

Improving Digital Circuit Synthesis of Complex Functions using Binary Weighted Fitness and Variable Mutation Rate in Cartesian Genetic Programming

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Abstract: Cartesian Genetic Programming (CGP) is regularly applied to synthesize and realize digital circuits for small arithmetic and digital-logic functions. CGP benefits in obtaining hardware-efficient circuits through its heuristic search-space exploration, which is hard to reach in a rule-based synthesis process. However, the traditional CGP configuration has limitations in evolving large and complex circuits, requiring a large number of generations. High computation time and energy requirements hinder its usage from evolving complex digital circuits. This paper investigates and demonstrates the desired modifications to existing CGP in the form of Binary Weighted Fitness (BwF) and exponentially varying mutation rate (eVar) to evolve functionally correct solutions extremely fast. The benefits are demonstrated for the basic non-linear power functions and are validated for usage in activation functions which are otherwise difficult to realize. Additionally, 12 different CGP configurations with changes in mutation scheme and evolutionary strategy were also investigated for the power functions. A comparison with the benefits of BwF and eVar adopted CGP over the traditional CGP methods is presented and discussed.

1 INTRODUCTION

The ultimate goal of logic synthesis process is to build optimized version of gate-level designs with minimum number of cells and logic depth, which directly benefits the circuit's performance on silicon (Berndt et al., 2021; Kocnova and Vasicek, 2020). The current ABC synthesis tool (Brayton and Mishchenko, 2010) employs directed acyclic graphs to represent circuits. The graph is structured around two-input AND nodes and their associated edges, which are referred to as AND-Inverter Graph (AIG). The optimization involves minimizing AIG size by iteratively replacing the subgraphs with pre-computed ones, but retaining the node functionality (Mishchenko et al., 2006). Although simple and scalable, this synthesis method fails to represent XOR and XNOR gates with less than 3 AIG nodes each. Hence the current synthesis method is not considered robust enough to represent real-world designs which are generally non-linear in nature (Fišer et al., 2010; Sekanina et al., 2014).

Evolutionary algorithms involving cartesian genetic programming (CGP) are adopted to synthesize circuits, especially for the ones that are hard to realize (Sekanina et al., 2014; Prashanth and Rao, 2022; Miller and Harding, 2008). However, with the growing complexity of the co-processor design requirements, the evolutionary approach tends to either fail for gate count above 10K or concedes exorbitant time to realize the gate level circuits (Vasicek, 2015). An advanced method in the form of a cut-based method for evolutionary synthesis was proposed in (Vasicek, 2015), offering less number of gate designs but at the cost of slower convergence. A boolean network scoping driven re-synthesis approach was attempted where the CGP was applied on the extracted sub-circuits, and placed back to the original circuit with an intention of global level optimization. The sub-circuits picked for CGP driven re-synthesis either concedes time if the size is large, or does not offer much benefits at global level if the size of the sub-circuit is small. To overcome this problem a cut-based method for evolutionary synthesis was proposed in (Vasicek, 2015) offering less number of gates design, but at the cost of slower convergence. A search-based strategy to optimize and approximate

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a sub-circuit towards FPGA system design was presented in (Vasicek and Sekanina, 2016) that adopted CGP to re-synthesize the circuit. Overall, CGP offered better trade-off metrics between hardware design parameters and error metrics when compared with other traditional practices (Miller and Harding, 2008). However, the runtime incurred to synthesize circuits is extremely high, especially for a higher number of inputs and for complex non-linear functionalities (Hodan et al., 2020). Moreover, due to the surge in the applied machine-learning, and artificial intelligence techniques, higher-order computations in the order of 32-bits or 64-bits data-format are mandated (Miyasaka et al., 2021). Evolving hardware designs for designs with large number of input require faster genetic programming algorithms, without compromising on the fitness achieved. On the contrary, higher-order functional design is likely to impose tight constraints on the fitness, since a minute deviation is expected to induce large errors in the processed data. Hence, there is a timely need for running CGP and arriving at the solution much faster without compromising on the fitness.

Sections 2 and 3 describe related work and CGP configurations. In section 4 we introduce the proposed modifications to CGP, and section 5 analyse the impact on basic non-linear functions. Section 6 showcases the advantage of modifications when used in the synthesis of activation functions in Neural Networks.

