=$;NO@J8

BjL\

?J2=%b%G%kXN0dEAE*A*Br5!9=$NF3F~

;XF3650w

=j ??M}M: 5R0w65<x · 0B@> M40lO: 65<x

7DXf5A=NBg3XBg3X1!

M}9)3X8&5f2J 7W;;5!2J3X@l96

1997 G/EY

89624234

KLOF @2G7

=$;N O@ J8 MW ;]

@l 96	7W;;5!2J3X	3X @R HV 9f	89624234	%U%j%,%J ;a L>	%-%?%o%- %O%k%f%- KLOF @2G7

(O@ J8 Bj L>)

?J2=%b%G%kXN0dEAE*A*Br5!9=$NF3F~

(Fb MF $N MW ;])

Fb MF $N MW ;] $O Ls 25 9T Dx EY $G 5- F~ $N $3 $H

0dEAE*%"%k%4%j%:%` (GA) $O!$2r8uJd$N=i4|=8CD$r%i%s%@%`$K@8@.$9k3HG9-0hE*$JC5:w$r9TC?8e!$C5:w$,?JsG2r$,<}B+$7!$C5:wE@$,:GE,2rIU6a$K=8$^$k!%$7$+$7!$$RH?$S2r=8CD$,<}B+7F7^$&$H%"%k%4%j%:%`<B9TCf$KLdBj$,JQ2=9kh&$J>u67$G$OBP=h$7K/$$!%hC$F!$F0E*$J4D6-$K$*$$$F$O!$GA $O0dEA;R7?$N<}B+Kh$j2r$r5aaDDb!$2r=8CD$H7F$OB?MM@-$rJ]D3H,K>$^$l!$$=$N2r7h:v$N0lDH7F!$2r8uJd$HJk%9%H%j%s%0$rFsK\Hw$($kFsK\:? GA $,Ds0F$5lF$$$k!%

K\O@J8GO!$F0E*$J4D6-K*$$$F$bFsK\:? GA K*$$$F5i$K2r$NB?MM@-$rJ]$D$?$a$N5!9=$r9M;!!&Ds0F9k!%$^$::G=i$K!$F0E*4D6-KBP9$k0lK\:? GA!$FsK\:? GA APJ}$NDI=>@-$r4Q;!9k$?$a!$$=li$rMQ$$$F=E$_$r5,Dj7?%K%e!<%i%k%M%C%H%o!<%/Kh$j!$%(%s%3!<%I!&%G%3!<%ILdBjJI$NLdBj$r2r$+$;!$I>2A$9$k!%$=7F GA <B9TCf$KLdBj$rJQ$($J$$;~!JQ($?;~$N?6Iq$$$r4Q;!$7!$@w?'BN$NK\?t$N0c$$!$$*hSFsK\:? GA $GMQ$$$k%9%H%j%s%0A*BrItJ,$N%k!<%k$N0c$$$Khk5sF0$NJQ2=$rHf3S!&8!F$$9$k!%

$=$N7k2L!$B?$/$N>l9gFsK\:? GA $O!$0lK\:? GA hj$b4D6-$NJQ2=KBP7DI=>@-$,9b$/!$4h7r$G$"$k$H$$$&3H$,J,$+$k!%$^$?!$%9%H%j%s%0$rA*Br$9$kB?$/$N%k!<%k$NCfGb!$FsK\$N@w?'BN$NFb!$0lJ}$r<g$KMQ$$$k%k!<%k$,NI$$$3Hb<(5l$k!%$3lh$j!$FsK\:? GA K*$$$FEqBAKGx5lJ$$NN0h$NB8:_$d!$$=$NNN0h$K$"$k>pJs$,B?MM@-$N8~>eKO6KaF=EMWG"k3Hr@bL@9k!%

$=$3$G!$$3$N@-<A$rMxMQ$7!$EqBAKGx5lJ$$NN0hK"$k%G!<%?$K!$$b$&0lJ}$N%9%H%j%s%0$N%G!<%?$rH?E>7?bN;}$?$;$k5!9=$r<h$jF~$l$?!$Complemantal GA (CGA) $H$$$&FsK\:? GA $rDs0F$9$k!%Complemental GA $NI>2A<B83$rF1MM$K9T$$!$=>Mh$NFsK\:? GA $HHf3S$7$FF0E*$J4D6-K*$$$FM-8zG"k3Hr<($9!%

Summary of M. S. Thesis

Major	Student No.	SURNAME, Firstname
Dept. of Computer Science	89624234	Haruyuki Kitawaki

Title

Effectiveness of genetic selection mechanism to evolutionary model

In Genetic Algorithms (GAs), randomly created initial population that consists of the candidates of solution for a problem, called genotypes, gradually converges around global or local optima as the search proceeds. Once the population converges, it doesn't search globally, so that it is hard for simple GA to adapt to changing problem usually seen in a dynamic environment. Therefore, in a dynamic environment, it is better to keep higher diversity, while converging the population. A remedy is proposed as "two-chain GA" in which each genotype has two strings (candidates for a problem) and a selection rule to choose one string as its phenotype among them.

In this paper, we propose a new mechanism of keeping much higher diversity in the framework of two-chain GA, Complemental GA (CGA). First, we investigate the adaptability of one-chain GA and two-chain GA to changing problems. Genotypes of each GA represent the weights of Neural Network, and we use them to solve normal and reformed version of Encode-Decode Problem. We study how the number of strings of a genotype and the difference of selection rule affect the behavior of each GA when the condition of the problem changes or not.

The results show that two-chain GA adapts faster to the changes of the problem and more robust than one-chain GA. Also, better results are obtained when we use the selection rule that insists on choosing one string usually among some rules. According to these results, we explain that the existance of string that is not exposed to natural selection and the information on the string are very important for keeping high diversity.

Lastly, we make use of the characteristics of two-chain GA and propose Complemental GA, in which one string of genotype that is not exposed to natural selection is complementary to another string of the same genotype. Through the experiments, we show that Complemental GA is more effective than other previously proposed two-chain GAs in a dynamic environment.

Graduate School of Science and Technology, KEIO UNIVERSITY

(The summary of thesis should be written within 35 lines)

L\ <!

?^ L\ <!

I= L\ <!

Bh 1 >O

=xO@

1.1 O8aK

:#8e$N7W;;5!4D6-$Nh&$J3+J|7O$G$O!$K\<AE*$K7OA4BN$N5sF0$O6K$a$FF0E*$G!$$+D=$NF r"i+8aM=B,9k3H$O=PMh$J$$ [=j95]!%7?$,$C$F!$$3Nh$&$J4D6-2<$G1?MQ$5lk%= %H%&%'%"%(!<%8%'%s%HEy$r9M$($?>l9g!$A4Fr$"$i$+$8$a@EE*$K@_7W9k3H$OIT2DG=$G!$% %8%'%s%H<+?H$K<+N'@-!&E,1~G=NO!&3X=,5!G=$r;}$?$;$k3H$,=EMW$HJCF/$k!%$3$N:]$K! EAE*%"%k%4%j%:%` (Genetic Algorihtm!$0J2< GA)[Hol75] Nh$&$J?J2=E*$J<jK!$b6KaFM-8z$G $"$k$H9M$(il$k!%

@8J*$N?J2=$NNr;KK*$$$F!$=i4|$K$OHf3SE*9=B$$,C1=cG"C?bN$,!$<+A3EqBAEy$N2aD 7P$F!$8=:_$Nh&$JJ#;($+$DB?MM$J9=B$$r;}$D@8J*$,AO$j=P$5lF$-$?$H9M$(il$F$$$k!% $O!$$3$N@8J*$N?J2=$N2aDx$KCeA[$rF@$?bNG"$j!$C5:w!&3X=,!&:GE,2=$N<jK!$H7F9)3XE MM!9$J6ILL$K$*$$$FMxMQ5l!$NI9%$J@.2L$r>e$2F-$?!%$H3m$,!$GA GO=i4|$K%i%s%@% @8@.$5l?=8CD$r!$4v@BeKbo$?$C$F<+A3EqBA$H$$$&dAr+1k3H$GM?$(il$?LdBj$KE $k2r$r5aakbNG"k?$a!$$=$N7k2L$H7F=8CDA4BNO"$kFCDj$N0dEA;R7?$K<}B+$7$F$$$ 8~$,$"$k!%$D$^$j!$B?MM@-$r;}$D=8CD$NCf$+$iE,7?8DBN$rA*$S=P$9$3HN7+jJV7$, GA $*$1$k=EMW$J2aDxG"k?$a!$$RH?$S<}B+$7F7$^$C$?=8CD$O!$LdBj$,JQ2=9kh&$J>u6 BP=h$G$-$J$$!%3+J|7OK*$$$FF0E*$J4D6-$K8~$-9g$oMPJi$J$$%(!<%8%'%s%H$r9M$($?>l9 $O!$$3$N@-<A$OITE,@ZG"$k!%

hjE,1~@-$r;}$?$;$kKO@w?'BN$N?t$rA}d7$?$j(;2>HG-$k%k!<%k$rA}d9)!$@w?'BN$N MF$r8zN(E*$KJQ2=5;$?$j9kJ}K!Ey$,9M$(il$k!%A0<T$N@w?'BN$N?t$rA}d9J}K!$O3N$+$ 2LO"k,!$$I$NDxEY$N@w?'BN?t$rMQ0U$9lP$h$$$N$H$$$C$?LdBj$,$"$k!%7?$,$C$F%"%k% %:%`$N8zN($d!$LdBjd=$N5,LO$K0MB8$7$J$$$h$&$K9?aK$b!$8e<T$N@w?'BN$NFbMF$r8zN(E JQ2=$5$;$kJ}K!$rLO:w$9k3H,K\<AE*$J8&5f$G$"$k$H8@$($k!%

$^$?!$@w?'BN$rC;;~4V$KJQ2=$5$;$kKOFMA3JQ0[N($r>e$2kN$,:G$bC1=c$J2r7hK!$G$"$k $=$l$OF1;~$KM-8z$J>pJsNs$rGK2u7d$9$$!%$+$H$$$CF"$^$j$KFMA3JQ0[N($r2<$2$9$.$k$H

$NC5:wHO0O$,69$/$Jj9$.$F7^$&!%FMA3JQ0[N($ND4@0$OB?$/$N>l9gLdBj0MB8$G$"$kNG!$$
$HJB9T$7$FM-8z$JC5:w$r9T$($k?7$7$$ GA $N5!9=$,K>$^$l$k!%

01J}!$<+A33&$r8+F_kH!$C10l$N@8J*<o$,@8BV7O$r;YG[7F7^$&$o1GOJ$/!$B?<o@
J]$?$l$F$$$k@$3&$HJC$F$$$k!%$^$?!$$"$k4D6-2<$K$*$$$FFCDj$N7A<A$,<oFb$G;YG[E*$HJ
9gb"k,!$>u67$,JQ2=7?>l9g$KHf3SE*B.$d$+$K?7$7$$4D6-$KE,$7$?7A<A$,@8$_=P$5$l=8C
$K9-$^k3H,4Q;!5l$F$$$k [Wei94]!%D^$j!$@8BV7O$d@8J*$N0dEA5!9=NCfK!$B?MM@-$r
$_=P$7$=$l$r@x:_E*$KG"$l2?$i$+$N7A$GJ];}$7!LCNJkJQ2=$KBP1~$9k?aN5!9=$,Fb:
$F$$$k$H9M$(Fb$h$$$@m&!%$=$N0lDN2DG=@-H7$F!$(<g$K) 9bEy@8J*$KG\?t@-$N0dEA5!9=
DNA $N9=B$$,$"$k!%

1.2 K\O@J8$NL\E*

$=$3$G!$K\O@J8GO!$F0E*4D6-$KBP9k8z2LE*$J<jK!$H7F!BPr$J$9@w?’BN$GI=8=7?$r5
9kFsK\:?$N GA $r9M$($k!%6qBNE*$K$O!$I=8=7?$r7hDj$9k?aN5!9=$r?7$?$KDs0F!&F3F~$
%7%_%e%l!<%7%g%srDL8$F4D6-JQ2=$KBP9kBQ@-$dDI=>@-Ey$r8!>Z9k!%

1.3 K\O@J8$N9=@.

K\O@J8$O0J2<$Nh&$J9=@.$HJC$F$$$k!%

Bh 2>OGOGX7JH7$F!$<B:]$N@8L?BN$N0dEA;R!$$*hS@8L?8=>]$N%a%+%K%:%‘$KCeA[$rF@$
Js=hM}$NJ}K!$K$D$$$F@bL@9k!%6qBNE*KO0dEA;R$N;EAH$_$rLOJo$7$?0dEAE*%"%k%4%j%:%‘!
7PLV$N;EAH$_$rLOJo$7$?%K%e!<%i%k%M%C%H%o!<%/$K$D$$$F$N4pK\E*$J9=@.KD$$$F@bL@9k!
7F!$K\O@J8$K$D$$$F$N4XO"8&5f$H7F!$<g$K@w?’BN$r 2 K\MQ$$$?0dEAE*%"%k%4%j%:%‘KD$
$N8&5f;vNc$r>R2p9k!%Bh 3>OGO4{B8$N@w?’BN$r 2 K\MQ$$$?<o!9$N0dEAE*%"%k%4%j%:%‘$r<B
I>2A7=$NLdBjE@$r5s2k!%Bh 4>OGOBh 3>O$GF@$?CN8+$r3h$+$7!$?7$7$$@w?’BN$r 2 K\MQ$$
0dEAE*%"%k%4%j%:%‘G"$k!$Complemental GA (CGA) $rDs0F$7!$$=$NI>2A$r9T$&!%Bh 5>O$G$O
K\8&5f$NAm3gE*$J5DO@$r9T$$!$:#8e$N2]BjKD$$$F=RYk!%:G8e$K!$Bh 6>O$G7kO@$r=RYk!

Bh **2** >O

GX7J

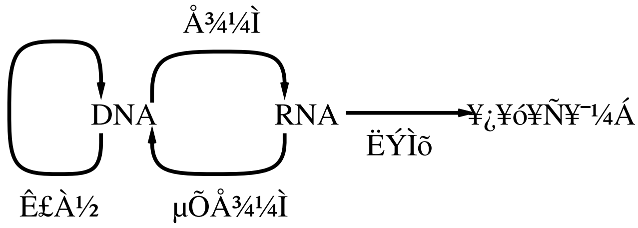
2.1 @8L?$N@_7W?^$H7F$N0dEA;R

@8J*K*$$$F!$7A<A$r?F$+$i;RXHEA$($k0x;R$NK\BN$O0dEA;R (*gene*) G"$j!$$3lO 1910 G Be$K Morgan iKhC$F!$:YK&$N3KFbK"$k@w?'BN (*chromosome*)[1] >e$N8GM-$N0LCV$K:B$r@j$a $F$$$k3H$,L@$i$+$KJC$?!%

$=$7$F!$1953 G/$K Watson $H Crick $O%G%*%-%7%j%\3K;@ (*DeoxyriboNucleic Acid, DNA*) $NFs =EMf@{9=B$$rL@i+$K$7!$DNA $,0dEA;R$N<BBNG"k3HrFM$-;_$a$?!%$=$N8e!$0dEA>pJs ;}$D DNA J,;R$NFs=E:?O[I1$F 1 K\$:DKJj!$$=l>l,Cr7?HJCF<+J,$HAjJdE*$J $7$$$b$& 1 K\$NJ,;R:?$r7A@.$9kH$$$&J}K!$G<+8JJ#@=$r9T$&$3H,<B>Z5l$?!%

2.1.1 0dEA>pJs$NEAC#

0dEA>pJs$NEAC#$N2aDx$O?^ 2.1$Nh&KJCF$$$k!%



?^ 2.1: 0dEA>pJs$NEAC#

0dEA>pJs$r2rFI$9$k2aDx!$$D$^$j0dEA;RH/8= (*gene expression*) $N2aDx$O<!$NFsCJ3,$hjJ$5 lk!%

1. 0dEA;R$N%L%/%l%*%A%I G[Ns$,%j%\3K;@ (*RiboNucleic Acid, RNA*) $K%3%T!<$5lk!%3l$r E><L (*transcription*) $H$$$&!%

