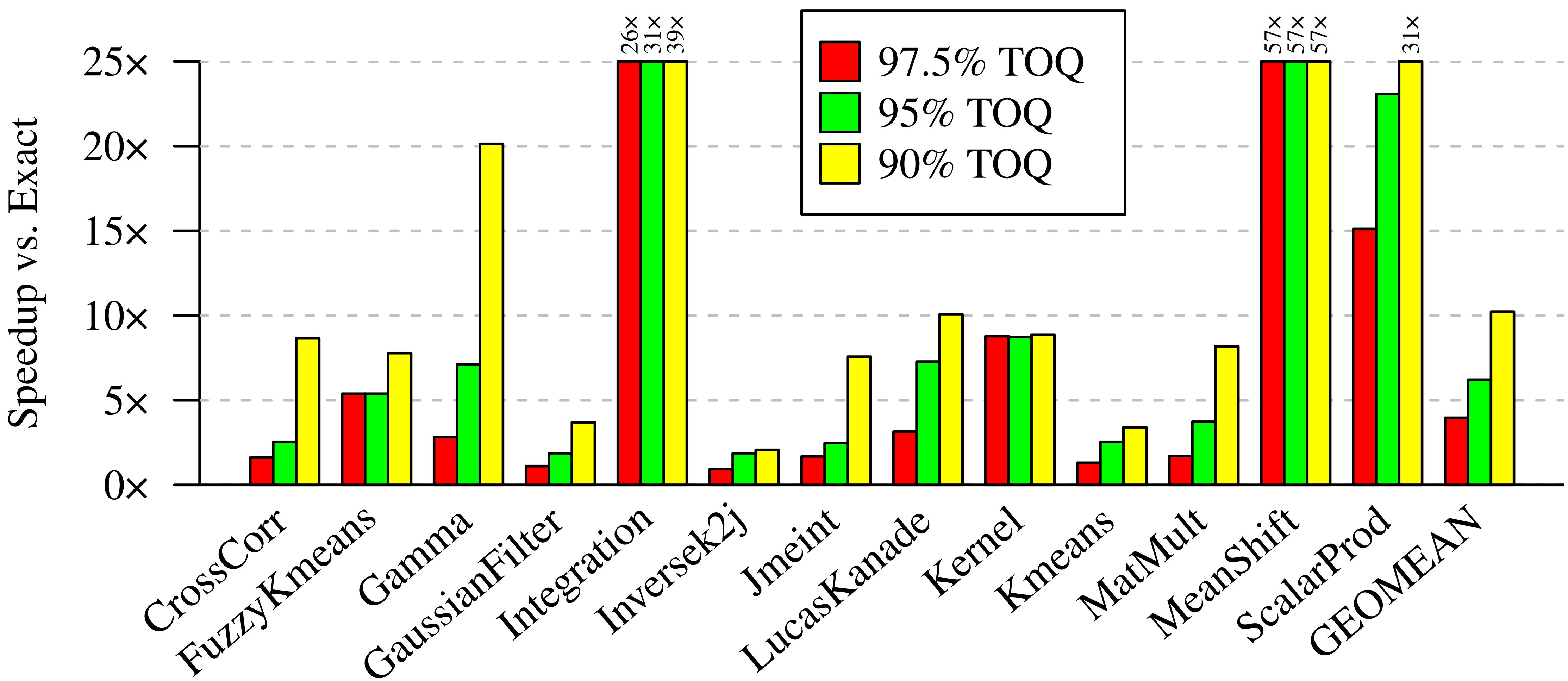
- End-to-end IRA speedup across 4 similarity metrics

Simpler metrics (mean, variance) yield improved end-to-end speedup



Differences in Output Quality

- Higher output quality ~ lower speedup



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Input Responsive Approximation (IRA)