2 RELATED WORK

CGP and its variants were explored and thoroughly investigated in the past (Miller, 2020; Manazir and Raza, 2019). To briefly summarize, the CGP variants in the form of graph-based crossover and applied mutation operators were discussed in (Miller, 2020). However, multiple mutations invariably run on multiple threads or processes till functional crossover is attained, which indirectly consumes more computational resources to allow for context switching between the multiple processes. The only possible advantage is attaining a quick graphical crossover, dependent on the initial seeding and highly correlated mutation operators. Modular CGP is another extended version of the original, where additional mutation operators allow CGP-encoded sub-functions to be re-evaluated and re-synthesized. However, evolving to a sub-functional genotype first-up is a computationally heavy task. Furthermore, evolved sub-functions may not necessarily converge to an optimized solution and a slight deviation in the generated sub-functions may lead to functionally incorrect de-

signs. A different method of taking CGP phenotype to machine code for faster execution was attempted. A whole set of implementations with a speedup in the CGP run was achieved by executing the runs on the hardware units such as FPGAs, and application-specific virtual reconfigurable circuit (VRC) (Vašíček and Sekanina, 2012; Hrbáček and Drahosova, 2013), which are categorically, a different set of approaches. Overall, most modifications aim to add more operative dimensions or shift the execution to a completely different platform to improve the operational speed. The current CGP methods exploited in the literature do not address any speedup mechanism to arrive at fitter solutions. This paper proposes two new modifications to the existing CGP methodology to achieve the desired synthesized gate-level circuits with lesser generations and, at the same time, extract a group of fitter solutions. The two mechanism includes:

1. Applying a different mutation rate, similar to (Thierens, 2002). Especially for realizing non-linear functions instead of a constant mutation rate adopted in the traditional methods, and
2. Incorporating a binary-weighted fitness function instead of the same weight across the data-format of the functions under synthesis.

The proposed modifications to the CGP run are highly useful for realizing hardware designs for non-linear functions, which are essential components of the modern-day neural network and its family of computational networks. Hardware realization of two types of non-linear functions is demonstrated to showcase the impact of the proposed CGP method - i) Power functions and ii) Activation functions. The paper contributes to introducing an **exponential mutation rate (eVar)** and **binary-weighted fitness function (BwF)** for synthesizing non-linear functions. As per the authors' knowledge, this is the first time a varying mutation rate and binary-weighted fitness across the data-format is adopted and analysed for circuit synthesis.

3 CARTESIAN GENETIC PROGRAMMING

In CGP, a directed acyclic graph (DAG) consisting of an array of gates is evolved iteratively for the desired function (Miller and Harding, 2008). Nodes of the DAG are gates picked from the predefined list employed to build the combinational circuit. The DAG, which is defined using encoded genotype, is mutated repeatedly in an attempt to obtain the corresponding phenotype (digital circuits) that performs better in the desired objective functions. Objective

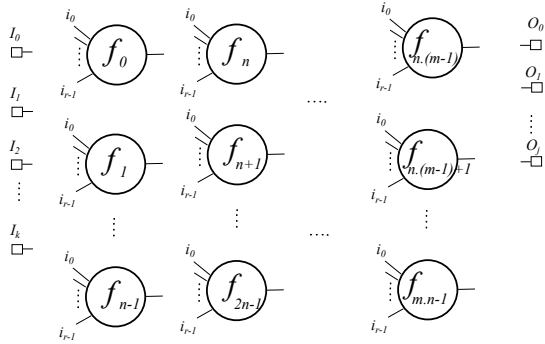


Figure 1: A schematic representation of Cartesian Genetic Programming (CGP) showing 2D DAG for inputs I , generating outputs O .

Table 1: CGP Parameters.

Parameter	Value	Description
No. of Generations	$G > 0$	The maximum no. of generations in a evolutionary run
Nodes (n)	$n > 0$	Number of usable nodes for the algorithm
Arity	$A > 0$	Arity of each node
Function Set		Available functions to be used as nodes
Mu	$\mu > 0$	No. of Parents passed to the next generation, also used to create children
Lambda	$\lambda > 0$	No. of children created using μ parents