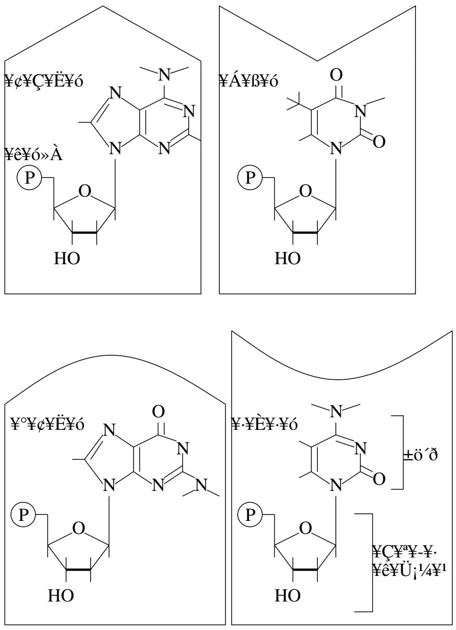
[1] !X?'!Y$N0UL#$N%.%j%7%c8l *chromo* $H!XBN!Y$N0U$N *soma* $+$iNB8l

2. RNA $,%?%s%Q%/<A (*protein*) $N@8;:$r;X<(9k!%3l$rK]Lu (*translation*) $H$$$&!%

3Nh&$K!$4pK\E*$K0dEA>pJs$O DNA $+$i RNA $r7P$F%?%s%Q%/<A$+$i0lJ}8~$XN.$l$k!%$3$ $r@8J*3X$G$O%;%s%H%i%k%I%0%^$H8F$V!%$7$+$75UE><L (*reverse transcription*) $H8F$PlkFCJL$J >l9g$G$O>pJs$O RNA $+$i DNA $K8eLa$jG-$k!%$^$?!$%?%s%Q%/<A$+$i RNA $X>pJs$,N.lk 5UK]Lu$OB8:_$7$J$$$H5l$F$$$k!%5UK]Lu$,B8:_$9lP!$%i%^%k%/$N$$$&3MF@7A<A$N0dEA$,2 HJ$k!%$D$^$j!$?F$,@8B8Cf$KF@$?7A<A (Nc$($PF@$?CN<1!$?HBNE*$JFCD’$J$I) $,$=$N?F$N;R$ H?1G5lk3HKJk!%3N3MF@7A<A$N0dEA$K$D$$$F6=L#[2]$,<s$9pv5lF$$$k!%3N;v >]GO DNA <+?H$OJQ2=$7$F$$$J$+$C$?!%$=N?$a!$DNA 0J30Kb?F$+$i;RXH7A<ArEA($ 2?$+$,B8:_9kNGOJ$$$+!$$H$$$C$??7$?$JLdBj$,@8$8$F$$$k!%

2.1.2 DNA

DNA K*$$$F!$0dEA>pJs$O%"%G%K%s (A)·%0%"%K%s (G)·%A%_%s (T)·%7%H%7%s (C) $N 4 <oN`$N%L %/%l%*%A%I J,;R (?^ 2.2) $N 3 DAHG7hDj5l$k!%3N 3 DAHr%3%I%s (*codon*) $H8F$V!%3N0E9f 2=$N;EAH$_$OA4$F$N@8J*$K6&DLNbNG$"$k3H$,H=L@$7$F$$$k!%



?^ 2.2: %L%/%l%*%A%I

$=$l$>$l$N%L%/%l%*%A%I$O!$%L%/%l%*%A%I$K6&DL$N86;R72$KJL$N<oN`$N1v4p$,7k9g$7$F$$$ $GB8:_$7$F$$$k!%3N6&DLIt0L$O%j%s;@4p$,7k9g7?%G%*%-%7%j%\!<%9$H8F$PlkE|G"$k

[2]%_%8%s%3$H$$$&%W%i%s%/%H%s$ODL>o$O;I$,$J$$$N$@$,!$$"$k>r7o$G;I$,$G$-$?%_%8%s%3$N;R$K$b;I$,EAC#7 $,@8$($F$$$?

A $O T $H!$C $O G $HAjJdE*$KBPrJ7F$$$k!%3lKh$j!$DNA $O01K\:?$, 2 K\AH$_9g$o
5C$?Fs=EMf@{9=B$$JNG!$$=l>lN 1 K\$OAjJdE*G"kH$$$($k!%Nc$($P JRJ}$, A N_$G
$-$F$$$k01K\:?$,$"lP!$$=lHBPrJ9b$&01K\$O T N_$G9=@.$5lk3HKJ$k!%

2.1.3 RNA

RNA $O DNA $H9=B$$ON`;w7F$$$k!%7+$7:GBg$N0c$$$O!$DNA $,Fs=EMf@{9=B$$r:NkN
$KBP$7!$RNA $O01K\:?$G$"$k3HG"$k!%M}O@E*$K$O RNA $bFs=EMf@{9=B$$r7A@.7&k,D
>oAjJd:?$OB8:_$7$J$$$N$G01K\:?$HJC$F$$$k!%RNA O=$NLr3d$KhC$F!$m-RNA(*messanger*
RNA!$G[Aw RNA)!$t-RNA(*transport RNA*!$1?HB RNA)!$r-RNA(*ribosomal RNA*!$%j%\%=!<%`
RNA) JI$N<oN`$,$"$k!%

RNA $H DNA $N0c$$$O!$<g$K0J2<$NFsE@$G$"$k!%

- RNA $NE|$O%j%\!<%9G"k,!$DNA K*$$$F$O%G%*%-%7%j%\!<%9$G$"$k!%
- DNA $N%A%_%s (T) NBeojK RNA GO%&%i%7%k (U) $,MQ$$$ilF$$$k!%

$[$HsI$N@8J*$O0dEA;RH7$F DNA $rMQ$$$F$$$k$,!$%&%$%k%9$JIN86;OE*$J@8J*$N01It
0dEA;RH7$F RNA $rMQ$$$F$$$k!%3N3Hhj!$@8L?$N@8CB;~KO!$RNA $,01HLE*$K0dEA;
H7$FMQ$$$ilF$$$?2DG=@-$b;XE&$5lF$$$k [Joh94]!%

2.1.4 %?%s%Q%/<A

@8J*$rFCD'$E1kNO%?%s%Q%/<AG"$k!%%?%s%Q%/<A$O!$DNA $d RNA $N9g@.!$A4FN:YK
$N%(%M%k%.!<$N@8;:!$J*<A$N9g@.$*$h$S3h@-!$$=$N3h@-D4@00x;R!$$5iK$=$l<+?H$N9g@.$N$
$N9ZAG$H7F5!G=7F$$$k!%

2.2 0dEAE*%"%k%4%j%:%`

0dEAE*%"%k%4%j%:%` (Genetic Algorithm!$GA) $O@8J*?J2=(A*BrEqBA!&FMA3JQ0[) $N86M}$KCeA[
$rF@$?%"%k%4%j%:%`$G$"$k!%$3$N%"%k%4%j%:%`$O Holland KhCFDs>'5l [Hol75]!$GoldBerg
iKhC$F9-$^C? [Gol89]!%GA $O!$@8L?%7%9%F%`$N8=>]$r7W;;$HB*$($k?M9)@8L?$N8&5fK*$
$F!$?J2=$N%b%G%k$H7FMM!9$JMQES!$2r@O$KMxMQ$5lF$$$k [Gol89, Tho96]!%$^$?!$@8J*=8CD$
4D6-$KE,1~?J2=$7$F$$$/2aDx$r%b%A!<%U$H$7!$DL>o$NJ}K!$G$OKDBg$J7W;;NLrMW9k?$a2r$
H,:FqG$"$kAH9g$;LdBj$JIKBP9k2r$NC5:w!&:GE,2=!$$"$k$$$O%m%\%C%HJI$N3X=,$N<
[CGNP97] H7$F!$9)3XE*Kb?tB?$/$N1~MQ$,$J5l$F$$$k [Dav91]!%

2.2.1 4pACMQ8l

0dEAE*%"%k%4%j%:%`O=$NM3Mh$h$j!$@8J*3X$+$iMQ8l$r<ZMQ$7$F$$$k!%$=$3$G!$$3$3$G$O;
9kMQ8lKD$$$F4JC1$K@bL@$9$k!%

8DBN (*individual*) $N0dEA>pJs$r$=$N;RB9KEA($k<BBV$,@w?'BN (*chromosome*) G"$k!%@w?'BN
$O3F0LCV$KINh&$J0dEA>pJs$,5-=R5lk+$,7h$^CF$*$j!$$3$N0LCV$r0dEA;R:B (*locus*)
$$$&!%3F0dEA;R:BKBP7F=$N7A<A$r7hDj9k>pJs$r;}$DbN$,0dEA;R (*gene*) G"$j!$0lDN
BN$rI=8=$9k?aKI,MW$J0lO"$N0dEA;RrAHK7?bN$,%2%N%` (*genome*) G"$k!%Nc$($P%R%
$N@w?'BN$O 46 K\$G$"$j!$$3l, 2 K\$EDAHKJC$F 23 AH$N@w?'BNBP$+$iJk%2%N%`HJCF
$k!%0dEA;R$N%Q%?!<%s$r0dEA;R7? (*genotype*) $H$$$$!$0dEA;R7?$K4p$E$$$F7A@.5l$?8DBN$rI=
7? (*phenotype*) $H$$$&!%

DL>o!$0dEAE*%"%k%4%j%:%`$GMQ$$$i$l$k2r$O!$%2%N%`$r0lD7$+;}$?$J$$0lG\BN (*haploid*) $
$"$k!%3lKBP7$F!$<B@$3&$N9bEy@8J*$NB?$/$OAjF1$J%2%N%`rFsD;}CF$$$kFsG\BN (*diplo*
G"$k!%0dEAE*%"%k%4%j%:%`$K$*$$$F$bFsG\BN$rMQ$$$k;v$G4h7r@-$rA}$9$3H,G-k3H
G'5l$F$$$k [GS87, OBED93, NW95, CCR96b, CCR96a, YN94, SG92, CGNP97] !%

FsG\BN$O!$F10l0dEA;R:BKFsDNNBPN)0dEA;R$r;}$C$F$$$k!%$"$k0dEA;R:BK*$$$FF10l$
N)0dEA;R$,@\9g$7$?$bNr%[%b@\9gBN$H8F$S!$0[$J$kBPN)0dEA;R$,@\9g7?bN$r%X%F%m@\9
$H8F$V!%%[%b@\9gBNGOI=8=7?$OC1=c$K$=$NBPN)0dEA;RKhCF5,Dj5lkNKBP7$F!$%X%
@\9gBNGOBPN)0dEA;R$NAH9g$;$KI=8=7?$,7hDj5l$k!%$3$3$GI=8=7?$KH?1G$5lkBPN)0dEA;
M%@-0dEA;R$H8F$S!$I=8=7?$KH?1G5l$J$$BPN)0dEA;R$rNt@-0dEA;R$H8F$V!%?M4V$N A!$B!$O
7l1U7?J,N`K!$rNc$K$H$l$P!$;0<oN`$NBPN)0dEA;R A!$B!$O N&$A!$A!$B $OM%@-0dEA;R!$O $
Nt@-0dEA;RG"$k!%$hCF!$AO!$BO Ji A 7?!$B 7?$HJj!$OO GJ$$$H O 7?HOJi$J$$

FsG\BN$O0lG\BN$KHf$Y30Mp$KBP7F6/$$!%Nc$($P!$$"$k8DBN$KFMA3JQ0[JI$N0[JQ$KhC$
B8KI,MWJ0dEA;R:B$K0[>o$,@8$8$?>l9g!$0lG\BN$GO=$N8DBN$O;`K4$7!$=8CDO=$N8DBN$,;
$F$$$?>pJs$r<:$&3HKJ$k!%$3lKBP7FFsG\BN$G$OI,$:$7b=Nh$&$J3HOJ$$!%0[>
@8$8$?0dEA;R$,M%@-$G$"$k>l9g$HNt@-$G$"$k>l9g$KJ,$1$F9M$($k!%0[>o$,@8$8$?0dEA;R$,Nt@
EA;RG"$k>l9g!$$=$N0dEA;R:B$KNt@-%[%b@\9gBN$r;}$D8DBN$O;`LG$9$k>l9g$,$"$k$,!$B>$N8
$O@8B8$G$-$k!%5U$KM%@-0dEA;R$K0[>o$,@8$8$?>l9g!$$=$N0dEA;R:B$KNt@-$N%[%b@\9gBN$r;}$
NO@8$-1d$Sk3H,G-$k!%=>$C$F!$$$$:lN>l9gGb=8CDO=$N8DBN$,;}$D>pJs$r<:o
2DG=@-$,$"$k!%0J>e$Nh&$K!$FsG\BN$G$O4h7r@-$,A}$7$F$$$k3H$,$o$+$k!%

J*!$$3$3$G$$$&0lG\BN!$FsG\BN$H$$$&NO!$GA Nb$D%9%H%j%s%0$, 1 K\$NbN$r0lG\B
2 K\$NbN$rFsG\BN$H8@CF$$$k$@$1G"$j!$<B:]$N@8J*$NFsG\BN$N$h$&$JF/$-$r7F$$$k$
8BiJ$$!%hC$F!$K\O@J8$G0lG\BN!$FsG\BN$H$$$&H-$O!$C1$K%9%H%j%s%0$r 1 K\;HMQ7F$$

2 K\;HMQ7F$$$k$@$1$H9M$($FD:$-$?$$!%

$^$?!$0lG\BN!$FsG\BN$NI=5-$NBeoj$K0lK\:?!$FsK\:?$HI=5-$9k3Hb$"$k$,!$$3lk

L#$OF1$8$G!$C1=c$K%9%H%j%s%0$NNs$r 1 K\;HMQ$7$F$$$k$+!$2 K\;HMQ7F$$$k$+!$$H$$$&$@$1

$"$k!%

2.2.2 0dEAE*%"%k%4%j%:%`$N=hM}2aDx

<+A3?J2=$K8+$ilk2aDx$*$h$S@w?'BN>e$N0dEA>pJsH7$F@8J*8DBN$N@-<A$,7Q>5$5lk;EA

$N$$$/D+$rLOJo$7$F!$$=$NE,1~E*$J2aDx$r9)3XE*$KMxMQ9k3H$rL\;X$7$?$bN,0dEAE*%

%4%j%:%` (GA) G"$k!%GA $O3NN(E*C5:w$N0l<jK!H7$FB*$(k3Hb2DG=G"k,!$=>Mh$+$

$NEAE}E*$JC5:w$N<jK!$HHfYF0J2<$NE@$KFCD'$,$"$k [Gol89]!%

1. %Q%i%a!<%?%;%C%H$=$NbNGJ$/!$$=lrId9f2=7?BP>]$rA`:n$9$k!%

2. C10lCm;kE@$K4p$E$/C5:w$GOJ$/!$B??t$NCm;kE@=8CD$KhkB?E@C5:w$r9T$&!%

3. C5:w$rM6F3$9kN$K8zMQ>pJs (L\E*4X?t) $@$1$rMxMQ$7!$%R%e!<%j%9%F%#%C%/$JINGI@8

   $*$h$SJd=uE*$J>pJsrI,MWH7J$$!%

4. 7hDjO@E*KGOJ$/!$3NN(O@E*$J5,B'$K4pE->uBV$rA+0\$5$;$k!%

$"$kM?$($il?LdBjKBP9$k%Q%i%a!<%?%;%C%H$O!$0l<!85G[Ns (%9%H%j%s%0) H7$FId9f2=

lk!%3lOAg&$I!$DNA $N1v4pG[Ns$Khk0dEA;R72KhCF@8J*$N@w?'BN$,7A@.5l$k

HKBP1~9k!%@w?'BN>e$N0dEA>pJs$,@8J*8DBN$N9=B$$r7hDj9kh&$K!$$3$N%9%H%j%s%0$OM

il$?LdBj$KBP9k2r$N8uJd$rI=8=9k!%

GA $O!$0dEA;R7?H7FN@w?'BN=8CDKBP7$F7+$jJV$70dEAE*A`:n$r;\$9!%0lHLE*$J GA K

1k0dEAE*A`:n$H$7$F$O!$A*Br (*selection*)!$FMA3JQ0[ (*mutation*)!$8r:5 (*crossover*) $N;0<oN`$,