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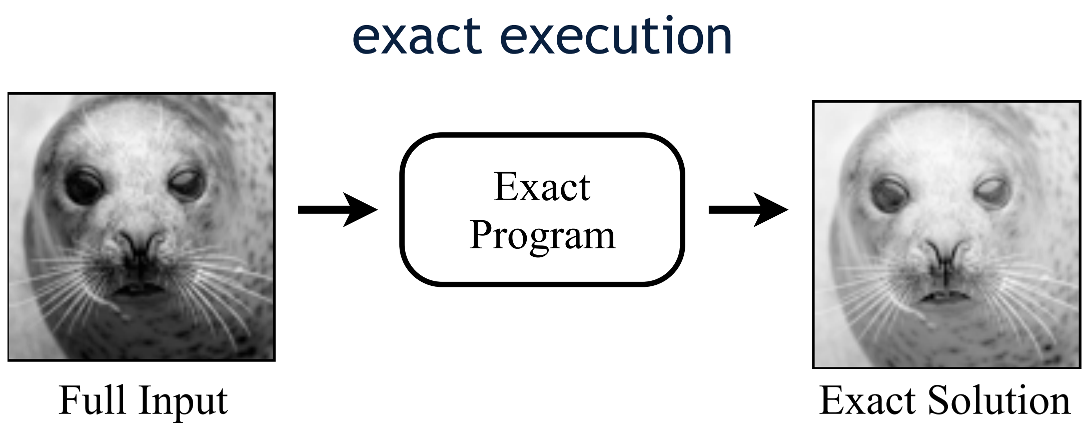
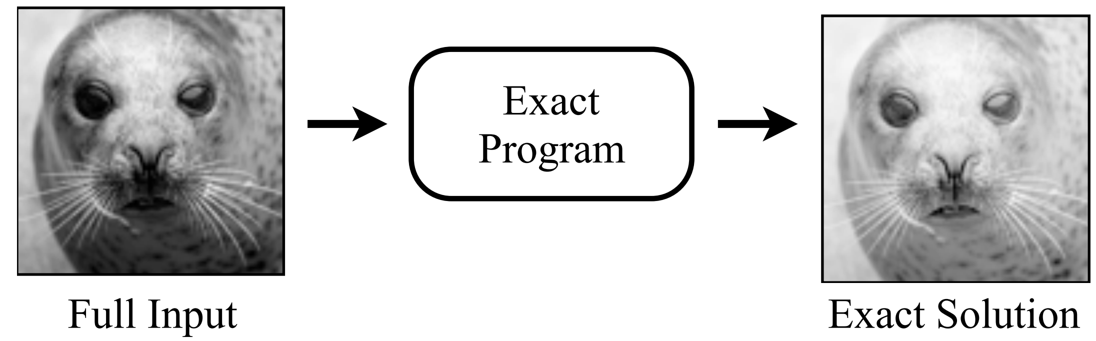


Input Responsive Approximation (IRA)