functions can be functional correctness of the circuit, hardware performance metrics (area, delay or power of the circuit) or a multi-objective function combining both functional correctness and hardware metrics. Figure 1 shows a general node-level representation of CGP DAG, where each node represents a functional block. For n rows and m columns, each node is a functional gate selected from a predefined set of $f \in F$. The arity r defines the number of inputs for each node. In this work, the function set F is a combination of basic standard two-input gates consisting of 2-NAND, 2-OR, 2-NOR, 2-OR, 2-XOR, 2-XNOR. The parameters listed in Table 1 are utilized to configure the CGP algorithm for synthesis. Algorithm 1 presents the $(\mu + \lambda)$ evolutionary strategy steps, which returns the fittest genotype in an algorithm run with randomly generated seed candidate solutions. The μ value indicates the number of solutions promoted to the next generation as parents. The λ value indicates the number of off-springs generated from the μ parents from the previous generation. In this work, different evolutionary strategies were also analyzed to identify the ideal μ, λ values for achieving faster evolution of non-linear digital circuits. To showcase the impact of a novel mutation rate and modified fitness function, non-linear activation functions and power functions were realized using the modified features of the CGP technique. The original CGP with constant

Table 2: CGP Configurations.

Configuration	Possible choices	Typical Choice
Evolutionary Strategy	$(\mu + \lambda)$	$(1 + 4)$
Mutation Scheme	Probabilistic, Probabilistic Only Active, Point, Single	Point
Selection Scheme	Select Fittest, Tournament	Select Fittest
Reproduction scheme	Mutate every parent, Mutate random parent	Mutate Every Parent
Fitness	Supervised Learning (SL), Binary weighted Fitness (BwF)	Supervised Learning
Mutation Rate	Constant, Variable	Constant

mutation rate and traditional fitness function for all the non-linear functions were also evaluated and compared against the proposed modified CGP techniques. All possible options and typically selected configurations are listed in Table 2. The four mutation schemes vary in terms of the mutations performed on node and chromosome level. The mutation schemes are elaborated below.

Probabilistic : Conducts probabilistic mutation on the given chromosome. Each chromosome gene is changed to a random valid allele with a specified probability.

Probabilistic Only Active : Conducts probabilistic mutation on the active nodes in the given chromosome. Each chromosome gene is changed to a random valid allele with a specified probability.

Point : Conducts point mutation on the given chromosome. A predetermined number of chromosome genes are randomly selected and changed to a random valid allele. The number of mutations is the number of chromosome genes multiplied by the mutation rate. Each gene has equal probability of being selected.

Single : Conducts a single active mutation on the given chromosome.

Although the paper emphasizes novel fitness function (BwF) and varying mutation rate (eVar), the other configurations, including evolutionary strategy, mutation scheme, selection scheme, and reproduction schemes were also investigated for the synthesis runs. *Select Fittest* selection scheme and *Mutate Every Parent* reproduction scheme was incorporated for all the evolutionary runs. As indicated in Table 2, typical CGP in the form of Supervised learning (SL), Constant mutation rates were compared against BwF, and variable mutation rate CGP technique towards synthesizing digital circuits of non-linear functions.

Algorithm 1: $(\mu + \lambda)$ evolutionary strategy.

```

forall  $i$  such that  $0 \leq i < (\lambda + 1)$  do
  | Randomly generate individual  $i$ 
end
Select  $\mu$  individuals, that are promoted as the
parents.
while the generation limit is not reached do
  forall  $i$  such that  $0 \leq i < \lambda$  do
    | Mutate the  $\mu$  parents based on the
    | mutation scheme to generate  $\lambda$ 
    | offsprings
  end
  Generate the fittest individual using the
  following rules:
  if an offspring genotype ranks better in a
  selection scheme then
    | Offspring genotype is chosen as fittest
  else
    | The parent chromosome remains the
    | fittest
  end
end

```

4 PROPOSED DESIGN

4.1 eVar

In traditional CGP, the mutation rate is configured to be a constant value in a view to have the same mutation rate across the generations and continue to evolve until a desired fitness or termination criteria is achieved (Miller and Harding, 2008). In this work, we intend to formulate a mechanism that intuitively selects between rough topologies in the initial generations and then mutates sub-parts of the best-performing circuit topologies—followed by minimal and single gate level selection in the final generations. This mechanism is inspired by varying learning rate in various ML optimization algorithms during the training phase. The fitness function used can achieve the selection between the rough topologies in the initial generations and subsequently among the finer sub-parts of the designs in the later runs. We tried several types of mutation rate variations, including linear and various non-linear decays. It is observed that an exponential variation of the mutation rate converges fastest to functionally correct circuits.

$$\text{mutation rate}(g) = R \times e^{\frac{-g}{0.1 \times G}}, \quad (1)$$

where,

G = Total number of generations,

g = current generation, and

R = initial rate of mutation.