<g$KMQ$$$ilk!%

J#@=$N2aDx$G$O!$8[3]$NK4p$E$-!$$$$/D+$NM-K>$J@w?'BN$r4{B8$N=8CDNCf+$iA*Br$7!$$=$l

iNItJ,%9%H%j%s%0 (0dEA;RNs!$%2%N%`) $r8r:5$KhCFAH_49$($k3H$G?7$7$$2r8uJdHJ$k@

BN$rF@$k!%3NA*Br$N2aDx$O!$%@!<%&%#%sM}O@$N<+A3EqBA$N2aDx$KBP1~9k!%9JoA!$$h$j

$KE,1~$7$?8DBN$ONtCF$$$k8DBNKHfY$F!$$h$jD9@8$-r7!$7k2L$H7FhjB?$/$N;RB9$r@_$

GA $O!$%i%s%@%`$K=i4|2=$5l?8DBN=8CD$N=i4|@$Be$+$i=PH/$7!$8E$$$@Ber?7$7$$@BeK

-49($kA`:n$r<!!9$K7+$jJV$7$F$$$/!%@$Be$,?J$`$KDl$F!$8DBN=8CD$OJ?6QE*$Khj9b$$E

[3] E,1~EY (fitness) Hb8F$V

EY$r;}$D=8CDXH?J2=9k!%D^$j7k2L$H7FM?$($il?LdBjKBP9$k!$$h$jE,$7$?2r$rI=$
?'BN$,@8$8F/k3HKJk!%

GA $N01HLE*$J=hM}2aDxr^HakH!$0J2<$Nh&KJ$k!%

1. =i4|8DBN=8CD$N@8@.(@$Be?t g !a 1)
2. Bh g @BeN=8CDFb$N8DBNA4$FKBP7$FE,1~EY$rI>2A
3. Bh g+1 @BeN8DBN=8CD$r@8@.
   - (a) E,1~EY$K1~$8$F!$?FHJ$k8DBN$rA*Br
   - (b) 8r:5·FMA3JQ0[KhCFBh g+1 @BeN=8CD$N8DBN$HJk;R8DBN$r@8@.
   - (c) $"$k7hail??t$N;R8DBN$,@8@.5lk^$G 3.(a) KLak
4. g=g+1 H7$F!$2. KLak

2.2.3 GA $N0dEAE*A`:n

GA GO<g$K!$A*Br!$8r:5!$FMA3JQ0[$H$$$&;0<oN`$N0dEAE*A`:n$r;\$9$3$HKh$j2r$r5aa
0J2<!$$3li$NA`:n$K$D$$$F@bL@9k!%

A*Br (selection)

A*BrHO!$8DBN$N=8CDNCf+$i<!@$Be$N?F$HJkY-8DBN$rA*=P$9$kA`:n$G$"$k!%%@!<%&%
M}O@$N<+A3EqBA$N86M}$K4p$E$-!$E,1~EY$N9b$$8DBN$[$I9b3NN($GA*$Plk3HKJ$k!%$7$+
$"$^jKM%=($J8DBN$,M%@h5l9.kHB?E@C5:w$NMxE@$,<:ol!$C5:w$N=i4|$NCJ3,$G6I=j2
4Yjd9/Jk3H$,$"$k!%$=N?$a!$:GE,CMC5:wJI$N2rK!$H7FFC$K9)3XE*$K GA rMQ
:]KOA*Br05 (*selection pressure*) $,$"$^$j6/$/$+$+$j9.$J$$$h$&$K9)IW9kI,MW$,$"$k!%MM!
$JA*Br$NJ}K!$,Ds0F$5lF$$$k [Gol89, KLLn93a] $,!$$3$3$G$O0J2<$NFsDr>R2p9k!%

:G=i$K4pK\%b%G%k$HJkE,1~EYHfNc@oN,KD$$$F@bL@9k!%3l$O!$%k!<%l%C%H!&%b%G%k$
$O%b%s%F%+%k%m!&%b%G%k$H8FPl!$3F8DBN$O8DBN<+?H$NE,1~EY$KHfNc7?3NN($G;RB9$r;D$;$
G=@-$,$"$k%b%G%k$G$"$k!%

<!$K%(%j!<%HJ]B8@oN,$K$D$$$F@bL@9k!%3l$O!$=8CDCf$G:G$bE,1~EY$N9b$$8DBNr=N
<!@BeK;D$9J}K!$G$"$k!%3NJ}K!$r:NMQ$9kH!$$=$N;~E@$G:G$bNI$$2r$,8r:5$dFMA3JQ0[$
2u5l$J$$$H$$$&MxE@$,$"$k!%$?$@$7!$%(%j!<%H8DBN$N0dEA;R$,=8CDCf$K5^B.$K9-$^$k2DG=@
9b$$$?$a!$6I=j2r$K4Y$k4m81b"$k!%01HL$K3N@oN,$O!$B>$NA*Br@oN,$HNAH_9go;$G;HM
lk!%

8r:5 **(crossover)**

8r:5HO!$A*Br$5l?FsDN?F8DBN$N@w?’BN>e$N0dEA;RrAH_49$($F?7$7$$;R8DBN$N@w?’B
D/$j=P$9A‘:nG"$j!$<B@$3&$NM-@-@8?#$r9T$&@8J*$NM:$H;s$,G[6v;R$r7k9g5;$F?7$7$$0
;RNAH_9go;$r;}$D8DBN$r;:$‘2aDx$KBP1~$9$k!%

8r:5KO!$0J2<$Nh&$JJ}K!$,$"$k [Gol89, KLLn93a]!%

- 0lE@8r:5

  @w?’BNrG0U$N0lE@$G@Z$j!$$=3r5/E@$K0dEA;R$r8r49$9$k!%

- J#?tE@8r:5

  @w?’BN$rJ#?tE@$G@Z$j!$0dEA;R$N8r49$r9k!%F10l$N@w?’BN$G0lE@8r:5$,J#?t2s5/$-$?
  NH$b9M$(il$k!%

- 0lMM8r:5

  0l0dEA;R:B4HKIAi$N?F$N0dEA;R$rMQ$$$k$+$r7hak!%

FMA3JQ0[**(mutation)**

FMA3JQ0[HO!$@w?’BN>e$N0dEA;Rr"$k3NN((FMA3JQ0[N() $GJQ2=$5$;$kA‘:nG"$k!%FMA3
0[$,9T$olJ$$>l9g$O!$=i4|$N0dEA;R$NAH$_9g$o$;0J30$N6u4V$rC5:w$9k3HOG-$J$$$N$
ailk2r$N<A$K$b8B3&$,@8$8$k3HHJ$k!%FMA3JQ0[$KhC$F@w?’BN=8CD$NB?MM@-$,J]$?
hj9-$$2r6u4V$rC5:w$9k3H,2DG=HJ$k!%$?$@$7!$$"$^$j$K9b$$FMA3JQ0[N($r;HMQ$9k
Jk%i%s%@%‘%5!<%A$K4Y$j$+$M$J$$$N$G!$DL>o!DcaNCMr;HMQ9k!%

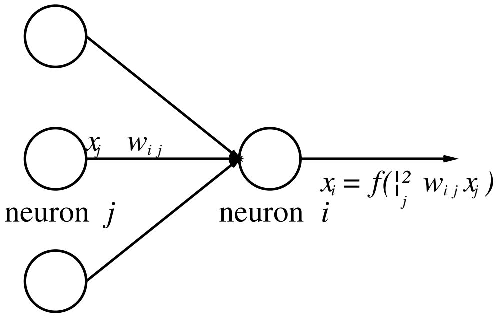
2.3 %K%e!<%i%k%M%C%H%o!<%/

0dEAE*%"%k%4%j%:%‘$HF1$8h&$K!$<B:]$N@8J*$N86M}$rLOJo$7$?>pJs=hM}%b%G%k$N0lD
%K%e!<%i%k%M%C%H%o!<%/ (*Neural Networks*) G"$k!%0dEAE*%"%k%4%j%:%‘$,0dEA;R$N9=B$$rLOJo
7F$$$kh&$K!$%K%e!<%i%k%M%C%H%o!<%/$OG>!$?@7P:YK&$rLOJo$7$F$$$k!%

2.3.1 <B@$3&$N?@7P:YK&LV

2.3.2 ?M9)%K%e!<%m%s$H%K%e!<%i%k%M%C%H%o!<%/

%K%e!<%i%k%M%C%H%o!<%/$O!$?M9)E*$J%K%e!<%m%s (*neuron*) $rB??tAj8_$K@\B3$7$?2sO)LV$G9
@.5l$k!%?M9)E*$J%K%e!<%m%s (0J2<!$C1$K%K%e!<%m%s$H5-$9) $O!$J#?t$NF~NO?.9f$r<u$1<h
$=$N4X?tH7$F=PNO$r7hDj9k (?^ 2.3)!% $3$3$G!$$x$ $O?.9fCM$r!$$w$ $O%K%e!<%m%s4V$N7k9g$N=
$_$rI=$9!%

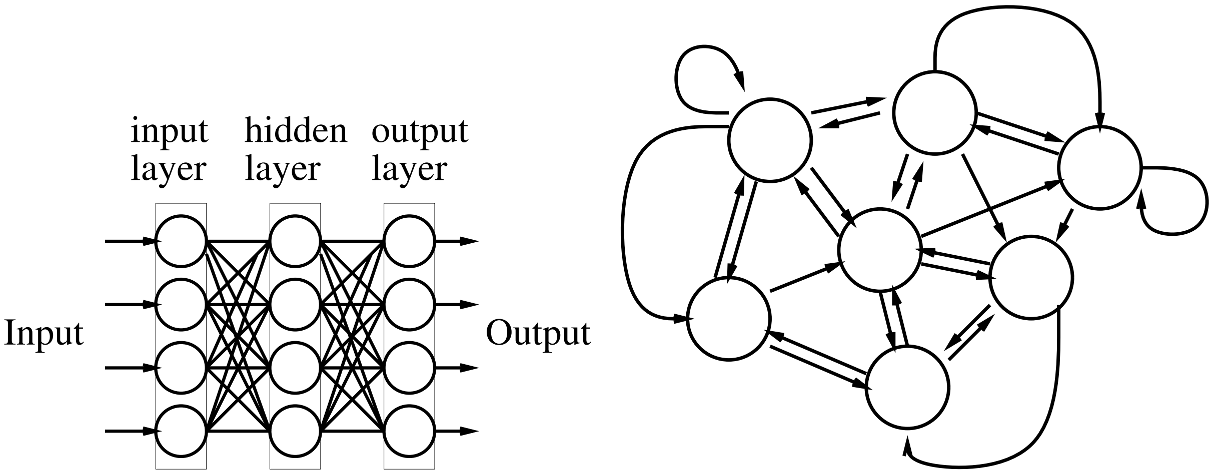


?^ 2.3: ?M9)%K%e!<%m%s

1946 G/$K!$McCulloch $H Pitts $O!$0J2<$N<0$GI=5l$k%K%e!<%m%s$N%b%G%k$rDs0F$7$? [MP43]!%

$$x_i(t+1) = 1\left[\sum_j w_{ij}x_j(t) - \theta_i\right] \qquad (2.1)$$

$3$3$G!$ $x_j(t)$ $O;~9o t K*1k%K%e!<%m%s j $N=PNOCM w_{ij} $O!$%K%e!<%m%s j $+$i%K%e!<%m%s i XN%7%J%W%97k9g6/EY$r!$ θ_i $O%K%e!<%m%s i $NogCM$rI=$9!%$^$? $1[x]$ $O $x \geq 0$ NH$- 1!$x<0 $N H- 0 HJ$kC10L%9%F%C%W4X?t$rI=7F$$$k!%1 $rNe5/>uBV!$0 $r@E;_>uBV$H9M$($k$H!$2.1<0$ %K%e!<%m%s j $+$iEAHB7??.9f $w_{ij}x_j$ $r=E$_IU1ilF2C;;5l!$%K%e!<%m%s i $KC#$7!$$=l, $"$kogCM θ_i $r1[$(kH%K%e!<%m%s i $,Ne5/$9k3Hr0UL#7F$$$k!%



(i) B?AX%U%#!<%I%U%)%o!<%I%M%C%H%o!<%/

(ii) Aj8_7k9g%M%C%H%o!<%/

?^ 2.4: %K%e!<%i%k%M%C%H%o!<%/$N9=B$$N<oN`

%K%e!<%i%k%M%C%H%o!<%/$O!$9=B$>e$N4QE@$+$i?^ 2.4 $K<($9h&$KFs<oN`$KJ,N`$5lk!%

2.4(i) $N3,AX9=B$$N%K%e!<%i%k%M%C%H%o!<%/%b%G%kGO!$?.9f$NN.lO0lJ}8~E*$J%U%#!<%I%U
%o!<%I7?G"$j!$?^ 2.4(ii) $NAj8_7k9g9=B$$N%K%e!<%i%k%M%C%H%o!<%/%b%G%kGO!$?.9f$NN.$l
=gJ}8~N_HO8BiJ$$!%

2.4 4XO"8&5f

$3$3GO!$%9%H%j%s%0$rJ#?t;HMQ7? GA $r07$C$?8&5f$K>GE@$r9J$C$F=R$Y$k!%

2.4.1 01G\BN$+$i==G\BN$^$G$NHf3S

Collingwood iO!$Indecisive(k) problem!$Max problem $N 2 DNC5:wLdBj$rMQ$$$F!$@w?'BN
$, 1 K\$+$i 10 K\$^GNC5:w$N@.8yN($rHf3S7? [CCR96a]!%

I=8=BN$rF@$kNK$O%^%9%/ (?^ 2.5) $rMQ$$$F$$$k!%

mask:	0	0	0	1	1	1	2	2	2
chromosome[0]:	A	A	A	a	a	a	a	a	a
chromosome[1]:	b	b	b	B	B	B	b	b	b
chromosome[2]:	c	c	c	c	c	c	C	C	C
phenotype:	A	A	A	B	B	B	C	C	C

?^ 2.5: %^%9%/

@w?'BN$,B?$$$Dx!$0l$D$N@w?'BN$,I=8=BN$K4sM?$9$kItJ,$O>.5/Jk!%%^%9%/$b0dEA$9$k
<B83$N7k2L!$H`iO0J2<$NCN8J$rF@$F$$$k!%

- 8DBN?t$,F1$8H-$O@w?'BN$, 2 K\0J>eG"lP7k2LOJQoiJ$$!%
- @w?'BN$NAm?t$,F1$8$KJkh&$K8DBN?t$r@_Dj9k$H!$2 K\@w?'BN$rMQ$$$?H-$,:G$b
  $/!$5 K\0J>eKJkH 1 K\$NH-hj$b7k2L$,0-$/$J$k!%
- %3%9%HE*$K:G$bBEEvJN$O@w?'BN$, 2 K\$NH-G"$k!%

2.4.2 M%@-%^%C%W

J#?t$NBPN)0dEA;R$NCf$+$iI=8=BNH7$FI==P$7F/$k0dEA;R$r7hDj9kNK!$dominance map
M%@-%^%C%W) $r;HMQ$9$kJ}K!$,$"$k!%

	0	i	1
0	0	0	1
i	0	1	1
1	1	1	1

(i)Goldberg (1987)

	0	o	1	i
0	00	00		0i
o	00	oo	1o	
1		1o	11	11
i	0i		11	ii

(ii)NG (1995)

?^ 2.6: M%@-%^%C%W

?^ 2.6(i) $O Goldberg i,MQ$$$?:G=i$NM%@-%^%C%W [GS87] $G!$?^ 2.6(ii) $O NG i,MQ$$$?2~
NI5l$?M%@-%^%C%W [NW95] G"$k!%APJ}Hb0dEA;R0x;R$K 0 $+ 1 $rMQ$$$kH-$K;HMQ$5lk

?^ 2.6(i) GO!$i<0<1 $H$$$&4X78$,$"$k!%$3lKhj!$1 $,M%@-!$0 $,Nt@-$G$"$k3H$rI=8=
7F$$$k!%

?^ 2.6(ii) GO!$(o,i)<(1,0) $H$$$&4X78$,$"$k!%$3$3$G!$o $H i!$0 $H 1 $OF1$8 6/5G$"$j!$o $O
0 $N!$i $O 1 $NNt@-0x;R$G$"$k!%D^$j!$oo $O 0!$ii $O 1!$1o $O 1!$0i $O 0!$00 $O 0!$11 $O 1 $,I=
8=BNH7$FA*=P$5lk!%?^ 2.6(ii) $G6uGr$NH3mOIAiGbh$$$3Hr<(7F$$$k!%D^$
10 JiI=8=BN$O 1 Gb$h$$$7!$0 Gb$h$$!%io $bI=8=BN$O 1 Gb 0 Gb$h$$!%

