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(54) **METHOD AND SYSTEM FOR  
REPRODUCTION IN A GENETIC  
OPTIMIZATION PROCESS**

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(57) **ABSTRACT**  
A reproduction method and system supports rapid conver-  
gence of a genetic optimization process. Mating, mutation,  
or both may be combined with biased parent selection  
during each mating season.

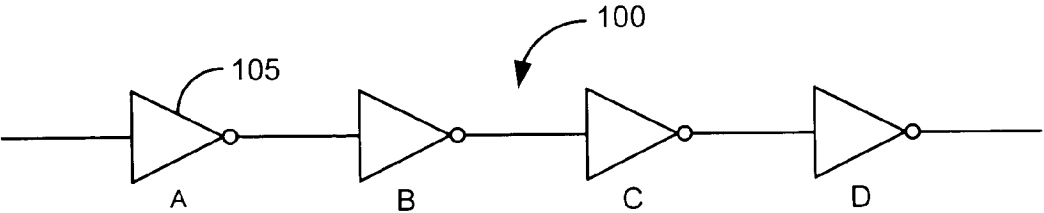


FIG. 1A

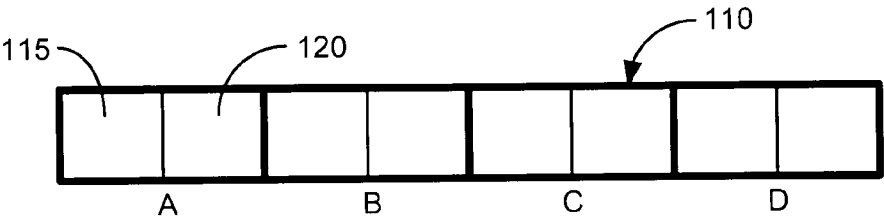


FIG. 1B

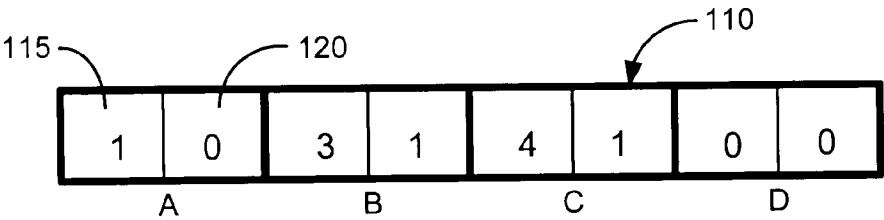


FIG. 1C

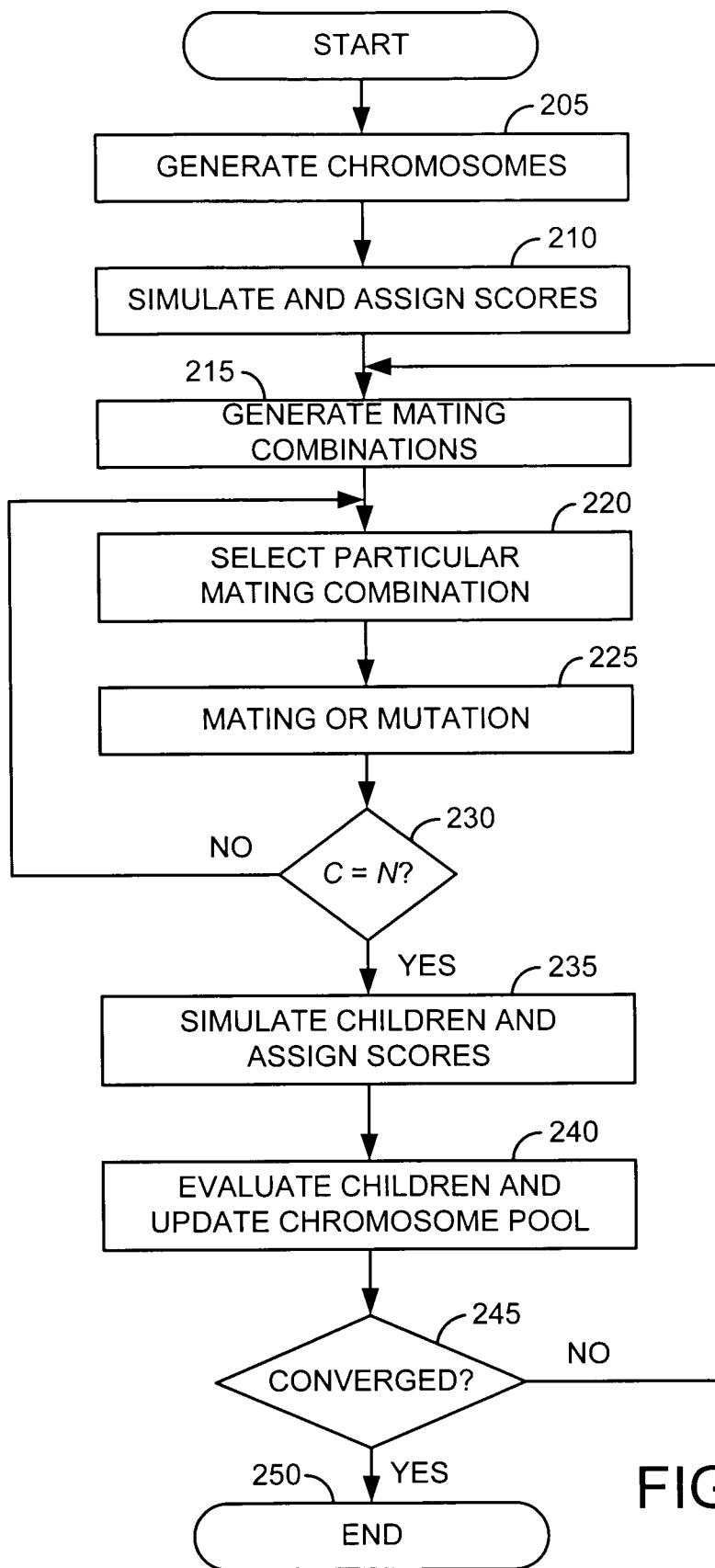