- Create a small *canary input* from full input

exact execution



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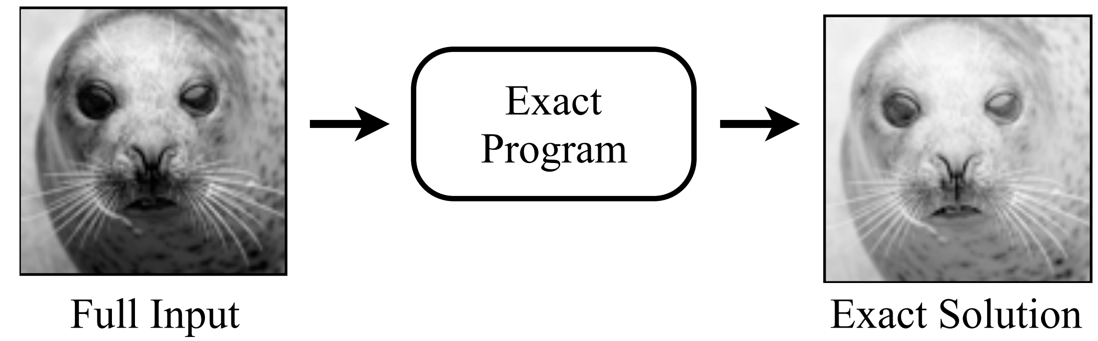
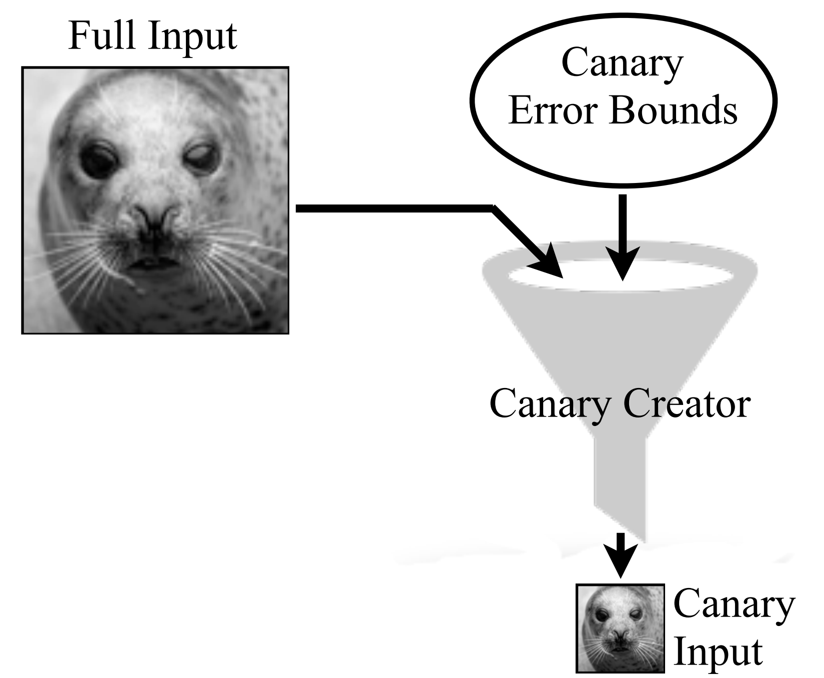