3lNh$&$J5!9=Kh$j2r$NB?MM@-$,J]$?lk3H$,3NG'$5lF$$$k!%

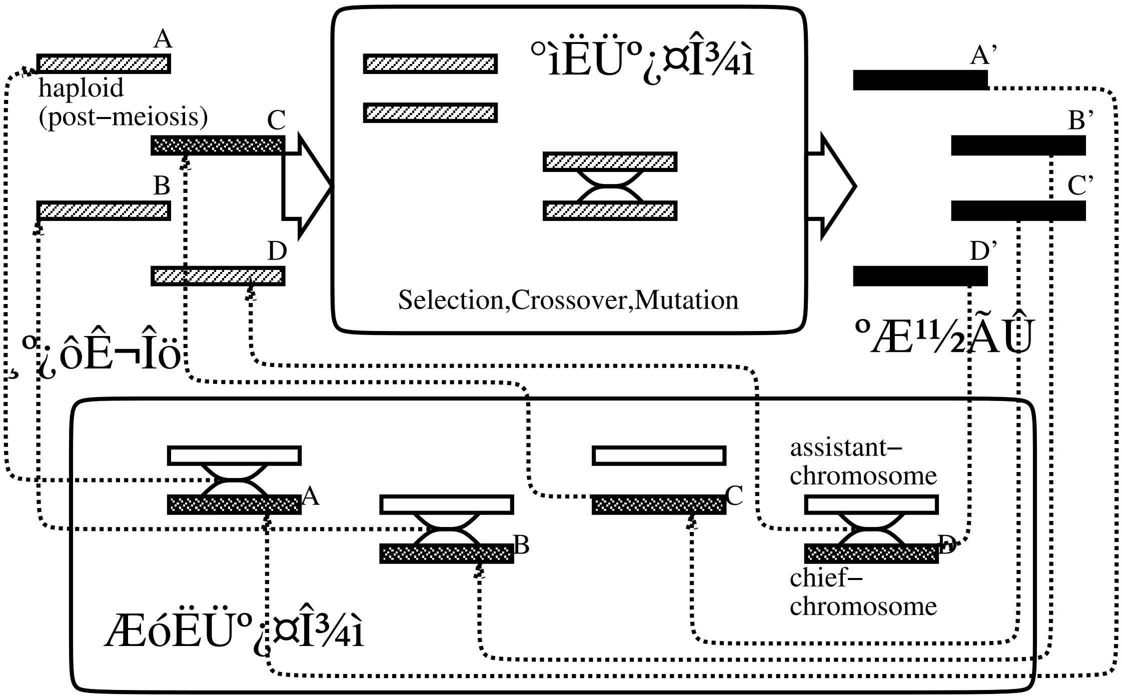
2.4.3 8:?tJ,Nv GA

5HEDiO!$pseudo-Meiosis(8:?tJ,Nv) GA(0J2< psM GA) $rDs0F$7!$traveling salesman prob-
lem(=d2s%;!<%k%9%^%sLdBj!$0J2< TSP) $rMQ$$$F$=$NM-8z@-$r8!>Z$7$? [YN94]!%

psM GA $NA4BN$NN.lO?^ 2.7NDLjG"$k!%0J2<$Nh&K7$F psM GA $OC5:w$r9T$&!%

1. chief chromosome(<g@w?'BN)!$assistant chromosome(I{@w?'BN) $r:n@.$9$k!%

2. 8r:5$r9T$$!$<g!$I{@w?'BNhj%9%H%j%s%0$, 1 K\$N0lK\:?$r:n@.$9$k!%C1$K!$<g@w?'BN



?^ 2.7: 8:?tJ,Nv GA

%3%T!<NH$-$b$"$k!%

3. 0lG\BN$N>l$GLdBjKh$jI>2A$5$l!$$=$N8e!$A*Br!$8r:5!$FMA3JQ0[$,9T$olk!%

4. ;RB9rD$/$j!$$=l,<g@w?’BNH7$FFsK\:?$N>lKLak!%3NH-!$I{@w?’BN$KFMA3JQ
$r5/$3$9!%

5. 2. KLak!%

0J>eNh$&$K!$psM GA $O!$<B:]$N@8J*$N@8?#5!9=(8:?tJ,Nv) $rLOJo$7$?$bNG$"$k!%psM GA $O!$<g@w?’BNKh$jDL>o$N GA $HF1$8C5:w$r9T$$!$I{@w?’BN$r;}D3HKhjB?MM@-$r0];}$$ 3H$rL\E*$H7F$$$k!%

3l$G!$50 ET;T!$100 !_ 100 %^%9$N TSP LdBj$r2r$-!$C1$J$k%9%H%j%s%0$, 1 K\$N GA(0J2< C1=c GA) $HHf3S$7$F$$$k!%3NH-!$8DBN?t$O psM GA $, 100!$C1=c GA $O 200 G"$k!%$=$7 $F 4000 @$Be$^$G9TCF$$$k$,!$100 @Be4HKET;T$N0LCV$r x!$y J}8~$K:GBg±5 %^%90\F0$5$; $F$$$k!%8DBN$NA*BrJ}K!$H7F%(%j!<%H@oN,$H%k!<%l%C%H@oN,$r:.9g7?bN$r;HMQ$7$F$$

7k2LE*KO8DBN?t$,H>J,$Kb+$+$oi:!$:G>.0\F05wN%$OB?>/ psM GA N[$&$,NI$+$C$?!%$ $?!$<}B+$O psM GA N[$&$,B.$+C?!%

3N<B83$GF@$?CN8JH7$F!$0J2<N3Hr5HEDiO5s2F$$$k!%

- I{@w?'BN$NB8:_$*hS$=$NFMA3JQ0[N($,2r$NB?MM@-$rJ]$DNK=EMW$JLr3d$r1i8F$$$k
- %(%j!<%H@oN,;~!$%(%j!<%H8DBN$r2?8DBNK9k+$G2r$,$+$J$jJQ2=$9$k!%

2.4.4 %K%e!<%i%k%M%C%H%o!<%/$rMQ$$$?01G\BN GA $HFsG\BN GA $NHf3S

Calabretta iO!$%K%e!<%i%k%M%C%H%o!<%/$rMQ$$$FFsG\BN GA $NHf3S8&5f$r9TC? [CGNP97]!%

Khepera $H$$$&%m%\%C%H$rMQ$$!$60cm×35cm $N4D6-Cf$KD>7B 20mm $N food area $r@_Dj$7!$

food area $G?)NH$r3NJ]7D$D!$4D6-CfrI1@$1C5:w$G$-$k$+$H$$$&2]Bj$r%m%\%C%H$KM?$(

$$$k!%

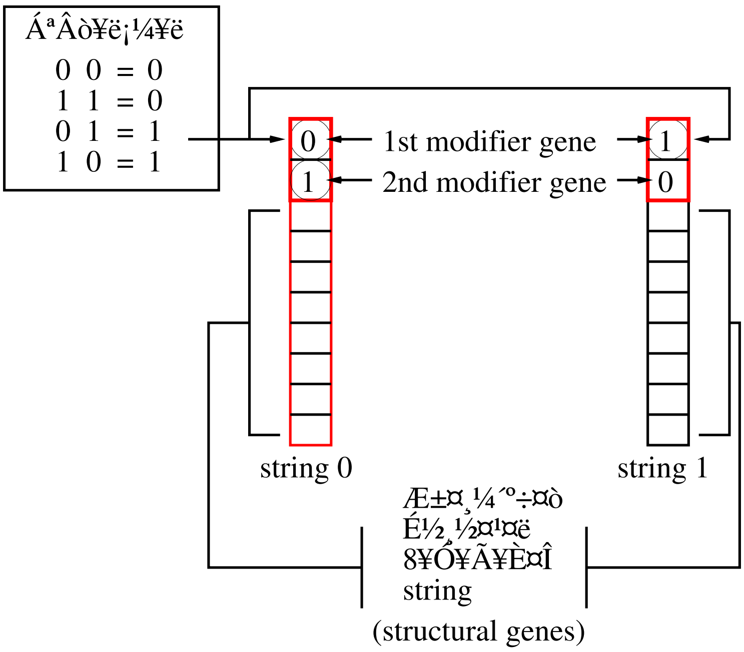
%K%e!<%i%k%M%C%H%o!<%/$O 10 F~NO 2 =PNO$NFsAX9=B$$G$"$k!%8 F~NO$O%m%\%C%H$N@V30@~%;

%5!<H7$F;H$o$l!$1 F~NO$O%m%\%C%H$,8=:_J];}7F$$$k?)NH$NNL!$;D$k 1 F~NO$O8=:_food are

$K$$$k$+$I$&$+$NH=Dj$KMQ$$$ilF$$$k!%=PNO$O%m%\%C%H$N;}DFsD$N<VNX$KBP9kbNG

$=$l$>$l$K%P%$%"%9r+1k%f%K%C%H$,IUB0$7$F$$$k!%3lKh$j!$%K%e!<%i%k%M%C%H%o!<

Am<4:w?t$O 22 K\$G$"$k!%



?^ 2.8: Calabretta iN GA

%K%e!<%i%k%M%C%H%o!<%/$N<4:w$O!$?^ 2.8$G<($9 GA Kh$j!$D>@\%(%s%3!<%I K!Kh$j@_Dj

lk!%

01K\$N<4:w$N=E$_$r7hDj$9kN$K!$?^ 2.8$GI=$7$? 2 K\$N%9%H%j%s%0$rMQ$$$k!%3l$O modifie

gene $H$$$& (string $"$?$j 2 %S%C%H!$7W 4 %S%C%H) FsK\$N string NIAi$+$rA*Dj9kItJ,$H!$

structural genes $H$$$&<4:w$N=E$_$rI=$9ItJ, (string $"$?$j 8 %S%C%H!$7W 16 %S%C%H) NFsDhj
JC$F$$$k!%string $O 0 $+ 1 $N 2 %S%C%H$G%3!<%I 5lF*$j!$<4:w$NK\?tJ,$@$1?^ 2.8$NC10L9=
B$$,MQ0U5l$k!%structural gene $O-10 $+$i+10 $^$GNCMrI=8=9k!%

string!$$9Jo$AI=8=7?$NA*Br$O!$0J2<Nh$&$K9Tol$k!%

1. APJ}$N 1st modifier gene $r dominance rule $K3]$1$k!%
2. dominance rule($3$3GO XOR) Kh$j!$0 $+ 1 $+$,;;=P5l$k!%(?^ 2.8$G$O!$1st modifier gene $, 1!$0 JN$G 1 $,;;=P$5lk!%)
3. 2nd modifier gene $,;;=P7k2L$HEy$7$$$[$&$,<B:]$K<4:w$N=E$_$rI=8=9k string H7$FA*=P$5lk!%(?^ 2.8GO string 0 $,A*=P$5lk!%)
4. b7!$2nd modifier gene $,N>J} 1!$$^$?$ON>J} 0 Ji!$APJ}$N string $GI=8=$7$F$$$k<4:w $N=E$_$NJ?6QCM$r!$<B:]$N=E$_$H7FMQ$$$k!%

0J>e$N<B83$r9T$$!$0J2<$r7kO@H7$F5s$2$F$$$k!%

- modifier gene $H$$$&A*Br5!9=$N8z2L$,FMA3JQ0[N(r"2k8z2LhjbBg-$$!%
- FsG\BN GA $NA*Br$5lJ$+$C$? string $,!$A*Br$K4X78$J$$$?$a5-21NN0h$H7FF/$-!$M-MQ
$J%S%C%HNs$rJ];}9k!%
- 4D6-$NJQF0$KBP$7!$FsG\BN GA $O5-21ItJ,$,$"$k$*$+2G01G\BN GA hj4h6/G"$k!%
- FsG\BN GA $@$HFMA3JQ0[N($,Dc$/Fb4D6-$NJQF0$KBP7F==J,DI?o@-$,$"$k!%
- 8r:5$rMQ$$$J$/$H$bFsG\BN GA $O4D6-$NJQ2=$KDI?o$G$-$k!%

7+$7!$0J2<$NE@$K$D$$$F$N5DO@$,IT==J,G"kH9M$($k!%

- J<EqBAKGx5lJ$$ItJ,$,B?MM@-$rJ]DN$KLrN)$C$F$$$k$+$H$$$&E@KD$$$F$OM}O@
$J@bL@$OJ5lF$$$J$$!%
- FsG\BN GA $NA*Br$5lJ$$ string $K!$M-MQ$J%S%C%HNs$,J]B8$5$lkH$O8B$i$J$$!%
- F0E*$J4D6-$N@_Dj$,E,Ev$G$"$kHO;W$($J$$!%
- I==P5;$k string $rA*Dj$G$-$J$$$H$-$N!$=E$_$rJ?6Q2=$9kH$$$&A`:n$,$I$NDxEYF/$$$
$$$kN+$,ITL@$G$"$k!%

Bh **3** >O

FsK\:? **GA** $N8!F$

3.1 <B83$NL\E*

3N<B83GO0J2<$N;v$r8!>Z9k3H$rL\E*$H7F$$$k!%

- FsK\:? GA $N@-G=$H0lK\:? GA $N@-G=$NHf3S
- 4pK\E*$JFsK\:? GA $NFCD'$NGD0.

FC$KCmL\$7$?$$$N$,!$4D6-JQF0;~$N8DBN$NE,1~EY$NDI=>@-$G$"$k!%

$=$3$G!$3F8DBN$r%K%e!<%i%k%M%C%H%o!<%/$H7FCj>]2=$7!$$=$N=E$_$r7hDj$9kN$K0dEAE
%k%4%j%:%`$r;HMQ$9$k!%%K%e!<%i%k%M%C%H%o!<%/$K2r$+$;$kLdBj (4D6-) $OA4$F$N%7%_%e%l!<%
%s$GF1$8bN$r;HMQ$9$k!%%K%e!<%i%k%M%C%H%o!<%/$N%H%]%m%8!<$O8GDj$H$7!$;HMQ$9$k0dEAE
%k%4%j%:%`N_rJQ(!$$=$N?6Iq$$$r4Q;!!$I>2A$9$k!%

3.2 <B83$N@_Dj

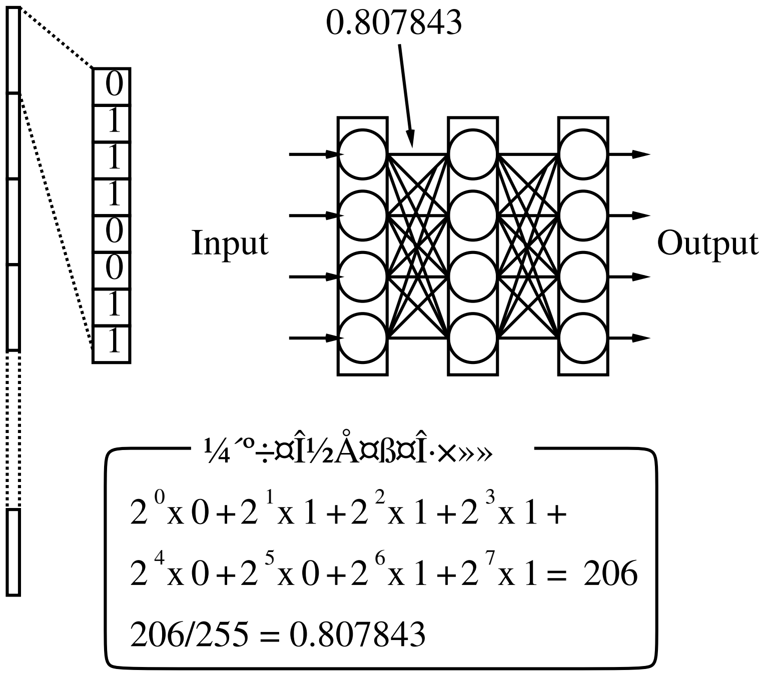
3.2.1 8DBN$N9=B$

0lK\:? GA $rMQ$$$?8DBN$N9=B$$O!$?^ 3.1$NDLjG$"$k!%

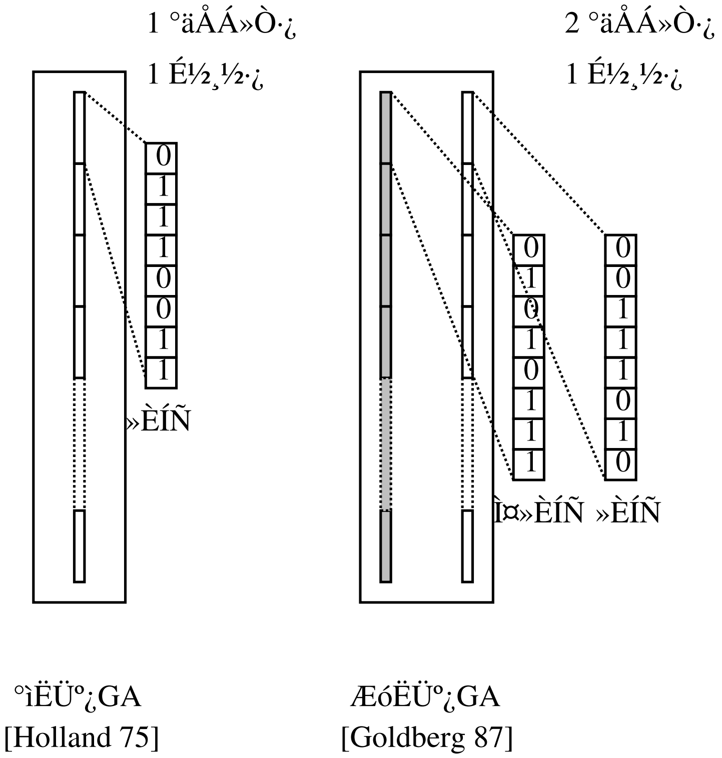
?^ 3.1KD$$$F4JC1$K@bL@$9$k!%<4:w 1 K\$N=E$_$O!$2 ?J?tI=8=!$D9$5 8 $N%S%C%HNs$Khj 0.
!A1.0 $N$$$:l+NCMK%;%C%H5l$k!%