Exponential variation of mutation rate used is stated in Equation 1. It is observed that a decay rate of 10 is apt based on our heuristic studies on evolving non-linear functions. If the mutation rate reduces lower than one gene, the mutation scheme was changed to mutate at least one gene for further generations to continue the evolution process. The sequence of a first-up rough design requires high mutations to evolve to a relatively adequate design topology. Further fine-tuning the design topology with fewer mutations requires lower mutation rates. The process of following exponentially varying mutation rates was found to inherently reduce the evolution time to achieve similar fitness as other variations. The selection between multiple mutated designs at all generations is driven by the configured fitness function.

4.2 BwF

Binary weighted fitness (BwF) was introduced to evolve designs which are closer to the data-formatted functional output. The traditional **SL (Supervised Learning)** fitness can either be devised to formulate a minimizing or maximizing objective function for the evolutionary algorithm. For the minimizing case, SL uses Hamming distance between the evolved circuit output data-bits and expected output data-bits over all input combinations, indicating the total number of incorrect circuit output data-bits. In the maximizing case, the number of correct output data-bits of the evolved circuit is used as the fitness score. In this work, we use the minimizing case as stated in Equation 2, where z is the number of inactive nodes in the solution circuits.

$$SL \text{ fitness} = \begin{cases} b & \text{when } b > 0 \\ b - z & \text{otherwise} \end{cases} \quad (2)$$

This method continues to evolve designs till the number of generations is exhausted, even if a functionally correct circuit is found while trying to minimize z . We minimize the circuit size by minimizing the number of active gates. However, running the SL configured CGP method to evolve the best-fit design mandates millions of generations, especially for realizing non-linear functions under investigation. Besides, the SL method adopts a similar hamming distance rule across all bits, leading to smaller refinements along all the design paths associated with the output bits. The SL process ceases to drive major topological changes for most significant bits (MSBs) associated design paths and thereby lags in evolving best-fit design solutions in consolidation with all the output bits of the investigated non-linear functions. BwF attempts to improve the selection among the available solutions by considering the weighted fitness across the output bits of

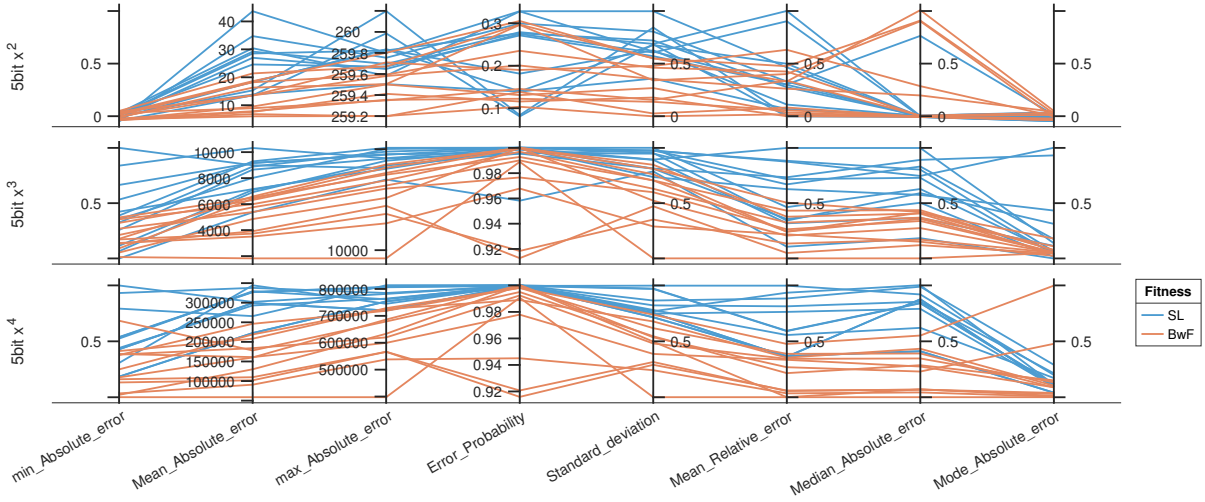


Figure 2: Error metrics comparisons for BwF versus SL methods, when employed with all possible CGP configurations, for generating 5-bit power functions : x^2, x^3, x^4 .