FIG. 2

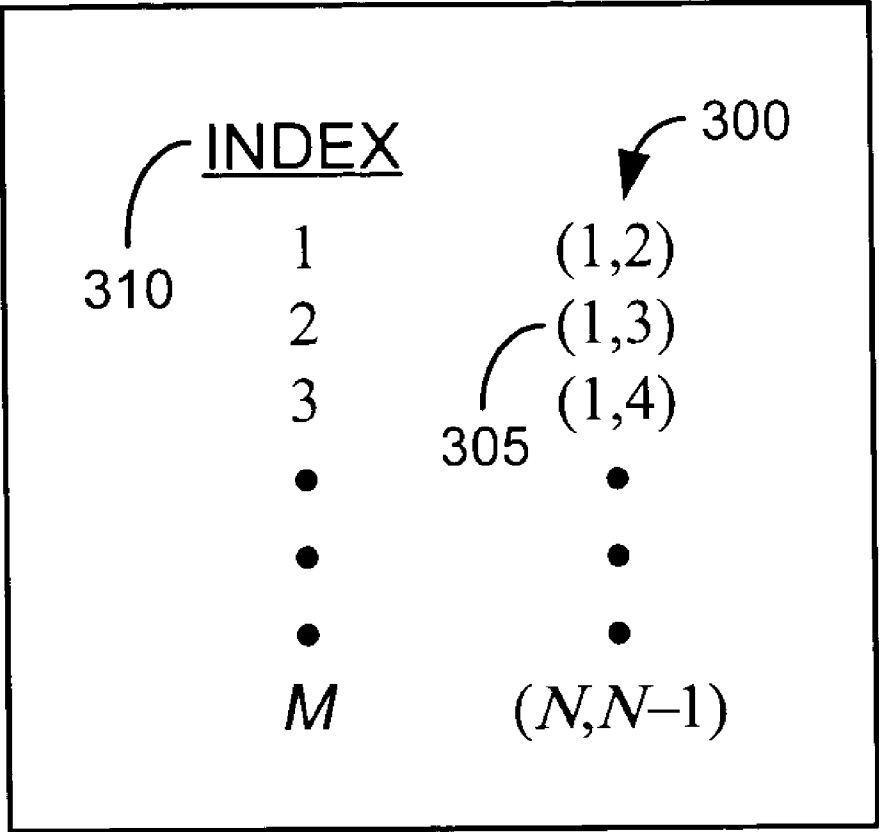


FIG. 3

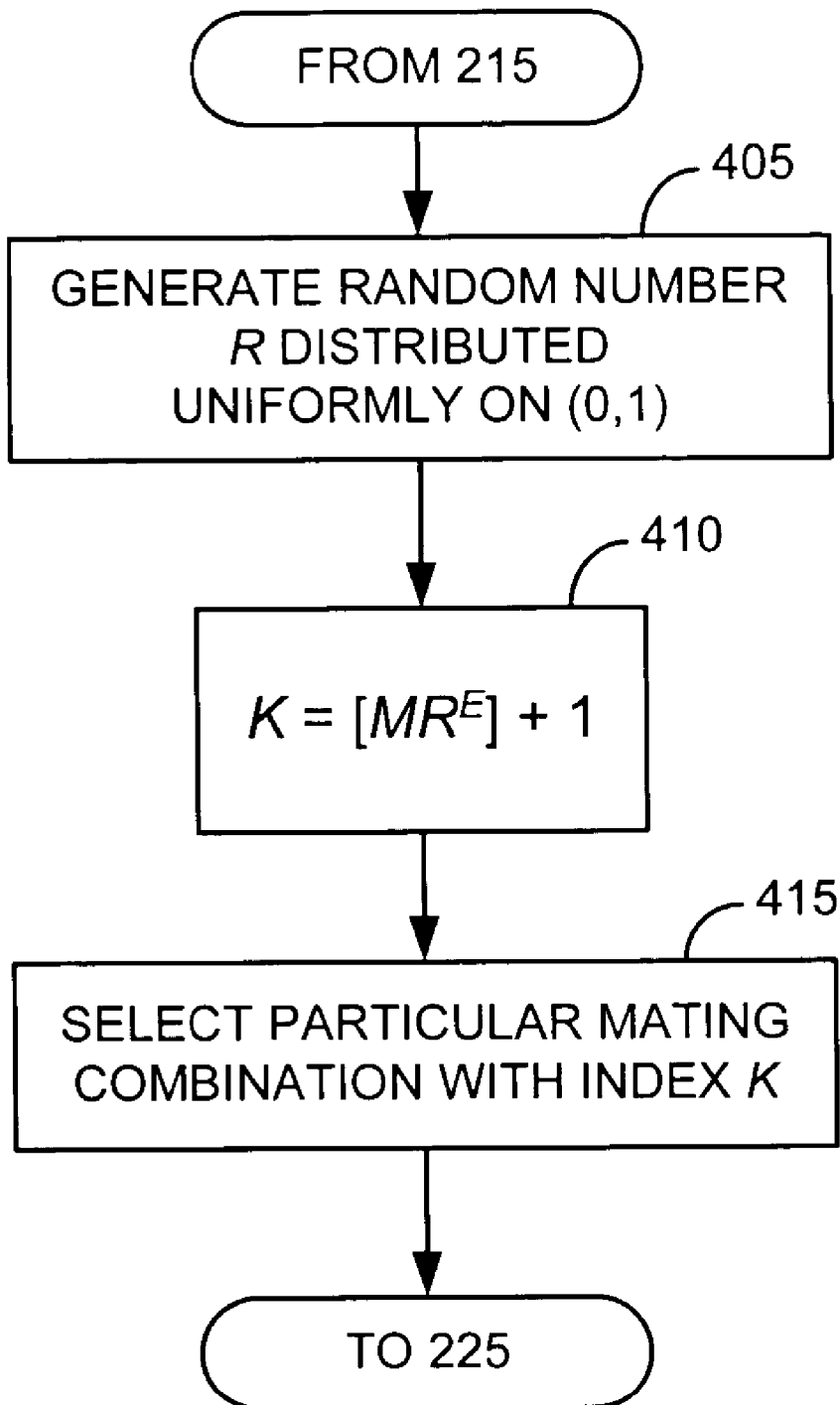


FIG. 4

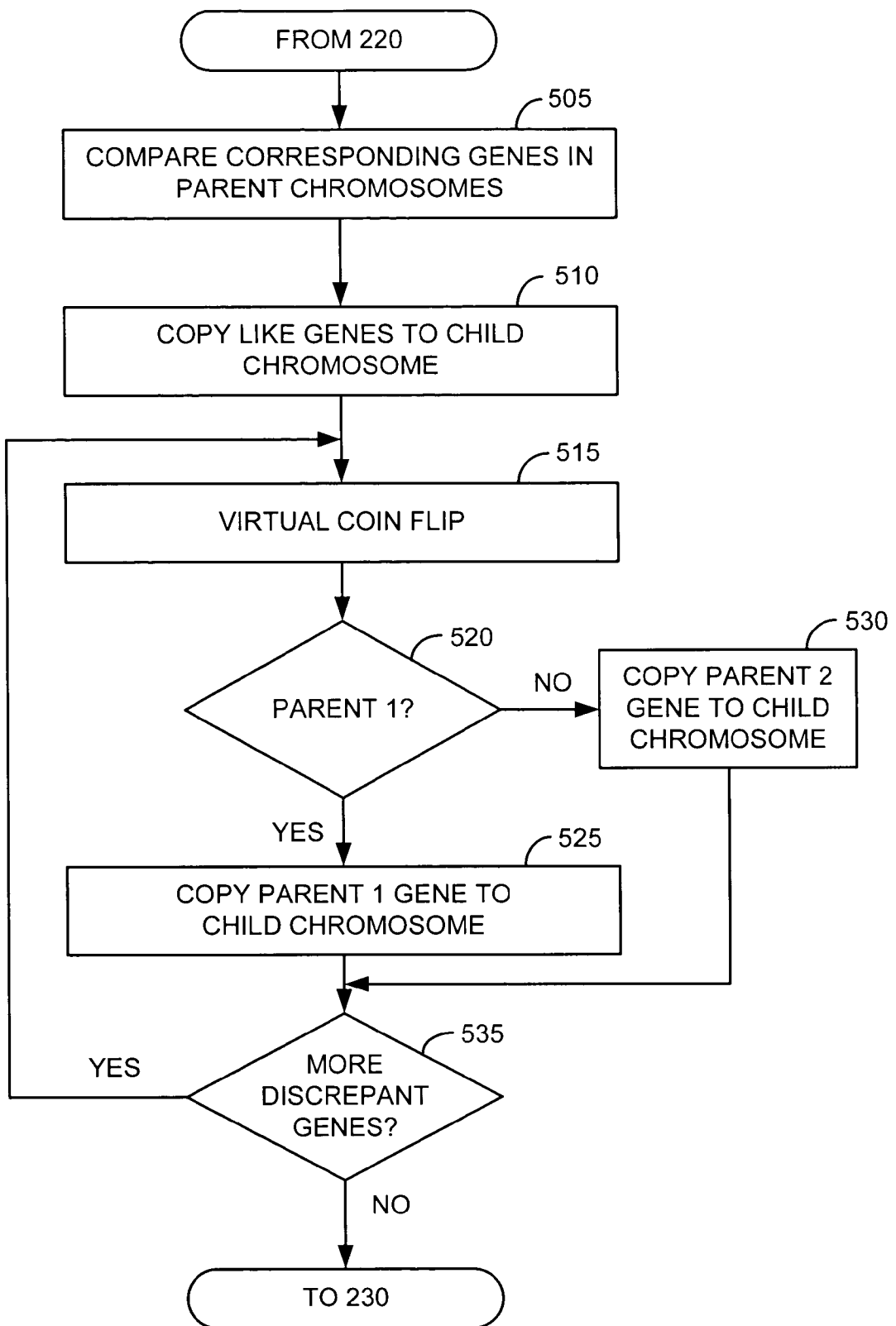


FIG. 5

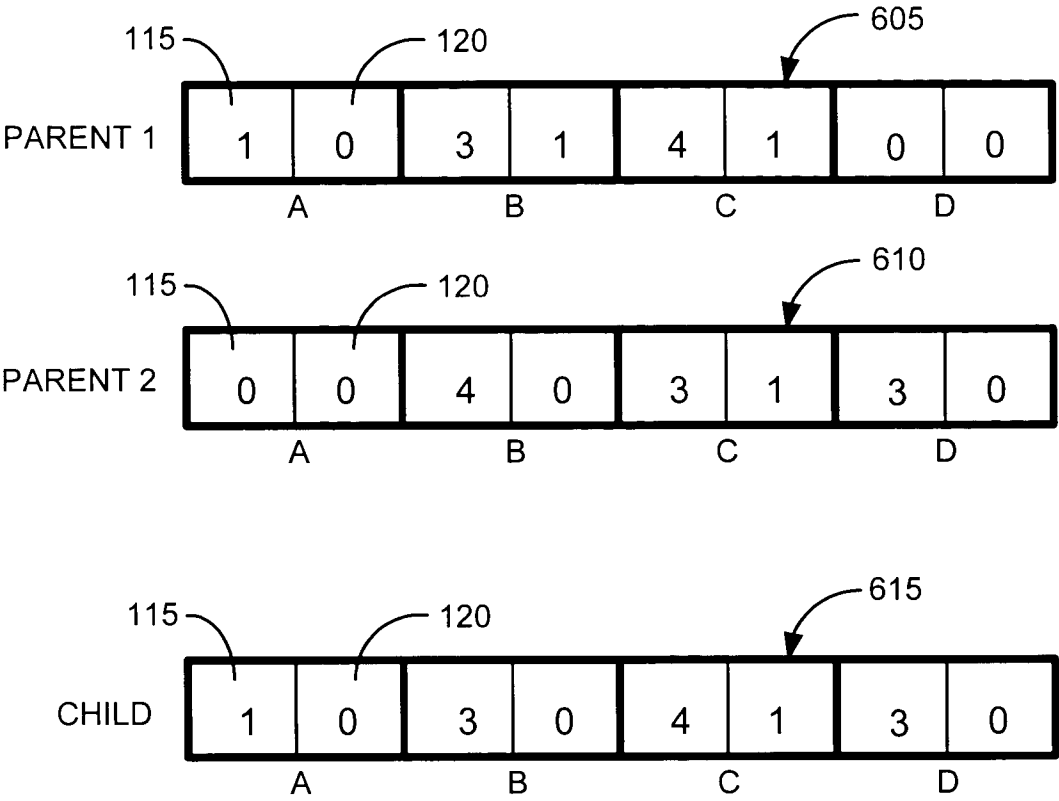


FIG. 6

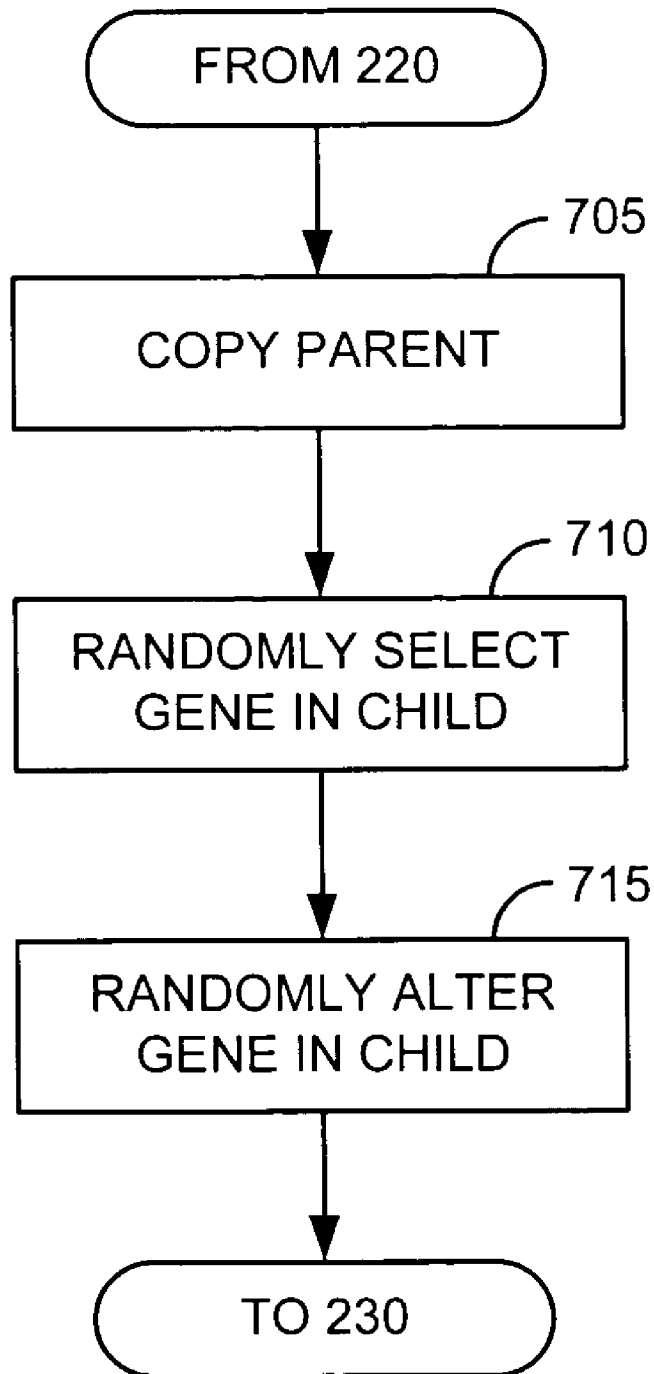


FIG. 7



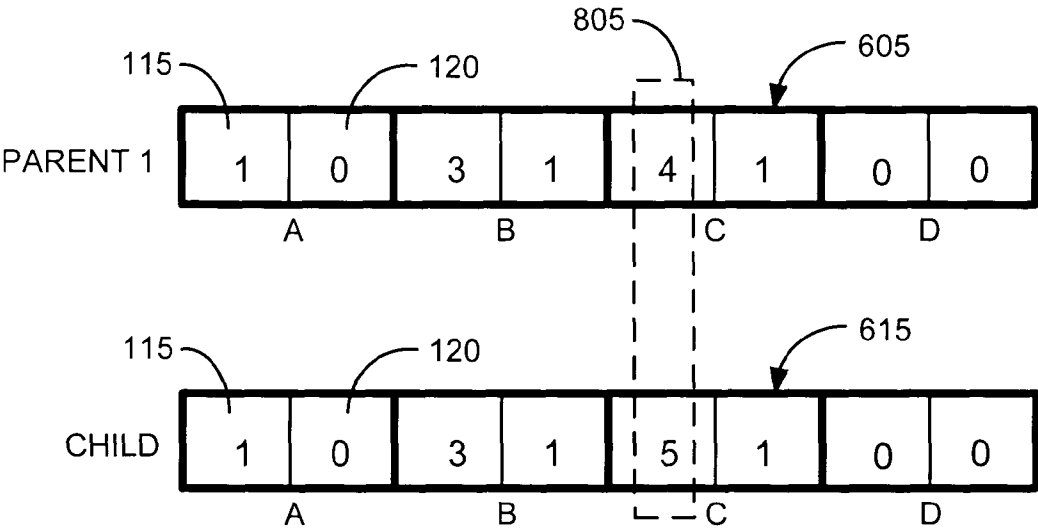


FIG. 8

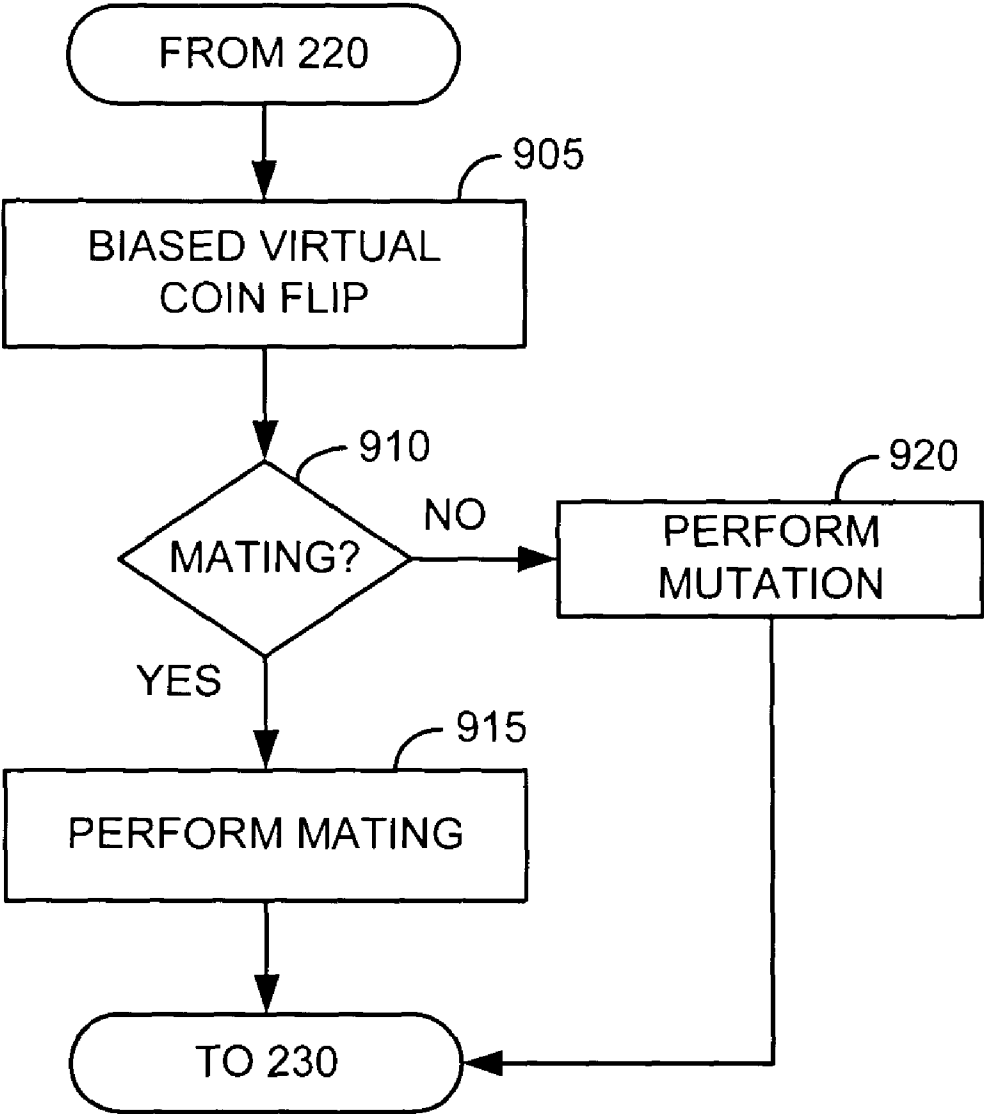


FIG. 9

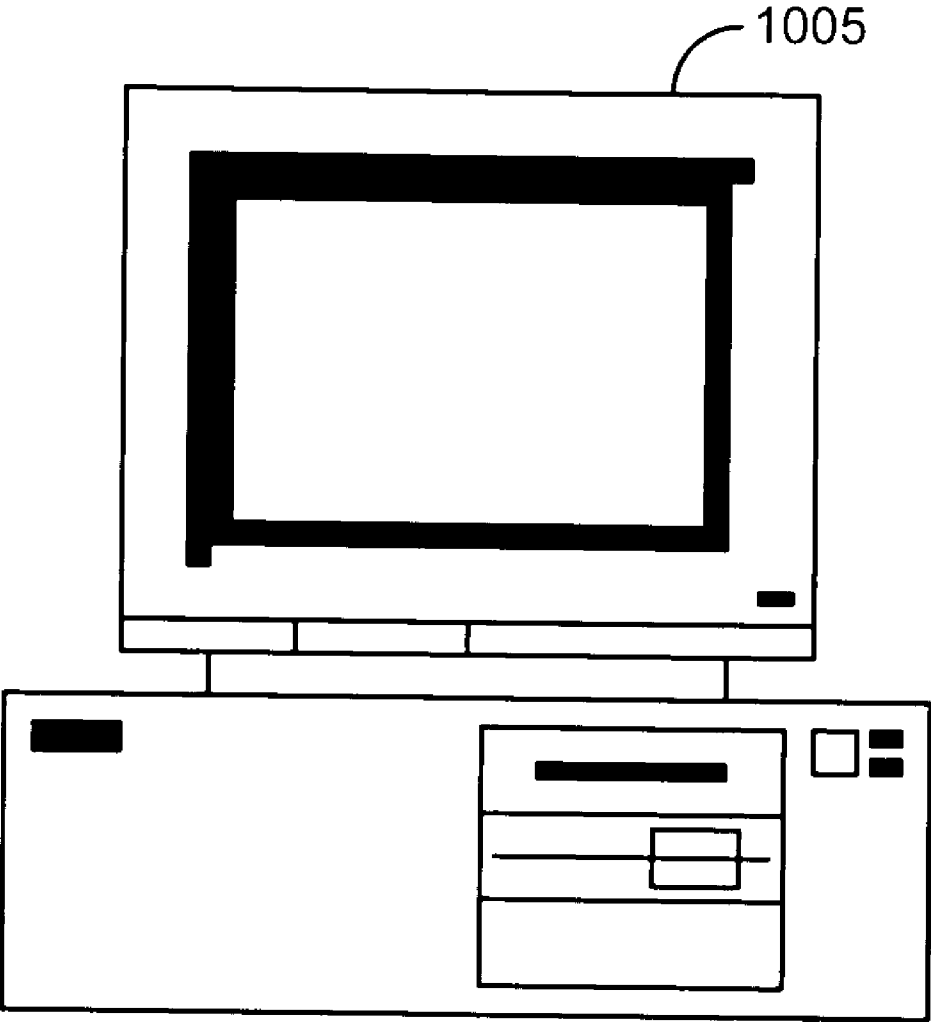


FIG. 10

## METHOD AND SYSTEM FOR REPRODUCTION IN A GENETIC OPTIMIZATION PROCESS

### FIELD OF THE INVENTION

[0001] The present invention relates generally to computerized optimization techniques and more specifically to techniques based on a genetic model.