0l8DBN$"$?jN GA $N%S%C%HNs$ND9$5$O!$1 DN<4:w$N=E$_$r7hDj9k0dEA;R$ND9$5 × <4:
$NK\?t$HJk!%Nc$($P!$F~NOAX!$Cf4VAX!$=PNOAX$K%K%e!<%m%s$, 4 D:D"$j!$3FAX4V$N7k9
A47k9gG"$k8DBN (?^ 3.1) $r5,Dj$9$k%S%C%HNsD9$O (4×4 + 4×4) × 8 = 256 %S%C%HG"$k!%

FsK\:? GA $rMQ$$$?>l9g (?^ 3.2) $b!$%K%e!<%i%k%M%C%H%o!<%/ItJ,$K4X$7FOF1$8 9=B$$r;HM
9k!%$?$@$7!$<B:]$K<4:w$N=E$_$r5,Dj9kItJ,$r7hDj$7J1lPJi$J$$E@$, 0lK\:? GA $H
Jk!%?^ 3.1$N%K%e!<%i%k%M%C%H%o!<%/8DBN$r5,Dj$9$kFsK\:? GA $N%S%C%HNsA4BN$ND9$5$O!$%k
%k7hDjItJ,$ND9$5$, 2 $@$H9k$H!$(10 × (4×4 + 4× 4)) × 2 = 640 %S%C%HHJ$k!%



?^ 3.1: 4pK\E*$J8DBN$N9=B$ (0lK\:?)



?^ 3.2: FsK\:? GA $N35G0?^

3.2.2 <B83>r7o

B>$N@_Dj$K$D$$$F$O0J2<$Nh&$J>r7o$H7?!%

- 0dEAE*%"%k%4%j%:%`ItJ,KD$$$F
  - EqBA$O!$$^$:E,1~EY=g$K8DBNrJBYD>$7!$$=$N>e0L 20!s$r4 2s%3%T!<$7!$2<0L 80%$H
    9k(%(%j!<%HJ]B8@oN,)!%$=$N2<0L 80%$KFMA3JQ0[$rFMA3JQ0[N($K4p$E$-5/$3$9!%$3
    $NFMA3JQ0[A`:n$O!$%k!<%k$r5,Dj9k%S%C%H!$=E$_$r5,Dj$9$k%S%C%H$N6hJLL5$/9T$
    lk!%
  - 8r:5$O9T$o$J$$!%
- %K%e!<%i%k%M%C%H%o!<%/ItJ,KD$$$F
  - %K%e!<%i%k%M%C%H%o!<%/$N%H%]%m%8!<$O8GDjH9$k!%
  - %K%e!<%i%k%M%C%H%o!<%/$OF~NO%N!<%I?t 4!$Cf4V%N!<%I?t 4!$=PNO%N!<%I?t 4 $N%U%#!
    %I%U%)%o!<%I7?G"$k!%
  - %N!<%I4V$OA47k9g$G$"$k!%
  - =E$_$h$j?.9f$r7W;;9k<0$O!$2.1<0$rMQ$$$k!%
  - ogCM$O 0.5 G"$k!%
  - F~NO!$=PNO$O 2 ?J?tI=8= (0 $+ 1)!$D9$5 4 G"$k!%
  - 8m:95UEAHBK!Ey$N$$$ofk3X=,$O9T$o$J$$!%(=E$_$O@w?'BNN_Kh$j7hDj$5lk!%
- 4D6-!$$=$NB>$K$D$$$F
  - 8DBN?t$O!$0lK\:?GA KD$$$F$O 100!$FsK\:?GA KD$$$F$O 50 H7$FE}0l9k!%Fs
    K\:?$N8DBN?t$,0lK\:?$NH>?t$JNO!$0l8DBN$rI=8=9k%S%C%H?trJkY$/6QEy2=$
    k?aG$"$k!%
  - %K%e!<%i%k%M%C%H%o!<%/XNF~NOKBP9$kM}A[=PNOCM (2rEz) $OI= 3.1$Nh&$K5,Dj
    9k!%

0J>eNh$&$K!$F~NO$KBP9k=PNO (2rEz) $,$^C?$/@5H?BP$KJkh&$K4D6-$r@_Dj7?!%
6- 1 $O!$%(%s%3!<%I!&%G%3!<%I LdBj$H$$$&!$%K%e!<%i%k%M%C%H%o!<%/$G$OI8=`E*$JLdBjG"
4D6- 2 $O4D6- 1 $H@5H?BP$N2rEz$r@_Dj$9k3HKhj!$4D6- 1 Cf$GF@$? GA $N2r$rMQ$$$k3H$
G-$:!$?7$?$KC5:w$r9T$oMPJiJ/Jkh&$J>u67$r@_Dj7?!%

3liFsD$N4D6-$r8r8_$KLdBj$H7FM?$($k3HKh$j!$$=$N4D6-JQF0$KBP9k GA $NG=NO
4Q;!G-$k!%

I= 3.1: 4D6-@_Dj

F~NOCM	M}A[=PNOCM	
	4D6- 1	4D6- 2
0001	0001	1110
0010	0010	1101
0100	0100	1011
1000	1000	0111

0J2<$K!$A4BNE*$J%7%_%e%l!<%7%g%s$NN.lr<($9!%

1. =i4|@_Dj
   (a) %K%e!<%i%k%M%C%H%o!<%/$N%H%]%m%8!<$N@_Dj!%
   (b) LdBj$N@_Dj!%
   (c) GA $N8DBN?t!$%S%C%HNs$ND9$5$N@_Dj!%
2. 5,Dj7?@$Be?t$^$G0J2<$NA`:n$r7+$jJV$9!%
   (a) @w?'BNhj%K%e!<%i%k%M%C%H%o!<%/$N=E$_$r5,Dj$7!$I>2A!%
   (b) I>2ACM=g$K8DBN$r%=!<%H!%
   (c) >e0L 20%$r 4 2s%3%T!<$7!$;RB9$HJk8DBN$r@8@.!%
   (d) ;RB9$K!$FMA3JQ0[JI$N0dEAE*A`:n$r9T$&!%
   (e) @$Be?t$Khj!$4D6-$rJQ$($k!%

3.3 7k2L

3.3.1 0lK\:?%b%G%k

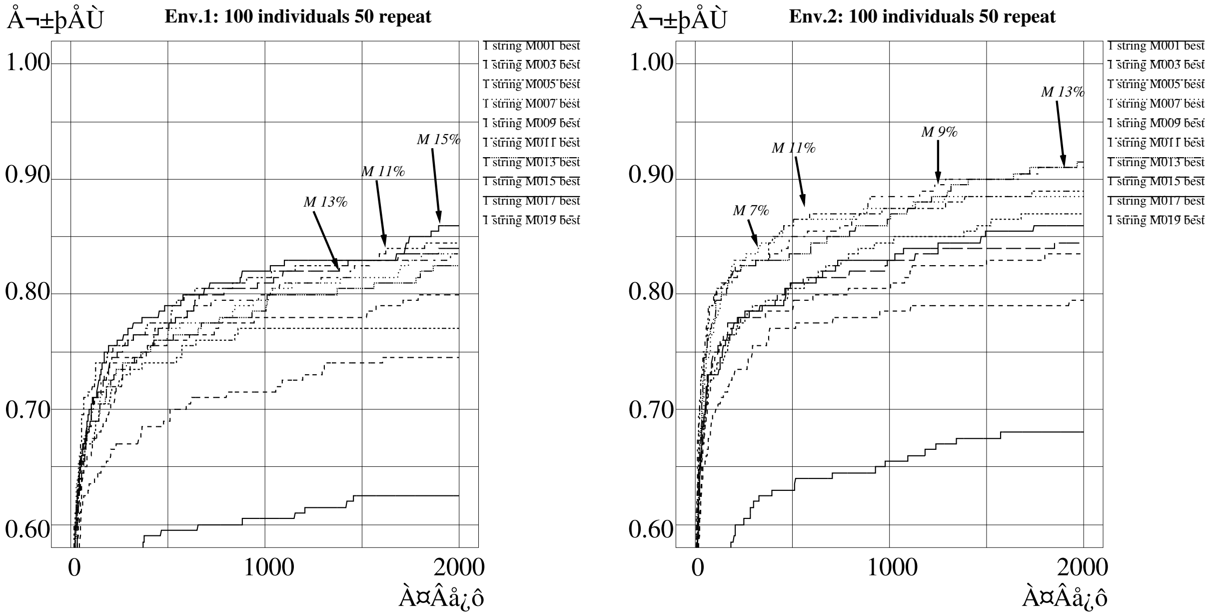
$^$:!$Hf3SBP>]$HJk0lK\:?%b%G%k$N7k2L$r<($9!%

@EE*$J4D6-$G$N7k2L (M=Hw<B83)

:G=i$K!$4D6- 1!$4D6- 2 N=l>lG4D6-rJQ($:$K<B83$r9TC?!%$3lO!$0J2<$NL\E*$,$"

- 4D6- 1!$4D6- 2 $,@_Dj$G$"$2$?%K%e!<%i%k%M%C%H%o!<%/$N%H%]%m%8!<GI$NDxEY$N@-G=$
<($7F@$k$+$r3NG'9k3H!%
- @EE*$J4D6-2<$G$N<}B+>u67$r3NG'9k3H!%
- 4D6-$rJQ2=$5$;$kK"$?$j!$2?@$BeL\$GJQ2=5;kY$-$+7hDj9k;qNAH9k3$H!%

FMA3JQ0[N($r 1%$+$i!$19%$^$G 2%$-$6$_$GJQ2=5;$F 2000 @$Be$^$G%7%_%e%l!<%7%g%s$r
9TC?!%$=$l$>$l!$50 ;n9T9T$$!$$=$NJ?6Q$r<hC?!%?^$N=D<4 (fitness) $,E,1~EY$G$"$j!$2#<
(generations) $,@$Be?t$r<($7$F$$$k!%%K%e!<%i%k%M%C%H%o!<%/K"$k 4 DNLdBjN&$A!01D
$N2rEz$KD- 0.25 $NE,1~EY$,M?$($ilkNG (8DBN$N) E,1~EY$N:GBgCM$O 1!$:G>.CM$O 0 HJ$k
$^$?!$K\O@J8$G$$$&:GBgE,1~EYHO$=$N@BeG$N0lHV9b$$E,1~EYG"$j!$J?6QE,1~EYHO$=$
Be$KB8:_$9$kA48DBN$NE,1~EY$NAmOB$r8DBN?t$G=|;;$7$?$bNG$"$k!%J*!$?^Cf$N!VM!W$NI
$OFMA3JQ0[N($rI=7F$$$k!%(Nc!VM005!W$O!$FMA3JQ0[N($, 5%$G$"$k3H$rI=$9!%)



(i) 4D6- 1

(ii) 4D6- 2

?^ 3.3: 0lK\:? GA $NFMA3JQ0[N($H:GBgE,1~EY$N4X78

?^ 3.3$O!$$=l>lN4D6-K*$$$FFMA3JQ0[N($rMM!9$JCM$K@_Dj$7$?$H$-$N:GBgE,1~EY$N@$
?d0\$G$"$k!%

?^ 3.3(i)(ii) $r8+$k$H!$APJ}HbE,1~EY$O 0.75 $r1[$($F$$$k!%3N3Hhj!$4D6- 1!$2 $OF~
NO%f%K%C%H 4 8D!$1#$l%f%K%C%H 4 8D!$=PNO%f%K%C%H 4 8D$H$$$&%K%e!<%i%k%M%C%H%o!<%/$N%H%]
%8!<G"$kDxEY$N@-G=$r<($9$3$H$,3NG’$5l?!%

<!$KE,1~EY$N>e>:$N>u67$K$D$$$F8+F_$k!%?^ 3.3(i)(ii) $NAPJ}$H$b 200 $+$i 300 @$BeL\$^$G
$K5^=T$J>e>:r7!$BgBN 500 @$BeL\$0$i$$$^GKO[HsINFMA3JQ0[N($GE,1~EY$, 0.75 $r1
$($k!%D^$j!$500 @$BeL\IU6a$^GK$O:G9b$NE,1~EYG"$k 1 $r3MF@$G$-$k8DBN$,=P8=$9kH
$($ilk!%$=$N$"$H$N<}B+$OCY$$!%$@$$$?$$ 1000 @$BeL\$r1[$($kHFCKE,1~EY$N>e>:$O4KK}

Jk!%

B>$K5s$2il$kE@$H7F$O!$?^ 3.3(ii) $NJ}$,?^ 3.3(i) hjA4BNE*$KE,1~EY$,9b$$!%FC$K?^ 3.3(i)
$G!$FMA3JQ0[N(3%GOE,1~EY$, 0.75 $r1[$(k3HO$J$$$,!$?^ 3.3(ii) GO1[$($F$$$k!%

$^$?!$4D6-$KhC$FE,1~EY$N>e>:$,B.$$FMA3JQ0[N($O0[$J$k!%4D6- 1 GOFMA3JQ0[N(11%$+
15%0i$$$,E,1~EY$N>e>:$OB.$$$,!$4D6- 2 GO 7%$+$i 13%0i$$$,$h$$!%

%9%H%j%s%0$r 1 K\MQ$$$? GA GO!$FMA3JQ0[N($, 1%$d 3%$JINDc$$CMGOE,1~EY$,Hs>o$
Dc$$!%3l$O%(%j!<%HJ]B8@oN,$r GA $NEqBAJ}K!$H7F:NMQ7F$$$k$?$a!$%7%_%e%l!<%7%g%s
:G=i$G7hDj$7$? GA $N%S%C%HNs$,@52r$+$i1s$$>l9g!$$=lrH/8+9k3H$,$G$-$J$$$+iH9M
il$k!%$^$?FMA3JQ0[N($, 19%$d 17%$Nh&K"$^$jKb9b$$/FbE,1~EY$N>e>:$OB.$/$OJi
$$!%3l$OFMA3JQ0[N($,9b9.$F%i%s%@%`%5!<%A$K6a$/$J$j!$==J,$J6I=jC5:w$,9Tol$F$$$
$H9M$(il$k!%

7k6I!$$3$NLdBj$K$*$1$k%9%H%j%s%0$r 1 K\MQ$$$k GA GN:GE,$JFMA3JQ0[N($O!$10%A08e$G$
k3H,o+C?!%

F0E*$J4D6-$G$N7k2L

0J>e$G<($7$?M=HwE*<B83$N7k2L$r<u$1$F!$%7%_%e%l!<%7%g%sGO!$<!$K5s2k>r7o$G9T$&$
K7$?!%