the design evolved instead of considering hamming distance across all the established output bits. The BwF fitness function is stated in Equations 3-4. The binary-weighted sum (BWS) is a weighted score, giving positional weightage to error in individual output bits derived from the evolved circuit design ($C(O_i)$) when compared with the expected ($E(O_i)$) functional output, where i^{th} output bit is scaled by the error contributed. BWS is used over all input combinations to calculate the BwF of a solution. We also include the term z to minimize the circuit size post a functionally correct circuit is evolved.

$$BWS = \sum_{i=0}^{n_o-1} 2^i \times \delta_i \quad (3)$$

$$\text{where } \delta_i = \begin{cases} 1 & \text{if } O_{Exp}(i) \neq O_{Cir}(i) \\ 0 & \text{if } O_{Exp}(i) = O_{Cir}(i) \end{cases}$$

$$BwF \text{ fitness} = \begin{cases} BWS & \text{when } BWS > 0 \\ BWS - z & \text{otherwise} \end{cases} \quad (4)$$

5 EXPERIMENTAL RESULTS

In the initial generations, BwF is expected to aid in selecting the best functionally equivalent topology among the solutions, as discussed in section 4.1. Based on the evaluated fitness score, BwF allows selecting topologies with the least deviation in the output function from the expected function, which otherwise was not possible in the SL method due to its equal weightage rule associated with the output bits.

The evolution process is slowed with reduced mutations in the later generations, only modifying small sub-parts of the circuits. Towards the final generations, BwF continues to evolve the designs at the gate-level. The BwF adopted CGP along with eVar mutation rate is observed to not only obtain circuits with the least deviation from the expected non-linear function but also to evolve the circuit with fewer generations, as discussed in the following sections. The impact of BwF and eVar adoption in CGP is presented by synthesizing circuits of power functions and activation functions, which are hard to synthesize otherwise. Each configuration discussed in section 3 is run 20 times with the same generations limit for different configurations being compared. For example, 5bit x^3 has 12 configurations of mutation scheme and evolutionary strategy. Both BwF and SL with these 12 configurations are run 20 independent times in an attempt to obtain the average behaviour of circuits evolved with the specific configuration. The results discussed in the following sections are only an illustrative subset of all the experiments, the full comprehensive set of results is made available in (Prashanth, 2022).

5.1 Error Analysis

Eight different error metrics, including *Mean Absolute Error* (MAE), *Error Probability* (EP), *Standard deviation* (STD), *Mean relative error* (MRE), *Median of absolute error* (MeAE), *Mode of absolute error* (MoAE), *Maximum absolute error* (Max-AE), and *Minimum absolute error* (Min-AE) were investigated for eVar, and BwF modified CGP and traditional CGP configurations for the power and activation functions.