### BACKGROUND OF THE INVENTION

[0002] Due to the large number of variables involved, some optimization problems have an exceedingly large solution space. For example, selecting design parameters such as size and threshold voltage for each of thousands of instances (i.e., gates) in an integrated circuit to minimize power consumption while maintaining acceptable timing performance is such a problem.

[0003] One approach to solving complex optimization problems is genetic optimization, an iterative, computer-implemented technique in which candidate solutions are generated using a genetic model. The genetic model typically includes a set of N randomly generated chromosomes, each chromosome comprising a number of genes. Since each gene represents a particular state of a parameter to be optimized in one part of a system (e.g., the size of one instance in an integrated circuit), each chromosome represents a possible solution to the global optimization problem. In a typical application, the configuration specified by each chromosome is evaluated, and a figure of merit or "score" is assigned to each chromosome. For example, in the case of an integrated circuit design, a circuit having the characteristics of each chromosome may be simulated to assign a score indicating the desirability of its power consumption and timing performance. Once each chromosome has been assigned a score, the N chromosomes may be "mated" or "mutated" in various ways to create other potential solutions or "children," which may, in turn, be evaluated and assigned a score. If a child has a higher score than one of the original N chromosomes, the chromosome with the lowest score may be discarded. Eventually, the candidate solutions generated in this fashion may converge to the global optimum.