approximation with IRA



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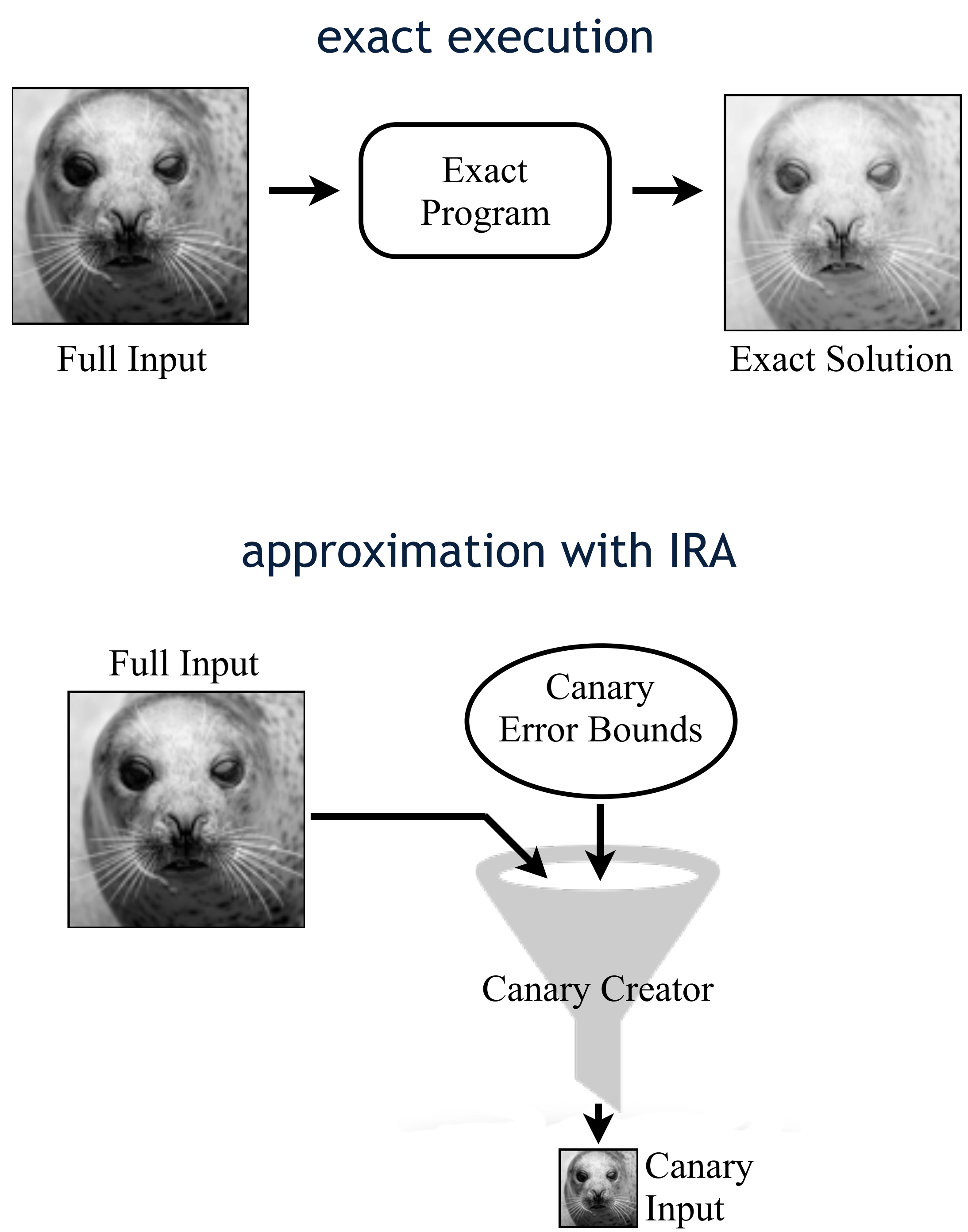
- Choose an approximation using canary



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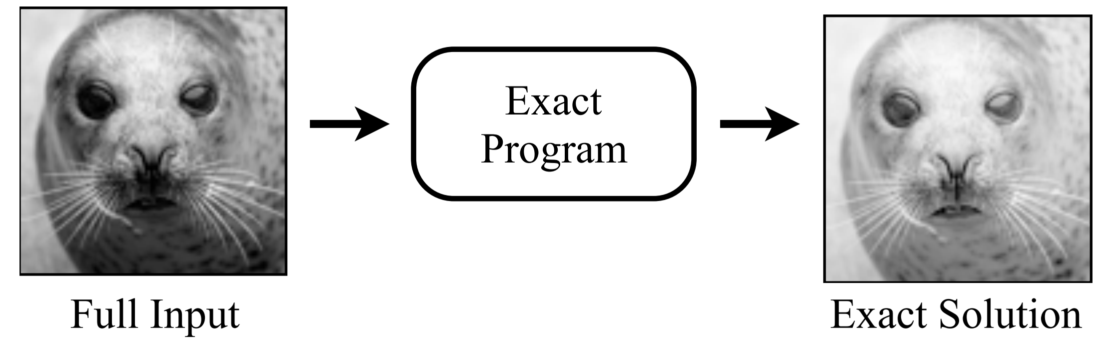