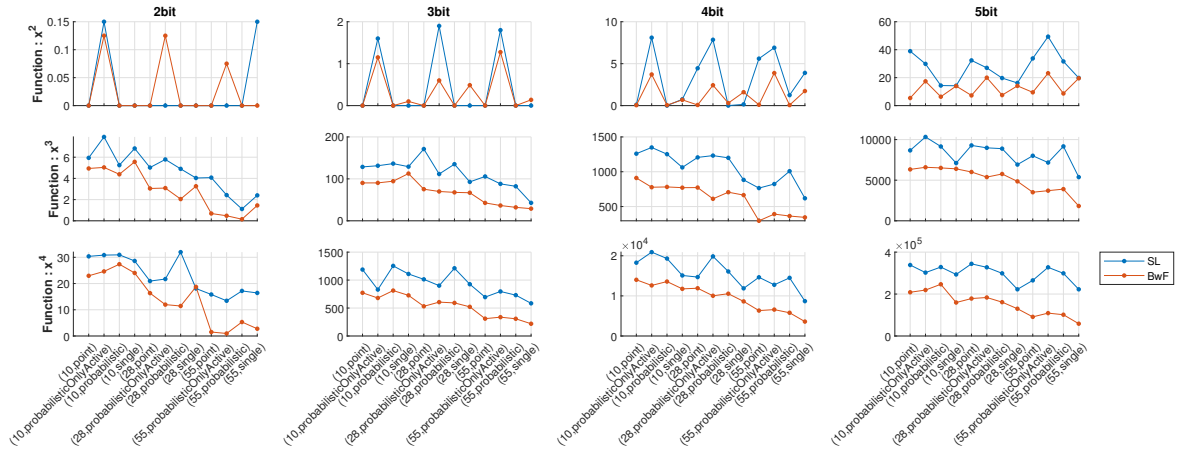


Figure 3: Comparison of CGP configurations w.r.t Mean Absolute Error (in y-axis). Configurations are pairs of evolutionary strategy(10 \rightarrow (1+10), 28 \rightarrow (2+8), 55 \rightarrow (5+5)) and mutation scheme. BwF performs better than SL for all CGP configurations.

The error metrics are defined in the Equations 5.

$$\begin{cases}
 EC = \sum_{\forall x \in R} (O_{Exp}(x) \neq O_{Cir}(x)) \\
 MAE = \frac{\sum_{\forall x \in R} |O_{Exp}(x) - O_{Cir}(x)|}{2^N} \\
 EP = \frac{EC}{2^N} \\
 STD = \sqrt{\frac{(AE(x) - MAE)^2}{2^N}} \\
 Max_AE = \max(|O_{Exp}(x) - O_{Cir}(x)|) \forall x \in R \\
 Min_AE = \min(|O_{Exp}(x) - O_{Cir}(x)|) \forall x \in R \\
 MRE = \frac{\sum_{\forall x \in R} \frac{|O_{Exp}(x) - O_{Cir}(x)|}{\max(1, O_{Exp}(x)})}{2^N}
 \end{cases} \quad (5)$$

The 5-bit data-format for power-two (x^2), power-three (x^3), and power-four (x^4) functions are shown in Figure 2 with the proposed eVar and BwF modified CGP. All three mutation schemes - (1+10), (2+8), and (5+5) with four different evolutionary strategies - *Probabilistic*, *Probabilistic Only Active*, *Point* and *Single* were configured independently to evolve the power function for 5-bits. Each colored line connecting different error metrics represents the average error metrics of 20 runs for a given configuration among the 12 investigated. The SL driven CGP method, which employs a constant mutation rate, and equal-weighted fitness showcased higher error metrics for different evolved circuits when compared to most of the circuits generated by the proposed eVar and BwF modified CGP method. The reduced error metrics confirm that the eVar and BwF configured CGP approach derives fitter circuits than SL based CGP approach.

5.2 CGP Configuration Analysis

Figure 3 shows the comparison between BwF and SL generated circuits for all the configurations. The

(5+5) evolutionary strategy consistently performs better than the (1+10) and (2+8) strategies. The (2+8) strategy is also found to perform better than (1+10) strategy. This result hints that creating fewer child solutions per parent in every generation is preferred. Fewer children per parent imply a higher number of circuit topologies are being carried forward to further generations. The mutation scheme has a large impact on the generated circuits MAE when using SL fitness function. Furthermore, there is no clear correlation between the mutation type and MAE over the functions (x^2, x^3, x^4) and bit width. BwF as fitness function is found to minimise the variation in MAE with mutation type selected. *Single* and *Point* mutation types perform better than *Probabilistic* and *Probabilistic Only Active* when BwF is used. BwF across 12 mutation scheme emerges with a clear accuracy advantage ranging from 5% to 50% of less MAE for x^3 , and x^4 power functions when compared with SL method. The same is not established for x^2 power function, which are smaller designs. Hence BwF is preferred to realise functions with higher bit-width and complexity.

6 APPLICATION : ACTIVATION FUNCTIONS

Activation functions are chosen to showcase the ability to evolve complex non-linear circuits using the proposed modifications to CGP. Digital circuits are usually clocked-sequential designs, requiring Flip-Flops to maintain intermediate results. Activation functions are difficult functions to realize in hardware, and tedious design effort is needed to approx-