[0004] A key aspect of such a genetic algorithm is reproduction, the method by which new solutions are generated during each "mating season." In one well-known approach, pairs of chromosomes or "mating combinations" are formed, and mating combinations are randomly selected for possible mating. If the composite score of a mating combination is higher than a predetermined threshold, the chromosomes are mated. Otherwise, they are not mated. However, this approach can lead to too many or too few children being produced during each mating season, if the threshold is set too high or too low. The consequence in either case is slower convergence.

[0005] It is thus apparent that there is a need in the art for an improved method and system for reproduction in a genetic optimization process.

### SUMMARY OF THE INVENTION

[0006] A method is provided for reproduction in a computer-implemented optimization process based on a genetic model. Both a system and a computer-readable storage medium containing program instructions are provided for carrying out the method.

[0007] Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIGS. 1A-1C are illustrations showing how instances in an integrated circuit may be mapped onto a genetic algorithm in accordance with an illustrative embodiment of the invention.

[0009] FIG. 2 is a flowchart of a genetic optimization process in accordance with an illustrative embodiment of the invention.

[0010] FIG. 3 is an illustration of a set of mating combinations in accordance with an illustrative embodiment of the invention.

[0011] FIG. 4 is a flowchart of a method for selecting a particular mating combination in accordance with an illustrative embodiment of the invention.

[0012] FIG. 5 is a flowchart of a mating method in accordance with an illustrative embodiment of the invention.

[0013] FIG. 6 is an illustration of the operation of the mating method shown in FIG. 5.

[0014] FIG. 7 is a flowchart of a mutation method in accordance with an illustrative embodiment of the invention.

[0015] FIG. 8 is an illustration of the operation of the mutation method shown in FIG. 7.

[0016] FIG. 9 is a flowchart of a method for combining mating and mutation in accordance with an illustrative embodiment of the invention.

[0017] FIG. 10 is an illustration of a system for carrying out the methods of the invention in accordance with an illustrative embodiment of the invention.

### DETAILED DESCRIPTION OF THE INVENTION

[0018] FIGS. 1A-1C illustrate how instances in an integrated circuit may be mapped onto a genetic algorithm in accordance with an illustrative embodiment of the invention. FIG. 1A is a gate-level diagram of a simple integrated circuit 100. In this simplified example, integrated circuit 100 comprises four instances 105, each of which is an inverter. Each instance 105 is labeled A-C to facilitate further description. FIG. 1B is a conceptual diagram of a chromosome 110 comprising a size gene 115 and a threshold voltage ( $V_t$ ) gene 120 for each instance 105 for a total of eight genes. Genes 115 and 120 may be represented conveniently as integers. For example, size gene 115 may comprise an integer between 0 and 5, inclusive, corresponding to predetermined physical sizes of the associated instance 105. Likewise, threshold voltage gene 120 may comprise an integer equal to either zero (low  $V_t$ ) or one (high  $V_t$ ). An example of a particular chromosome conforming to the foregoing scheme is shown in FIG. 1C.

[0019] FIG. 2 is a flowchart of a genetic optimization process in accordance with an illustrative embodiment of the invention. At 205, a set of N unique chromosomes may be

generated. For example, a random number generator may be used to assign a value to each gene **115** or **120** in each of the  $N$  chromosomes. The set of  $N$  chromosomes will also be referred to as a “chromosome pool” in this description. In practice, the values generated by the random number generator may be pseudorandom. The performance of a simulated integrated circuit **100** having the design characteristics specified by each of the  $N$  chromosomes may be simulated at **210**. In this illustrative embodiment, the power consumption of integrated circuit **100** is to be minimized while maintaining acceptable timing. At **210**, a score may be assigned to each chromosome indicating how well it meets the design goals. For example, the score may be a number proportional to the total power consumption of the integrated circuit **100**. At **215**, a set of mating combinations, each comprising a first and a second chromosome, may be generated from the  $N$  chromosomes comprising the chromosome pool. For example, if all possible mating combinations are generated for  $N=10$ , a total of  $M=45$  mating combinations results. At **220**, a particular mating combination for subsequent reproduction may be chosen from among the  $M$  mating combinations. The particular mating combination selected will also be called a “set of parents” for the purposes of this description. Parent selections will be explained more fully in a later portion of this description. A set of parents (mating) or a copy of a single parent (mutation) may be used at **225** to generate a child chromosome. Mating and mutation methods will be explained more fully in a later portion of this detailed description. At **230**, if the desired number of children has been generated, control may proceed to **235**. Otherwise, steps **220** and **225** may be repeated until the desired number of children has been produced. For example,  $N$  children may be produced during each mating season (one pass through the loop comprising steps **215** through **245**). However, more or fewer children may be produced during each mating season in other embodiments. At **235**, each resulting child chromosome may be simulated to determine its corresponding performance score. One advantageous technique is to send each child chromosome to a different dedicated processing node in parallel fashion. The best  $N$  chromosomes from among the original  $N$  and the child chromosomes may be retained for the next mating season at **240**. If the  $N$  chromosomes have converged to within a predetermined tolerance at **245**, the process may be terminated at **250**. Otherwise, control may return to **215**, and a new mating season may begin based upon the updated chromosome pool.

[0020] FIG. 3 illustrates a set of mating combinations **300** in accordance with an illustrative embodiment of the invention. Each mating combination **305** is shown in FIG. 3 as an ordered pair of the  $N$  chromosomes in the chromosome pool. Each mating combination **305** may be assigned an index **310** from 1 to  $M$ . A composite performance score (not shown in FIG. 3) may also be assigned to each mating combination **305**. One simple way to compute such a composite score is to compute the product of the score associated with each individual chromosome comprising the mating combination **305**. Mating combinations **300** may also be sorted or mapped to appropriate indices **310** in order of decreasing or increasing composite score. In this particular illustrative embodiment, mating combinations **300** are sorted from best to worst composite score, as indicated in FIG. 3.