- FMA3JQ0[N(
  - 10%

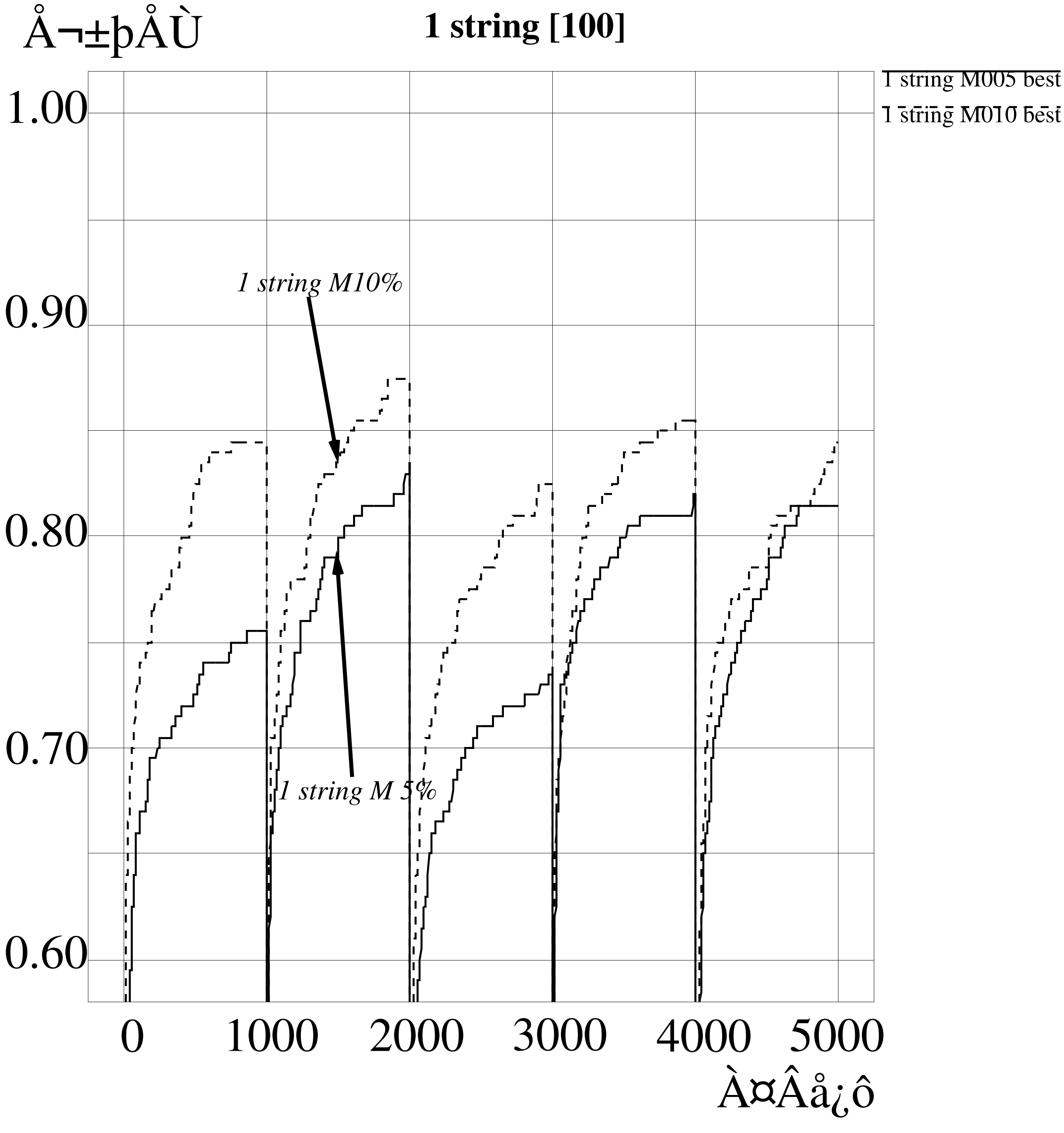
    E,EY$K<}B+$r5/$3$9FMA3JQ0[N(GN4Q;!$r9T$&$?$a!%
  - 5%

    :GE,GO$J$$Dc$$3NN(GN4Q;!$r9T$&$?$a!%
- 4D6-JQ2=$r5/$3$9@$Be?t
  - 1000 @$Be

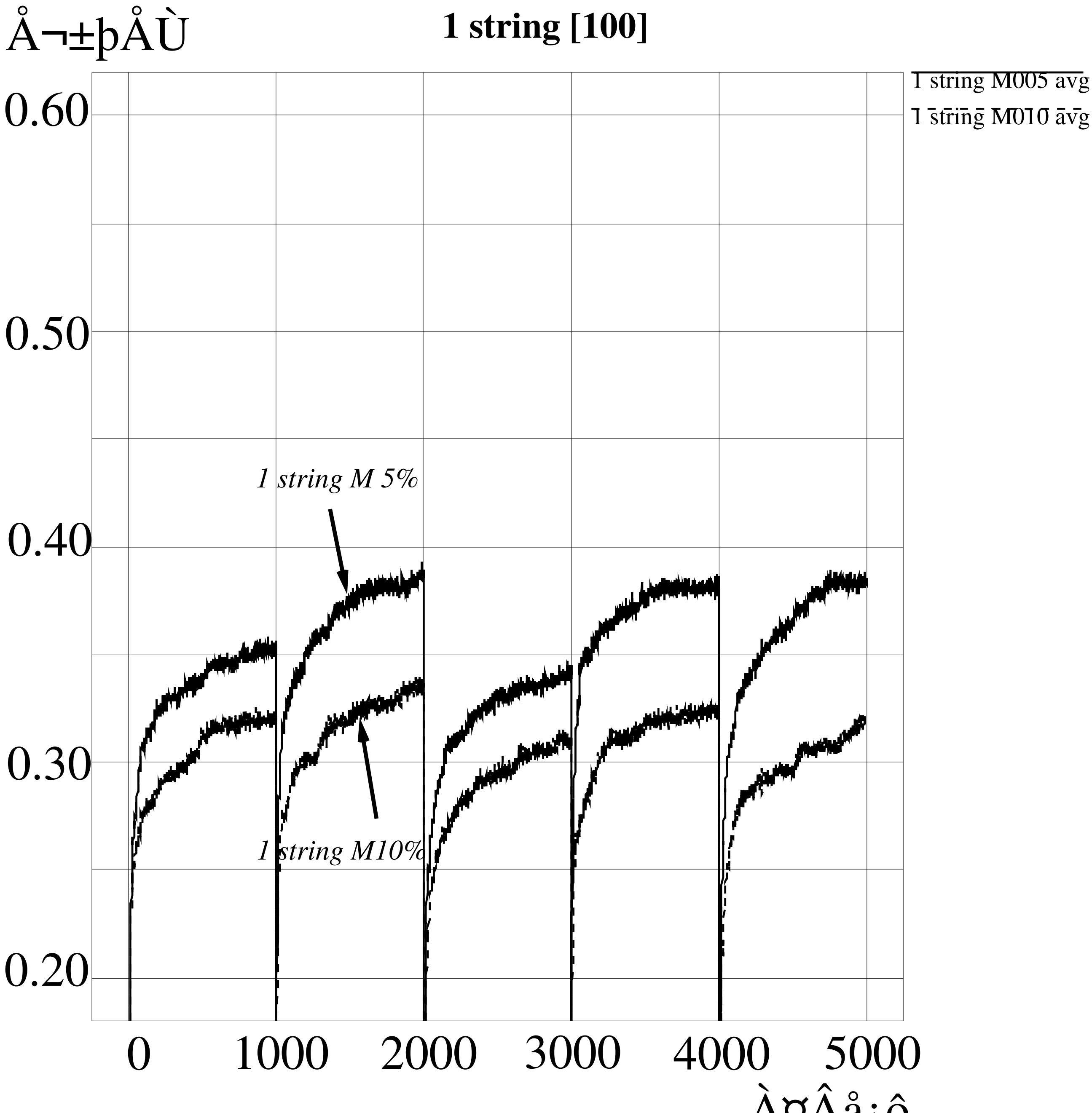
    $[$\==J,$J GA $N<}B+$r5;F+iNJQ2=KBP9$k5sF0$r4Q;!9k$?$a!$1000 @$Be
    4H$K4D6-$rJQ2=5;k3HK7?!%3l$r4D6-JQF08e$NMM;R$r 2 2s$:$D4Q;!$G$-$
    h&$K 5000 @$Be$^$G9T$&$3HK7?!%

$=$l$>$l 50 2s;n9T$7!$$=$NJ?6Q$r<hC?!%

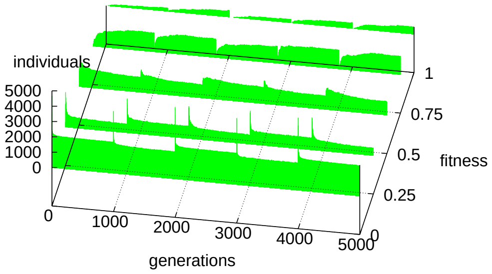
?^ 3.4$N:GBgE,1~EY$N5sF0r_kH!$@EE*$J4D6-$N7k2L$+ib?dB,G-kh$&$K!$FMA3JQ0[
10%N[$&$,9b$$:GBgE,1~EY$r3MF@$G$-$k3H$,$o$+$k!%$^$?!$$3lb@EE*$J4D6-$G$N7k2L$h



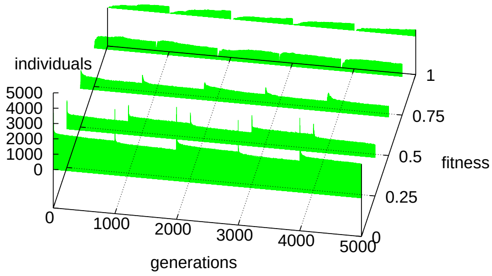
?^ 3.4: 01K\:? GA $N:GBgE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



?^ 3.5: 0lK\:? GA $NJ?6QE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



(i) FMA3JQ0[N(5%



(ii) FMA3JQ0[N(10%

?^ 3.6: 0lK\:? GA $N8DBN?t$NJ,I[

?dB,G-k,4D6-2(1000 $+$i 2000 @$Be!$3000 $+$i 4000 @$Be) N[$&$,4D6-1 hj$b:GBgE,1~
EY$,9b$$!%

$^$?@EE*$J4D6-$N7k2LG"$k?^ 3.3 $H!$:GBgE,1~EY$N>e>:$NMM;R$rHf3S$9kH!$4D6-1 GO
E*JH$-$H$"$^$jJQ2=$O$J$$$,!$4D6-2 GO!$@EE*$JH-$O 1000 @$BeaGFMA3JQ0[N($, 10%I
6aNH$-:GBgE,1~EY$, 0.88 0i$$$JNKBP$7!$F0E*$J4D6-$G$O<c43Dc$$!%3l$O4D6-1 $GF@
8DBN$N%S%C%HNs$,!$4D6-2 $G2r$r5aakH-$KK8$2KJCF$$$k$+$iG"kH9M$($ilk!%

<!$KJ?6QE,1~EY$G$"$k!%?^ 3.5$r8+$F$_$k$H!$J?6QE,1~EY$OFMA3JQ0[N(10%$N$[$&$,Dc$$!%$
lO9b$$FMA3JQ0[N(Kh$jC5:w$,9-HO0O$K9T$olk$?$aG"kH9M$($ilk!%

:G8e$K@$BeKh$k8DBN?t$NJ,I[>u67$r<($9?^ 3.6(i)(ii) $r8+$F$_$k!%3N?^KhkHFMA3JQ0
N(10%GOE,1~EY$, 0.25!$0 $N8DBN$,B?$/!$FMA3JQ0[N(5%GO 0.75!$0.5 $N8DBN$,B?$$$3H,$o
$+$k!%E,1~EY 1 $N8DBN$OAPJ}HbF1$8$0$i$$$G$"$k!%

0J>e$N7k2L$h$j!$FMA3JQ0[N(10%N[$&$,9-0hE*$JC5:w$r9T$$!$FMA3JQ0[N(5%$NH-hjI
$/E,1~EY 1 $r3MF@$G$-$k8DBN$r;:$_=P$;$k3H$,$o$+$k!%$=$NBe=~H7$F!$J?6QE,1~EY$ODc
9k!%

7k6I!$FMA3JQ0[N(10%$G$"$l$P%9%H%j%s%0$, 1 K\$N GA Gb==J,2r$r5a$ak3H,2DG=G
k3HO3NG'G-$?!%

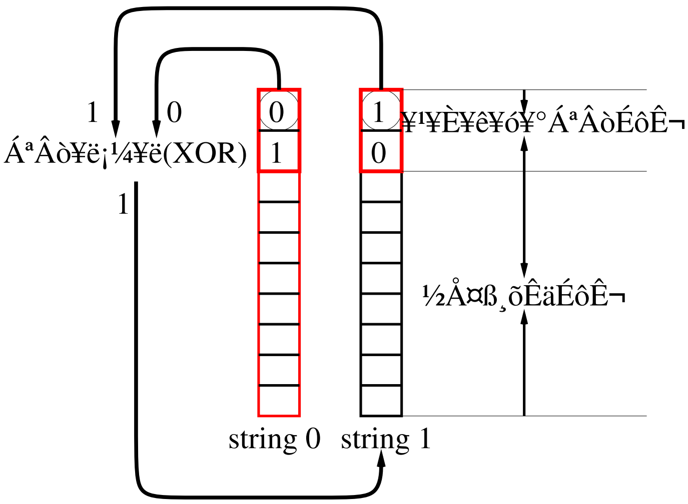
3.3.2 FsK\:?%b%G%k

K\@aGO%9%H%j%s%0$r 2 K\MQ$$$?MM!9$J%b%G%k$r5s$2!$$=$NF0E*4D6-$KBP9kDI=>@-!$4h7

$r8!>Z$9$k!%$J$*!$FCKCGi$J$$8B$jI>2ACM$O%7%_%e%l!<%7%g%s$r 50 ;n9T$7$FF@$?CM$NJ?6

G"$k!%

XOR N_$rMQ$$$?%b%G%k



?^ 3.7: FsK\:? GA(XOR)

$3$3GO4JC1$J%b%G%k$r:G=i$K5s$2$F@bL@$9$k!%

%K%e!<%i%k%M%C%H%o!<%/$N01<4:w$"$?$j!$10 %S%C%HD9$N string 2 K\$N01AH$_$r;HMQ9k (?

3.7)!%9=@.$O!$string 0 $+ string 1 $+$r7hDj9kNK;HMQ9kItJ, (%9%H%j%s%0A*BrItJ,) $, 2 %S%C

%H!_ 2 $G 4 %S%C%H!$<4:w$N=E$_$r5,Dj$9$k2DG=@-$,$"$kItJ, (=E$_8uJdItJ,) $, 8 %S%C%H!_ 2 $

16 %S%C%H!$7W 20 %S%C%H$G$"$k!%%9%H%j%s%0A*BrItJ,$O!$0J2<Nh$&$K7F<B:]$K=E$_H7$F

$$$k%9%H%j%s%0$rA*Br$9$k!%

1. N>%9%H%j%s%0$N 1 %S%C%H$a$r!$N>%9%H%j%s%0$N 2 %S%C%H$a$G5,Dj$5lkA*Br%k!<%k ($3
   3G$O!$XOR N_) KE,MQ9$k!%
2. XOR $N7k2L$rMQ$$$k%9%H%j%s%0$NHV9f$H7FE,MQ9k!%

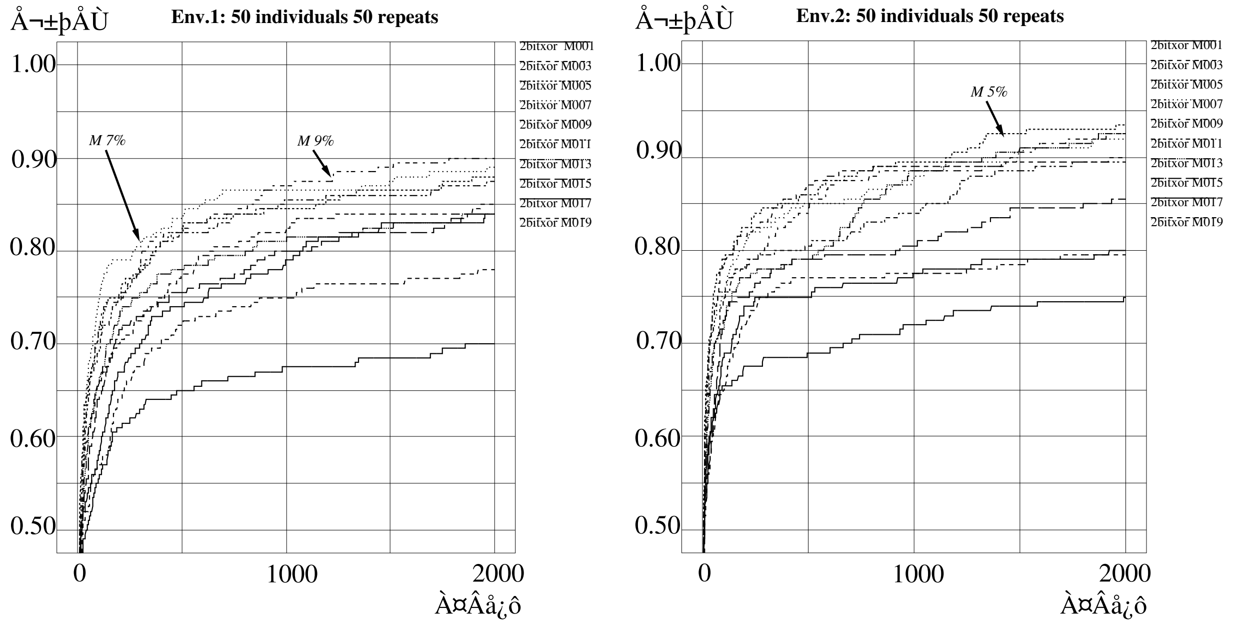
?^ 3.7NNcG$O!$N>%9%H%j%s%0$N:G=i$N%S%C%H$O 0!$1 G"$j!$$3$1$N XOR rHkH 1 G"$