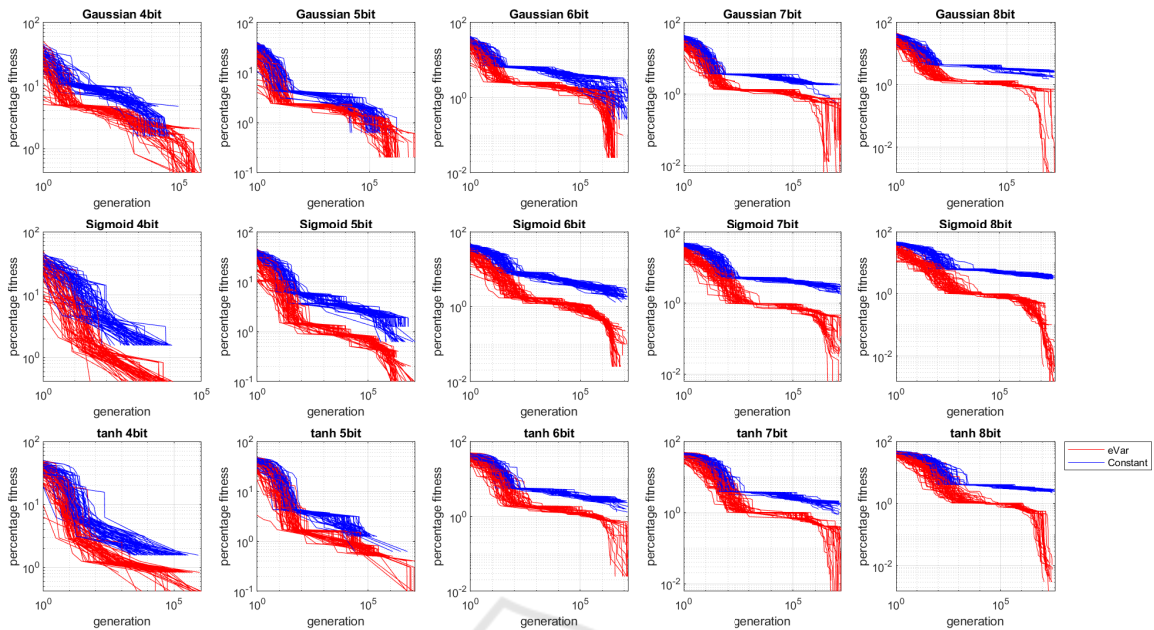


Figure 4: Comparison of convergence to full-fitness of constant mutation rate and exponentially varying mutation rate. Most eVar-BwF runs converge to functionally-perfect solutions within the generation plotted, while SL-constant mutation rate runs require more generations.

imate them to sequential designs. Our CGP evolved circuits are purely combinatorial circuits, which enable a large span of hardware-resource (silicon space, power) to speed of execution trade-off during the synthesis stage of a typical VLSI physical implementation flow.

to the input data format of Gaussian function since it offers adequate integer bits to represent the full range of output values between -1 to 1. Typical evolutionary strategy of (1+4) along with Point mutation scheme was adopted for this analysis.

$$\begin{cases} \text{Sigmoid}(x) = \frac{1}{1+e^{-x}} \\ \text{tanh}(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \\ \text{Gaussian}(x) = e^{-x^2} \end{cases} \quad (6)$$

6.1 Fitness Convergence

Sigmoid, Gaussian and Hyperbolic-tangent are described in Equation 6. Fixed-point representation of the data is used to represent the input and outputs of the activation function. Round-to-floor quantization scheme is used to obtain the fixed-point representation of the continuous activation functions. Figure 5

Figure 4 is the plot of percentage-of-fitness versus generations in logarithm scale for *Gaussian*, *Sigmoid*, and *hyperbolic-tangent* functions of 4-bit to 8-bit data-formats, when configured with (blue runs) constant mutation rate with SL, and (red runs) eVar mutation rate with BwF. We report the percentage of fitness since the order of magnitude of SL and BwF values are different. The graph also allows to recognize potential termination when a functionally perfect solution is found. The eVar mutation rate evolves to a similar percentage of fitness attained by constant mutation rate by at least a decade generation less for lower order bit-widths, and at least 10^5 generations less for 7, and 8-bit activation functions. Additionally, the best evolved design for eVar based CGP consistently achieved maximum fitness for a similar number of generations throughout the three activation functions investigated. Considering the evolved design at the last generation, the percentage of fitness achieved by the eVar applied CGP is better by at least a decade for lower order bit-width functions and at least 100

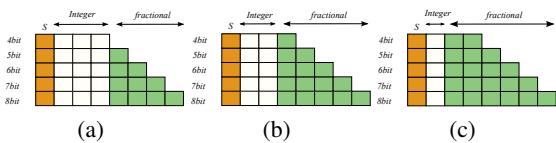


Figure 5: Input data format for (a) *Sigmoid*, (b) *Hyperbolic tangent*, and (c) *Gaussian* activation functions.

shows the input fixed-point data format used. The output data format for Sigmoid, Hyperbolic-Tangent, and Gaussian activation function was configured similar

times better for the 7 and 8-bit activation functions.