[0021] FIG. 4 is a flowchart of a method for selecting a particular mating combination or set of parents in accor-

dance with an illustrative embodiment of the invention. After **215**, a random number generator may be used at **405** to produce a real number  $R$  distributed uniformly on the open interval  $(0,1)$ . At **410**,  $R$  may be raised to a power  $E$ , where  $E$  is a real number greater than unity, and multiplied by  $M$ , the number of mating combinations. The greatest integer less than or equal to this product may be computed, and one may be added to generate an integer index  $K$  between 1 and  $M$ , inclusive. The particular mating combination **305** having an index equal to  $K$  may be selected as a set of parents at **415**. The index  $K$  as computed in FIG. 4 biases the selection of sets of parents in favor of those mating combinations **305** having a favorable composite score. The exponent  $E$ , being greater than unity, drives the fraction  $R$  closer to zero, resulting in a lower index  $K$  than would result from a uniformly distributed random index based on  $R$  alone. This approach also guarantees that a child will be generated on each attempt, unlike the prior-art threshold method. The exponent  $E$  may also be selected and adjusted by a user to provide precise control over the degree of bias. Once a set of parents has been selected, a child chromosome may be produced by either mating the first parent with the second parent or by mutating a copy of a single parent (**225**).

[0022] FIG. 5 is a flowchart of a mating method in accordance with an illustrative embodiment of the invention. Following **220**, corresponding genes of the first and second parents may be compared at **505** to determine which are alike and which are different. Those genes that are the same in both parents may be copied to a child chromosome at **510**. To assign a value for discrepant genes to the genes of the child chromosome, the loop beginning at **515** may be performed. At **515**, a “virtual coin flip” may be conducted using a random number generator. The virtual coin flip may be fair or biased, depending on the embodiment. If the first parent wins the toss at **520**, the value of the gene belonging to the first parent is copied to the corresponding gene of the child chromosome at **525**. Otherwise, the value of the gene belonging to the second parent is copied to the corresponding gene of the child chromosome at **530**. The virtual coin flip at **515** simulates the characteristic of dominance in genetics, and a discrepant gene so assigned to the child chromosome will be referred to in this description as a “dominant gene.” If all discrepant genes have been resolved, control may proceed to **230**. Otherwise, control may return to **515** for the assignment of another discrepant gene.

[0023] FIG. 6 illustrates the operation of the mating method shown in FIG. 5. First parent (“Parent 1”) **605** and second parent (“Parent 2”) **610** are mated to produce child **615**. Each corresponding gene having the same value in both parents is copied to child **615**. Here, the threshold voltage gene **120** of A, the threshold voltage gene **120** of C, and the threshold voltage gene **120** of D are copied to child chromosome **615**. The discrepant genes are copied randomly from either the first or the second parent, as explained in connection with FIG. 5. Here, size gene **115** of A is assigned the value of the first parent, size gene **115** of B is assigned the value of the first parent, threshold voltage gene **120** of B is assigned the value of the second parent, size gene **115** of C is assigned the value of the first parent, and size gene **115** of D is assigned the value of the second parent.

[0024] FIG. 7 is a flowchart of a mutation method in accordance with an exemplary embodiment of the invention.

After **220**, a copy or “clone” of one of the two parents may be made at **705**. Although either parent may be chosen, the first parent will be selected arbitrarily for the purposes of this description. At **710**, one or more genes may be selected in the child chromosome for subsequent mutation. In the particular embodiment shown in **FIG. 7**, one gene is chosen at random. The randomly selected gene is altered randomly at **715**, comprising the mutation. Control may then proceed to **230**. In some cases, mutation may produce a child that is closer to the desired solution than mating. As will be explained later in this description, a combination of mating and mutation has been found to be synergistic, especially when combined with a biased parent selection technique such as that shown in **FIG. 4**.

[**0025**] **FIG. 8** illustrates the operation of the mutation method shown in **FIG. 7**. In **FIG. 8**, first parent **605** has been copied or cloned to produce child **615**. Subsequently, size gene **115** of **C** indicated by the dotted bounding box has been randomly altered within the allowed range, resulting in a change from “4” to “5.”

[**0026**] **FIG. 9** is a flowchart of a method for combining mating and mutation in accordance with an exemplary embodiment of the invention. After **220**, a biased virtual coin flip may be performed at **905** to select between mating and mutation. For example, the biased virtual coin flip may select mutation for 80 per cent of the children produced and mating for the remaining 20 per cent. If the result at **910** is that mating is to be performed, a mating method such as that described in connection with **FIG. 5** may be executed at **915**. Otherwise, a mutation method such as that described in connection with **FIG. 7** may be performed at **920**. Once a child has been produced by either method, control may proceed to **230**. As mentioned above, combining a biased parent selecting method such as that shown in **FIG. 4** with both mating and mutation has been found to produce synergistic results. Such an approach can provide significantly more rapid convergence than conventional genetic optimization techniques.

[**0027**] **FIG. 10** illustrates a system for carrying out the methods of the invention, in accordance with an illustrative embodiment of the invention. **FIG. 10** depicts a general purpose computer **1005**. The methods of the invention may be programmed to execute on such a general purpose computer **1005** or, alternatively, the invention may be implemented in a special-purpose (e.g., high-performance) computer, in custom hardware, or in any combination of hardware and software. Program code implementing the invention may also be stored on a computer-readable storage medium. Examples of computer-readable storage media include solid-state read-only memory, magnetic disks, and optical disks.

[**0028**] The foregoing description of the present invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and other modifications and variations may be possible in light of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and various modifications as are suited to the particular use contemplated. It is intended that the appended claims be

construed to include other alternative embodiments of the invention except insofar as limited by the prior art.

What is claimed is:

1. A method for reproduction as part of a computer-implemented optimization process based on a genetic model, comprising the steps of:

- (a) generating a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from a set of chromosomes, each chromosome comprising at least one gene;
- (b) assigning a composite score to each mating combination; and
- (c) selecting a particular mating combination using a biased random value, the biased random value favoring mating combinations having a favorable composite score, the first and second chromosomes of the particular mating combination comprising first and second parents, respectively.

2. The method of claim 1, wherein assigning a composite score to each mating combination comprises computing the product of a first score associated with the first chromosome and a second score associated with the second chromosome.

3. The method of claim 1, wherein step (c) comprises:

sorting the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

generating a random value distributed uniformly between zero and one;

raising the random value to a predetermined power greater than one to produce the biased random value;

multiplying the number of mating combinations by the biased random value to compute a selection index; and

selecting as the particular mating combination the mating combination whose index corresponds to the selection index.

4. The method of claim 1, further comprising:

preventing the particular mating combination from being selected more than once.

5. The method of claim 1, further comprising:

duplicating one of the first parent and the second parent to produce a child chromosome; and

mutating a gene in the child chromosome.

6. The method of claim 5, wherein the gene to be mutated is selected randomly and mutating the gene in the child chromosome comprises randomly modifying the gene in the child chromosome.