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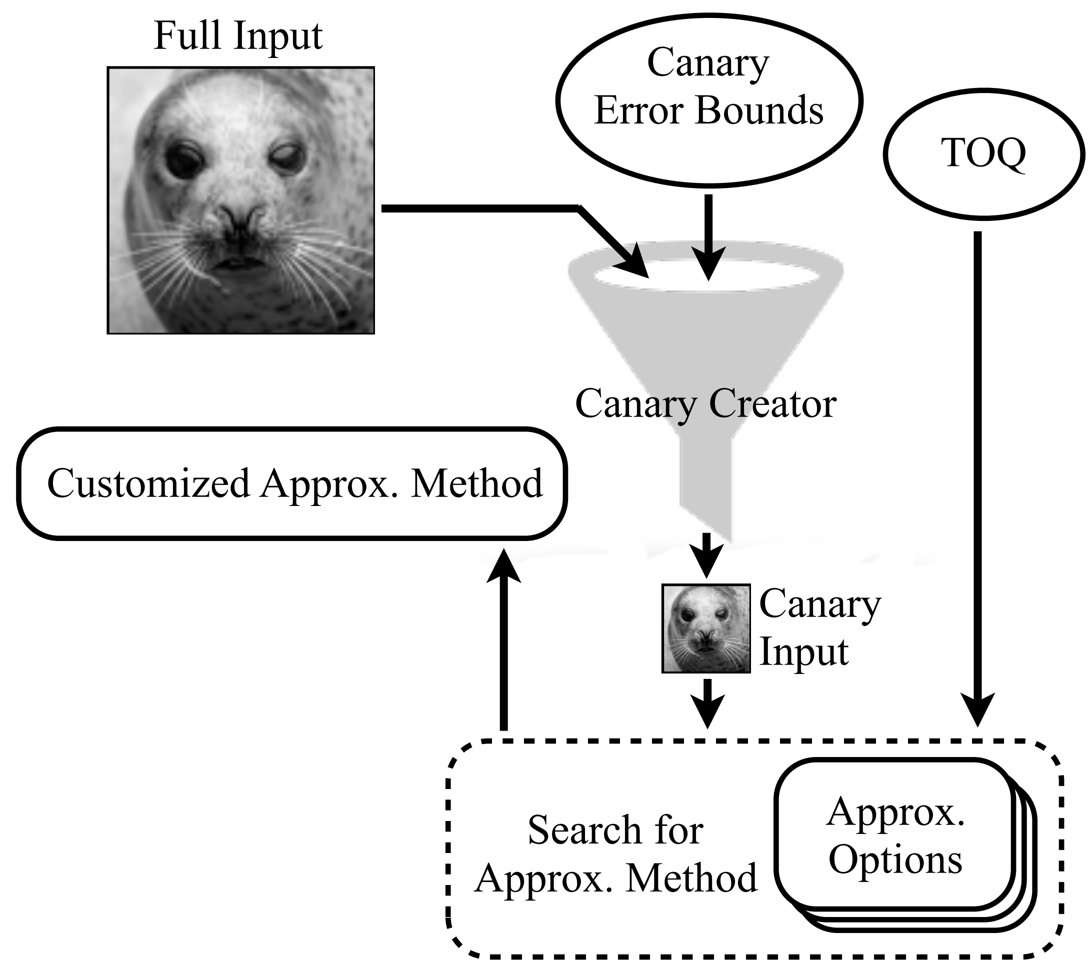

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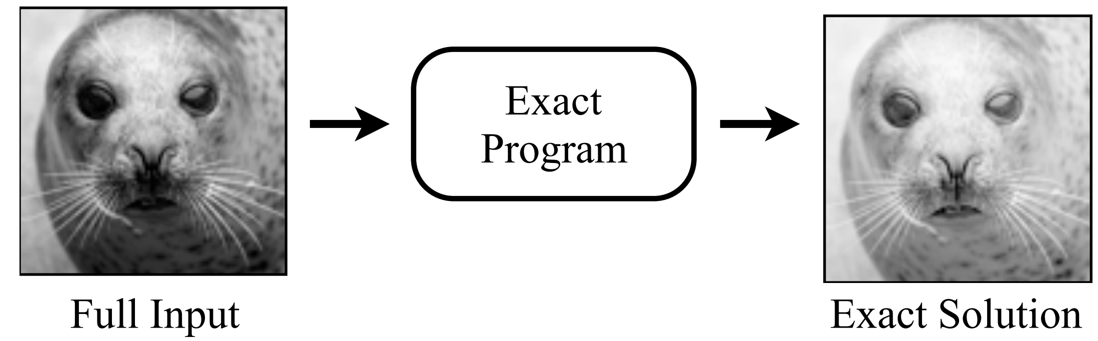