6.2 Correlation of Circuit Output

Figure 6 (a) shows the output profile of the circuit generated from the proposed scheme, which closely resembles the expected output non-linear profile. The absolute error remains zero for most of the input data, with dominant error values close to 0. Figure 6 (b) depicts the output profile of the circuit generated from the traditional SL method. It demonstrates erroneous output for different input data. The absolute error is not only spread across the input data range but also higher in magnitude. The error rate is also higher compared to the proposed BwF-and-eVar modified CGP approach. The error rate for both methods are indicated next to the absolute error graphs.

7 CONCLUSIONS

The circuits evolved from the proposed BwF and eVar method were synthesised faster and provided gate-level designs that furnished close to the exact output. The eVar mutation rate explores the design space much faster to evolve to a functionally correct solution. The BwF feature supports selecting and driving the evolutionary designs toward weighted fitness along the output bits, leading to reduced error metrics when compared with SL technique. Among the evolutionary strategies (5+5) is preferred, considering the lowest gate count and securing the best fitness among the three strategies configured for realising power functions. BwF achieves fitness improvement in terms of lower MAE ranging from 5% to 50% for x^3 and x^4 functions when compared with the SL method. The proposed eVar and BwF modified CGP was applied on activation functions such as *Gaussian*, *Sigmoid*, and *hyperbolic-tangent* to validate the effectiveness of the modifications. For 7-bit and 8-bit activation functions, eVar aids in evolving the circuit design faster by at least 10^5 times lesser generations, and BwF generates output profile close to required profile when compared to SL. BwF and eVar enabled CGP evolved circuits adhere closely to the non-linear profile of the activation functions studied in this work. Overall, BwF and eVar are two major tools in setting up CGP to evolve complex non-linear functions with significantly less computation effort. All the designs are made freely available in (Prashanth, 2022) for further usage by the research and designers community.

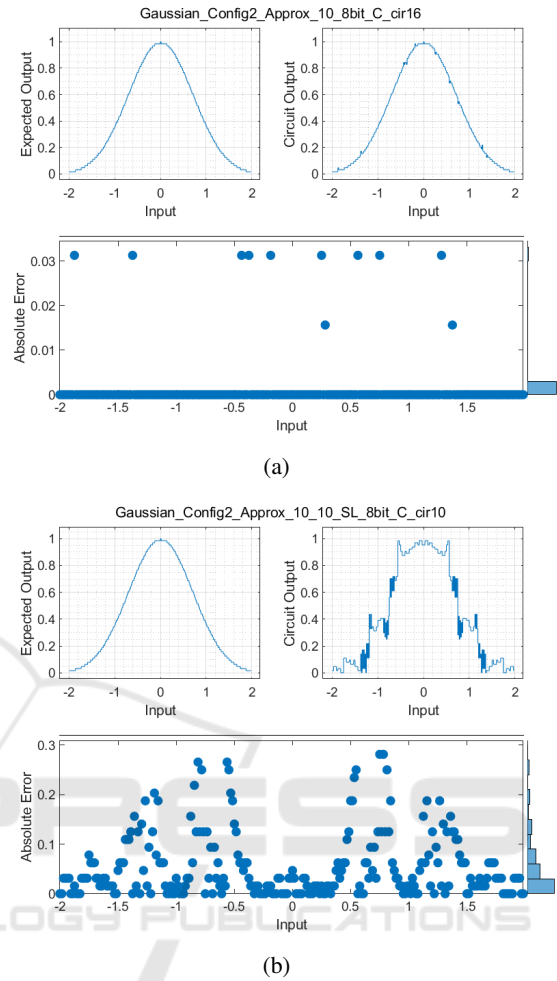


Figure 6: Circuit and expected output 8bit Gaussian CGP run example. (a) BwF helps to obtain circuits which closely resemble non-linear functions. (b) SL only considers hamming distance without assigning weightage to large errors.

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