7. The method of claim 1, further comprising:

mating the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

mutating a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

8. The method of claim 1, wherein each gene represents a characteristic of an instance in an integrated circuit, the characteristic comprising one of size and threshold voltage.

9. A method for reproduction as part of a computer-implemented optimization process based on a genetic model, comprising the steps of:

generating a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from a set of chromosomes, each chromosome comprising at least one gene;

assigning a composite score to each mating combination;

sorting the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

generating a random value distributed uniformly between zero and one;

raising the random value to a predetermined power greater than one to produce a biased random value;

multiplying the number of mating combinations by the biased random value to compute a selection index; and

selecting the first and second chromosomes of the mating combination whose index corresponds to the selection index as first and second parents, respectively.

10. The method of claim 9, further comprising:

preventing the mating combination whose index corresponds to the selection index from being selected more than once.

11. The method of claim 9, further comprising:

duplicating one of the first parent and the second parent to produce a child chromosome; and

mutating a gene in the child chromosome.

12. The method of claim 11, wherein the gene to be mutated is selected randomly and mutating the gene in the child chromosome comprises randomly modifying the gene in the child chromosome.

13. The method of claim 9, further comprising:

mating the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

mutating a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

14. The method of claim 9, wherein each gene represents a characteristic of an instance in an integrated circuit, the characteristic comprising one of size and threshold voltage.

15. A method for reproduction as part of a computer-implemented process based on a genetic model for optimizing the power consumption and timing of an integrated circuit comprising a plurality of instances, the method comprising:

providing a set of chromosomes, each chromosome comprising a plurality of genes representing a set of design choices for the instances in the integrated circuit, each instance being mapped to a first gene representing the size of that instance and a second gene representing the threshold voltage of that instance;

simulating for each chromosome the power consumption and timing performance of an integrated circuit corre-

sponding to the set of design choices specified by the genes in that chromosome;

assigning a score to each chromosome according to its simulated power consumption and timing performance;

generating a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from the set of chromosomes;

assigning a composite score to each mating combination, the composite score comprising the product of the score associated with the first chromosome and the score associated with the second chromosome;

sorting the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

generating a random value distributed uniformly between zero and one;

raising the random value to a predetermined power greater than one to produce a biased random value;

multiplying the number of mating combinations by the biased random value to compute a selection index; and

selecting the first and second chromosomes of the mating combination whose index corresponds to the selection index as first and second parents, respectively.

16. The method of claim 15, further comprising:

preventing the mating combination whose index corresponds to the selection index from being selected more than once.

17. The method of claim 15, further comprising:

duplicating one of the first parent and the second parent to produce a child chromosome; and

mutating a gene in the child chromosome.

18. The method of claim 17, wherein the gene to be mutated is selected randomly and mutating the gene in the child chromosome comprises randomly modifying the gene in the child chromosome.

19. The method of claim 15, further comprising:

mating the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

mutating a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

20. A system programmed to perform the following method:

(a) providing a set of chromosomes, each chromosome comprising at least one gene;

(b) generating a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from the set of chromosomes;

(c) assigning a composite score to each mating combination; and

(d) selecting a particular mating combination using a biased random value, the biased random value favoring

mating combinations having a favorable composite score, the first and second chromosomes of the particular mating combination comprising first and second parents, respectively.

**21.** The system of claim 20, wherein step (d) of the method comprises:

sorting the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

generating a random value distributed uniformly between zero and one;

raising the random value to a predetermined power greater than one to produce a biased random value;

multiplying the number of mating combinations by the biased random value to compute a selection index; and

selecting as the particular mating combination the mating combination whose index corresponds to the selection index.

**22.** The system of claim 20, wherein the method comprises the following additional steps:

duplicating one of the first parent and the second parent to produce a child chromosome; and

mutating a gene in the child chromosome.

**23.** The system of claim 20, wherein the method comprises the following additional steps:

mating the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

mutating a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

**24.** A system for performing reproduction as part of a computer-implemented optimization process based on a genetic model, comprising:

means for providing a set of chromosomes, each chromosome comprising at least one gene;

means for generating a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from the set of chromosomes;

means for assigning a composite score to each mating combination; and

means for selecting randomly a particular mating combination such that mating combinations having a favorable composite score are favored, the first and second chromosomes of the particular mating combination comprising first and second parents, respectively.

**25.** The system of claim 24, wherein the means for selecting randomly a particular mating combination such that mating combinations having a favorable composite score are favored further comprises:

means for sorting the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

means for generating a random value distributed uniformly between zero and one;

means for raising the random value to a predetermined power greater than one to produce a biased random value;

means for multiplying the number of mating combinations by the biased random value to compute a selection index; and

means for selecting as the particular mating combination the mating combination whose index corresponds to the selection index.

**26.** The system of claim 24, further comprising:

means for duplicating one of the first parent and the second parent to produce a child chromosome; and

means for mutating a gene in the child chromosome.

**27.** The system of claim 24, further comprising:

means for mating the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

means for mutating a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

**28.** A computer-readable storage medium containing program code to perform reproduction as part of an optimization process based on a genetic model, the computer-readable storage medium comprising:

a first code segment configured to generate a set of mating combinations, each mating combination comprising a first chromosome and a second chromosome selected from a set of chromosomes, each chromosome comprising at least one gene;

a second code segment configured to assign a composite score to each mating combination; and

a third code segment configured to select a particular mating combination using a biased random value, the biased random value favoring mating combinations having a favorable composite score, the first and second chromosomes of the particular mating combination comprising first and second parents, respectively.

**29.** The computer-readable storage medium of claim 28, wherein the third code segment comprises instructions causing the computer to

sort the mating combinations from most favorable to least favorable according to their associated composite scores, each sorted mating combination having an associated index;

generate a random value distributed uniformly between zero and one;

raise the random value to a predetermined power greater than one to produce a biased random value;

multiply the number of mating combinations by the biased random value to compute a selection index; and

select as the particular mating combination the mating combination whose index corresponds to the selection index.



**30.** The computer-readable storage medium of claim 28, further comprising:

- a fourth code segment configured to duplicate the first parent to produce a child chromosome; and
- a fifth code segment configured to mutate a gene in the child chromosome.

**31.** The computer-readable storage medium of claim 28, further comprising:

a fourth code segment configured to mate the first parent with the second parent to produce a child chromosome for a first predetermined fraction of children produced; and

a fifth code segment configured to mutate a copy of the first parent to produce a child chromosome for a second predetermined fraction of children produced.

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