NG!$string 1 $r;HMQ$9k3HK7hDj$7!$string 1 $N=E$_8uJdItJ,r=$N<4:w$N=E$_$H7F;HM

9k!%J*!$string 0 $H string 1 O"i+8a7h$^CF$$$k!%

3Nh&$JFsK\:? GA $rMQ$$!$F0E*4D6-$N%7%_%e%l!<%7%g%s>r7o$rC5$k$?$a@EE*$J4D6-$N<E

$r9T$C$?!%



(i) 4D6- 1 (ii) 4D6- 2

?^ 3.8: FsK\:? GA(XOR) $NFMA3JQ0[N($H:GBgE,1~EY$N4X78

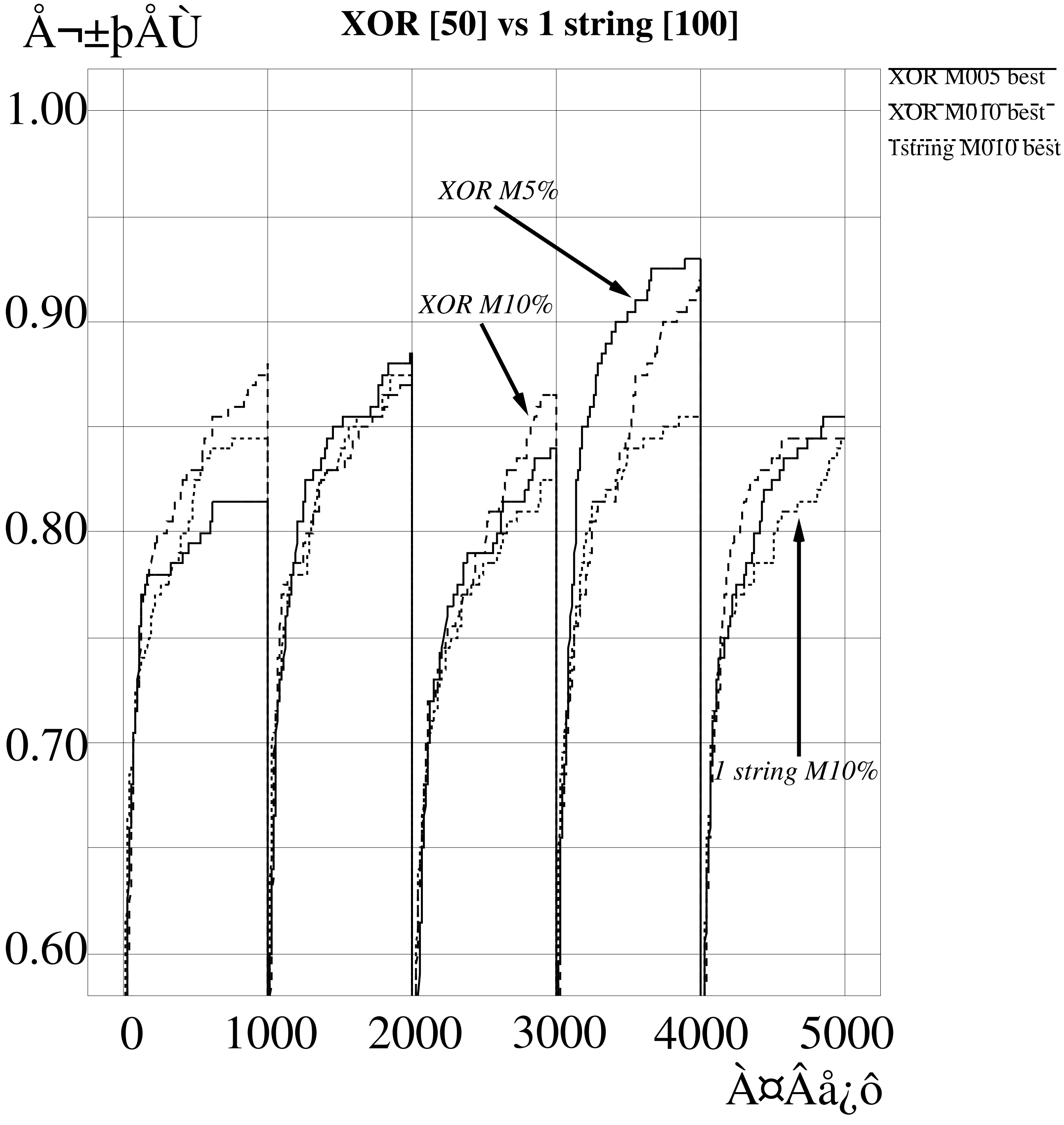
@EE*$J4D6-$G$O!$?^ 3.8hj0lK\:? GA hj$OB?>/Dc$$FMA3JQ0[N((0.7,0.9) $"$?jG:G$bB.$$
E,1~EY$N>e>:$NEY9g$r4Q;!$7$?!%

$^$?!$N>J}$N4D6-$G%9%H%j%s%0$, 1 K\$N GA hj$b9b$$:GBgE,1~EY$r3MF@$G$-$k3H$,$o$+
$?!%FC$K4D6- 1 $G 2000 @$BeaNH-KO:GBgE,1~EY$O 0.4 $[$I$bFsK\:? GA N[$&$,9b$+C?
E,1~EY$N>e>:$NEY9gO"$^$jAj0cOG'ailJ+C?!%

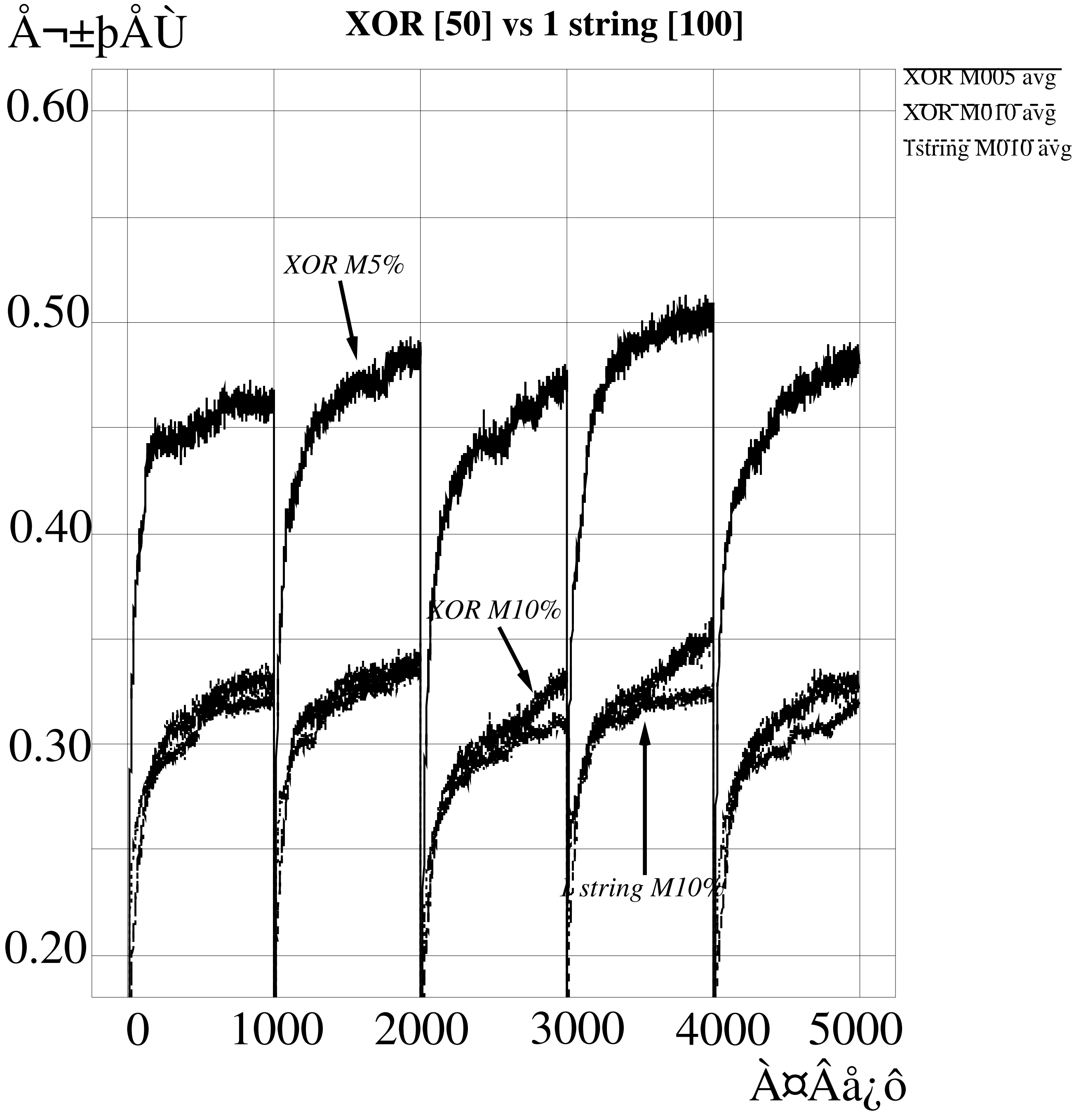
<!$KF0E*$J4D6-GN%7%_%e%l!<%7%g%sG"k,!$0lK\:? GA HNHf3SN?$a!$$"$($F:G$bNI
<}B+$r<($9FMA3JQ0[N(GOJ/!$0lK\:? GA $GNI9%$JE,1~EY$N>e>:$r<(7? 10%$H!$$=lh$j
Dc$$FMA3JQ0[N(GN?6k^$$$r4Q;!9k$?$a$K 5%$rF0E*$J4D6-$K$*$1$kFMA3JQ0[N($H7F;
9k!%

?^ 3.9!$?^ 3.10!$?^ 3.11K=$N7k2L$r<($9!%Hf3S$N$?$a$K!$?^KO0lK\:? GA $NFMA3JQ0[N(
10%NH$-$N7k2L$rJ;$;$F<($7F"$k!%$J$*!$0J8e$N<B837k2L$K$D$$$F$bF1MM$K0lK\:? GA $N
2L$rJ;$;$F<($9$3$HK9$k!%

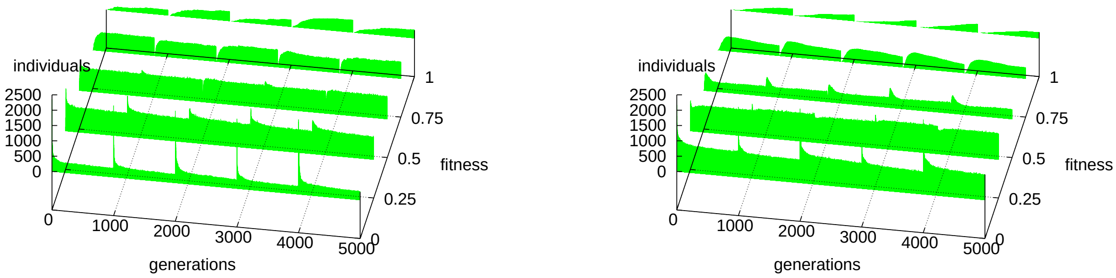
?^ 3.9K*$$$F$^$:CmL\$9Y-3H$O!$8DBN?t$,%9%H%j%s%0$, 1 K\$NH-$NH>?t$Kb+$+$o
$:$h$j9b$$:GBgE,1~EY$rFsK\:? GA(XOR) $rMQ$$$F$$$k8DBN$O3MF@$7$F$$$k3HG"$k!%$^$
FsK\:? GA(XOR) $O4D6- 1 GOFMA3JQ0[N(10%N[$&$,!$4D6- 2 GOFMA3JQ0[N(5%N[$&$,9b



?^ 3.9: FsK\:? GA(XOR) $N:GBgE,1~EY$N5sF0 (1000 @Be4 HKJQ2=)



?^ 3.10: FsK\:? GA(XOR) $NJ?6QE,1~EY$N5sF0 (1000 @Be4 HKJQ2=)



(i) FMA3JQ0[N(5% (ii) FMA3JQ0[N(10%

?^ 3.11: FsK\:? GA(XOR) $N8DBN?t$NJ,I[

$$E,1~EY$r3MF@$7$F$$$k!%$^$?!$FsK\:? GA(XOR) $NFMA3JQ0[N(5%$O!$:G=i$N4D6-1 NH$-(1 $+$i 1000 @$Be) $O01K\:? GA hj$bE,1~EY$N>e>:$,CY$$$,!$4D6-JQF08e!$$D$^$j 2001 $+$i 3000 @$Be!$4001 $+$i 5000 @BeG$O01K\:? GA hj$bB.$$E,1~EY$N>e>:$r<(7F$$$k!%

$^$??^ 3.10hj!$FMA3JQ0[N(5%$N>r7o2<K*$$$FFsK\:? GA(XOR) $OHs>o$K9b$$J?6QE,1~EY $r<($7$F$$$k3H$,J,$+$k!%$3$1$O?^ 3.11(i) $r8+$k$HM}M3$,o+$k!%FsK\:? GA(XOR) GOE, 1~EY 0 $N8DBN$,Hs>o$K>/$J$/!$$=$10J30$NE,1~EY$N8DBN?t$,%P%i%s%9h/J,I[7F$$$k!%FMA 0[N($,Dc$$$H9baNE,1~EY$N8DBN?t$,B?$/$Jk3HO01K\:? GA Gb$"$C$?$,!$E,1~EY 1 $r3M 7F$$$k8DBN?t$,FsK\:? GA(XOR) N[$&$,3d9gE*$KB?$$!%$3$1$OFMA3JQ0[$Khj6I=jC5:w$r =E$_8uJdItJ,$N8r49$KhjBg0hE*$JC5:w$rF1;~$K<B8=$7$F$$$k$+$iG"kH9M$($i1k!%

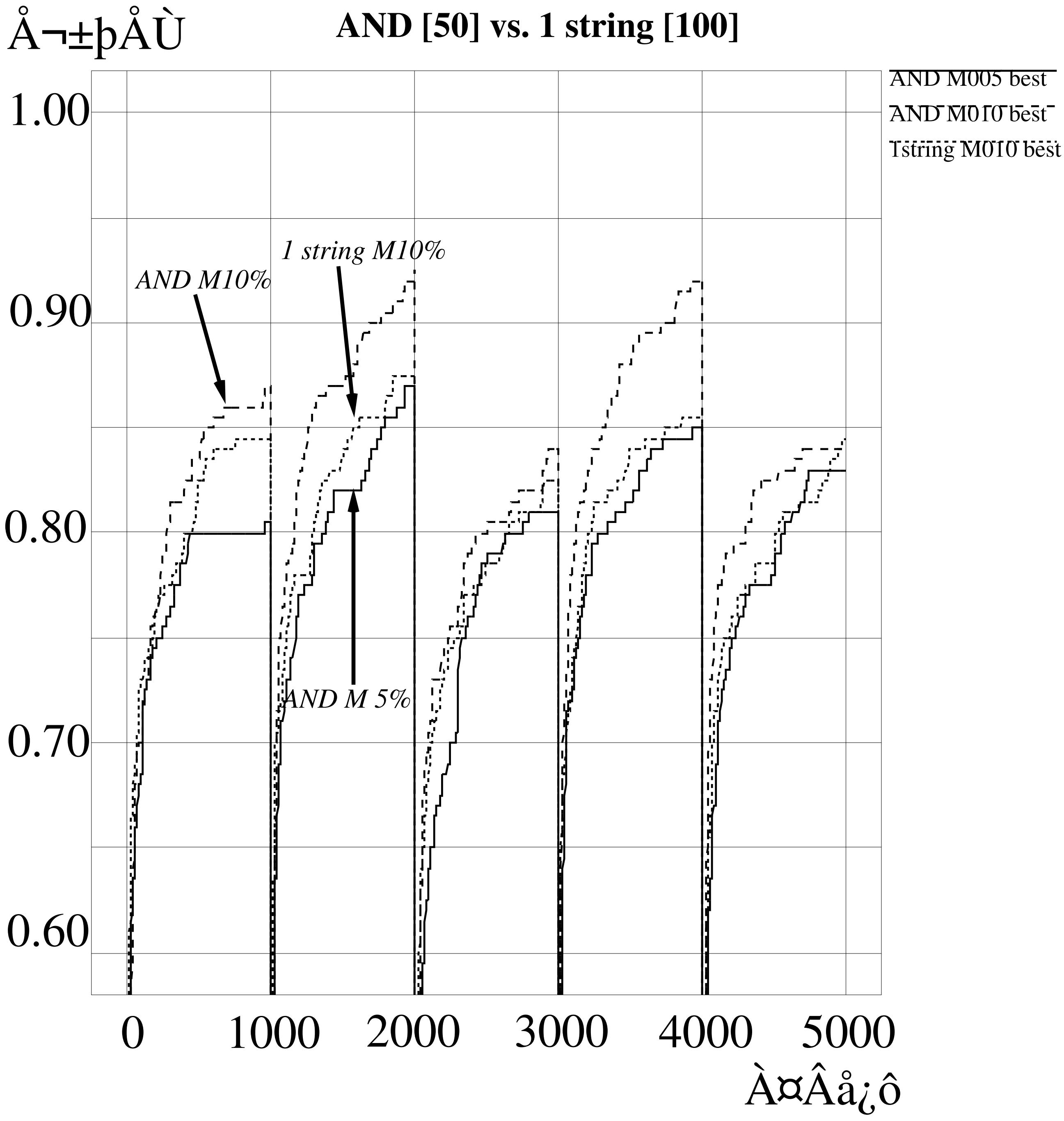
0J>eN3Hh$j!$FsK\:? GA(XOR) $O01K\:? GA hj$bB.$$E,1~EY$N>e>:$r<B8=G-!$F0E* $J4D6-$K$*$$$FDI?o@-!$4h6/@-$HbKNI9%G"k3H,3NG'G-$?!%