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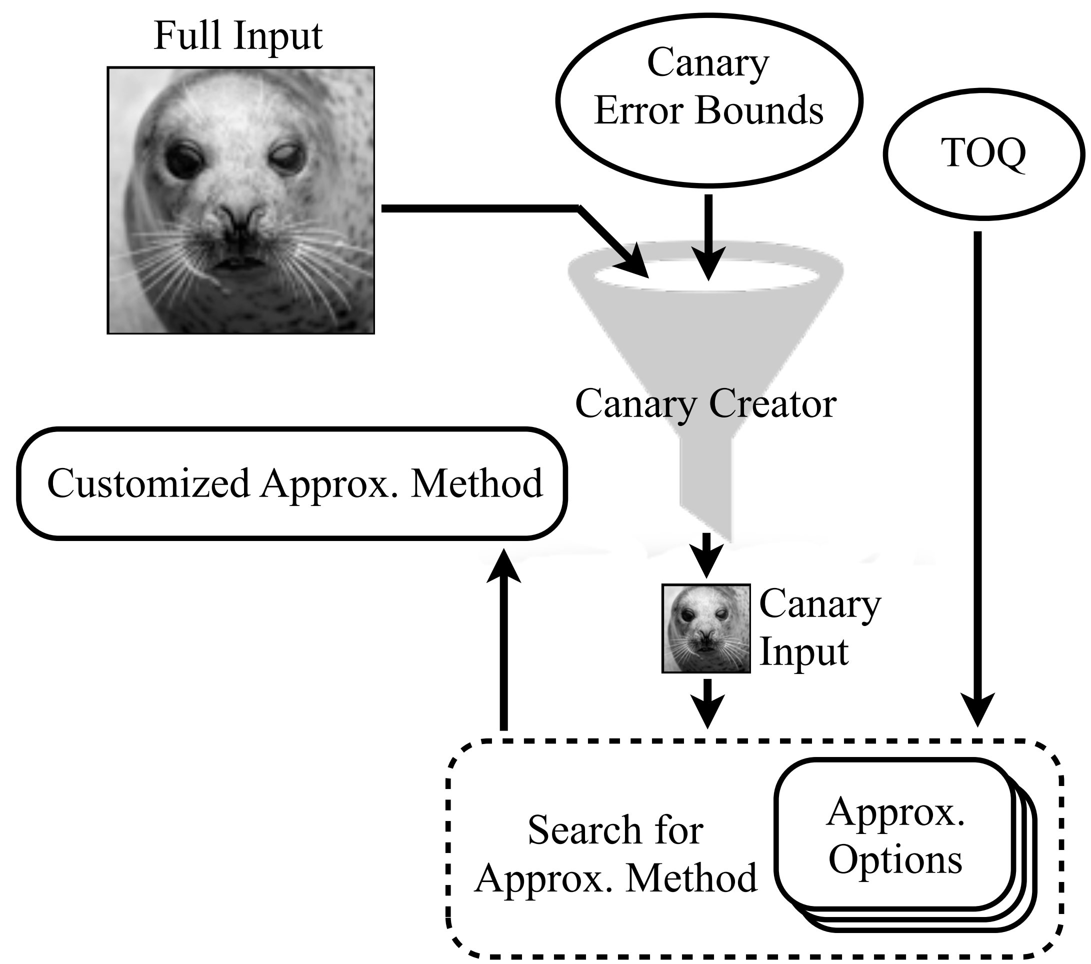

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