AND N_$rMQ$$$?%b%G%k

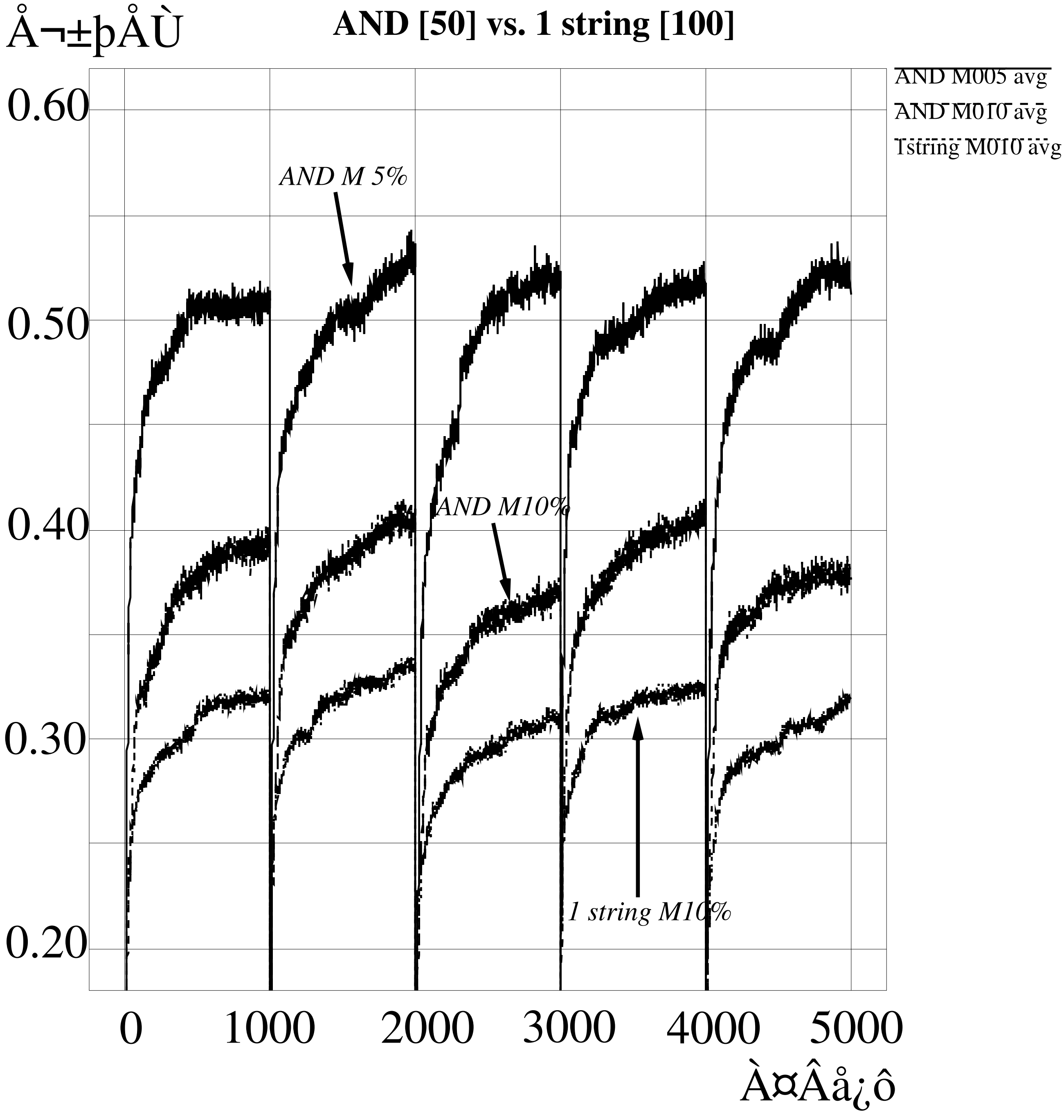
?^ 3.7$HF1MM$N9=B$$N GA $G!$%9%H%j%s%0A*BrItJ,$N%k!<%k$r XOR GOJ/!$AND N_$G%7 %_%e%l!<%7%g%s$r7F$_$?!%

AND $rMQ$$$?L\E*$O!$A*Br5l$k%9%H%j%s%0$K;X8~@-rb$?$i7?$+$C$?$?aG$"$k!%AN $,%k!<%k$J$i!$C1=c$K string 0 $,A*Br$5lk3NN($O string 1 $,A*Br$5lk3NN($N 3 G\$KJk!%$3 lHF1$8$3HO!$%9%H%j%s%0A*BrItJ,$N%k!<%k$r OR N_K7Fb5/3k (string 1 $,A*Br$5$ $k3NN($, string 0 $,A*Br$5lk3NN($N 3 G\$HJk)!%

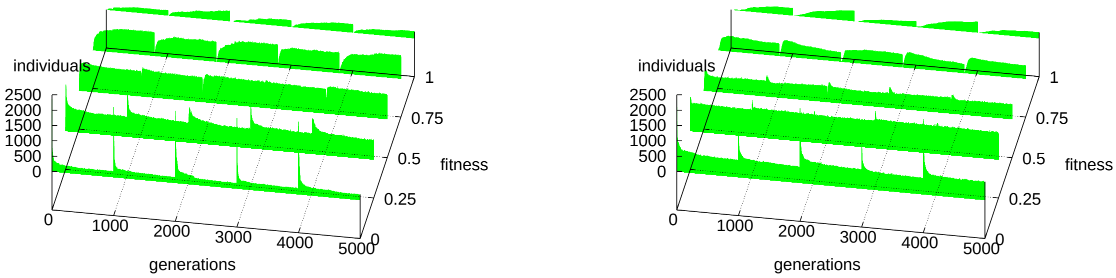
AND N_$rMQ$$$?H-$N:GBgE,1~EY$r<($9?^ 3.12$r!$XOR N_$rMQ$$$?H-$N?^ 3.9$HHf3S



?^ 3.12: FsK\:? GA(AND) $N:GBgE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



?^ 3.13: FsK\:? GA(AND) $NJ?6QE,1~EY$N5sF0 (1000 @Be4 HKJQ2=)



(i) FMA3JQ0[N(5% (ii) FMA3JQ0[N(10%

?^ 3.14: FsK\:? GA(AND) $N8DBN?t$NJ,I[

7F$_$k!%4D6-JQF08e$N4D6- 1 KBP9$k:GBgE,1~EY$,<c43 AND N[$&$,0-$$!%7+$7!$4D6-
KBP9$k:GBgE,1~EY$O AND N[$&$,<c43$h$$!%$^$?!$XOR GOFMA3JQ0[N(5%NH$-4D6- 2 $
FMA3JQ0[N(10%hj$b9b$$E,1~EY$r<($7$?$N$KBP$7!$AND GO>o$KFMA3JQ0[N(10%$NJ}$,9b$
E,1~EY$r<($7$F$$$k!%

$^$?!$J?6QE,1~EY$O3FFMA3JQ0[N(NH$-!$XOR hj$b AND N[$&$,L@i+$K9b$$!%$3$1$
?^ 3.14$+$i$bJ,$+$k!%

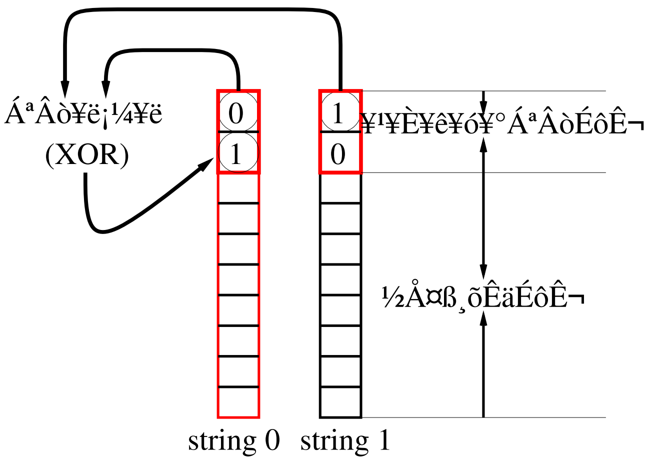
5F!$$J$<$3Nh$&$J:90[$,@8$8$?$N$@$m$&$+!%9M$($ilk3H$N0l$D$O!$=E$_8uJdItJ,
string 0 $,%a%$%sH7$F!$string 1 $,%5%V$H7FF/$$$F$$$k3H$,$"$k!%

XOR+average %b%G%k

<!$K!$Calabretta $i [CGNP97] $,MQ$$$?%b%G%k$N7k2L$r<($9!%$3$N%b%G%k$G$O!$<4:w$N=E$_
$r7hDj$9kN$K 2 %S%C%H$"$k%9%H%j%s%0A*BrItJ,$rMQ$$$k!%

$=$N>\:Y$J%W%m%;%9$r0J2<$K<($9!%

1. N>%9%H%j%s%0$N 1 %S%C%H$a$r!$A*Br%k!<%k (XOR N_) KE,MQ9$k!%
2. XOR $N7k2L$rN>%9%H%j%s%0$N 2 %S%C%H$a$H>H$i$79g$o$;!$F1$8%S%C%H$r;}$D%9%H%j%s %0$rA*Br9k!%$=$7$F!$$=$N%9%H%j%s%0$N=E$_8uJdItJ,$r%K%e!<%i%k%M%C%H%o!<%/$N <4:w$N=E$_$H7FMQ$$$k!%
3. b7N>%9%H%j%s%0$N 2 %S%C%H$a$,F1CM$@C?>l9g (00 $+ 11)!$N>%9%H%j%s%0$N=E$_8uJd ItJ,$N<B?t$r7W;;$7!$$=$NJ?6Q$r%K%e!<%i%k%M%C%H%o!<%/$N<4:w$N=E$_$H7FMQ$$$k!



?^ 3.15: FsK\:? GA(XOR+average) %b%G%k

3N<4:w$N=E$_7hDj%W%m%;%9$NFCD'$Khj!$0J9_$3lr"XOR+average" %b%G%k$H8F$V3H$K
9k!%

?^ 3.16r_kH!$XOR+average %b%G%k$OA4BNKEOj01K\:? GA hj5[INI/OJiJ$$!%
FC$K!$FMA3JQ0[N($, 10%$NH-$O01K\:? GA hj$bE,1~EYODc/$JCF7^$&!%

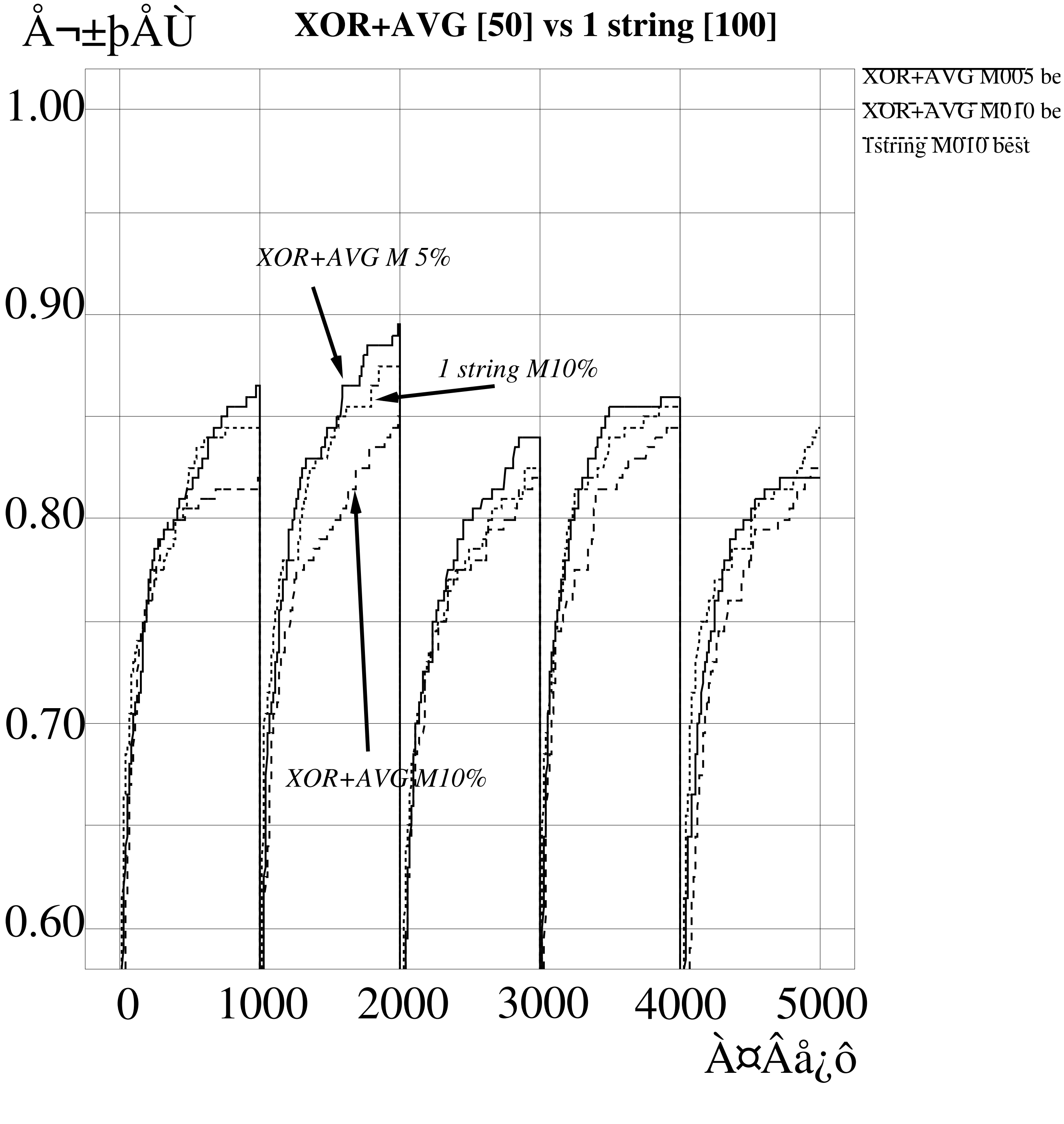
3l$O!$XOR %k!<%kN_NH$- (?^ 3.9) $O01K\:?$h$j:GBgE,1~EY$ONI9%$@$C$?$3HHHf3S$
$F9M$(kH!$J?6Q2=$H$$$&A`:n$,B?MM@-$r;&$7!$GA $NC5:wG=NO$,01K\:?K*1k 50 8DBN$N
9g$K6a$/JCF7$^$C$?$?aH;Wol$k!%

J#?t$N%k!<%k$r;}$D%b%G%k

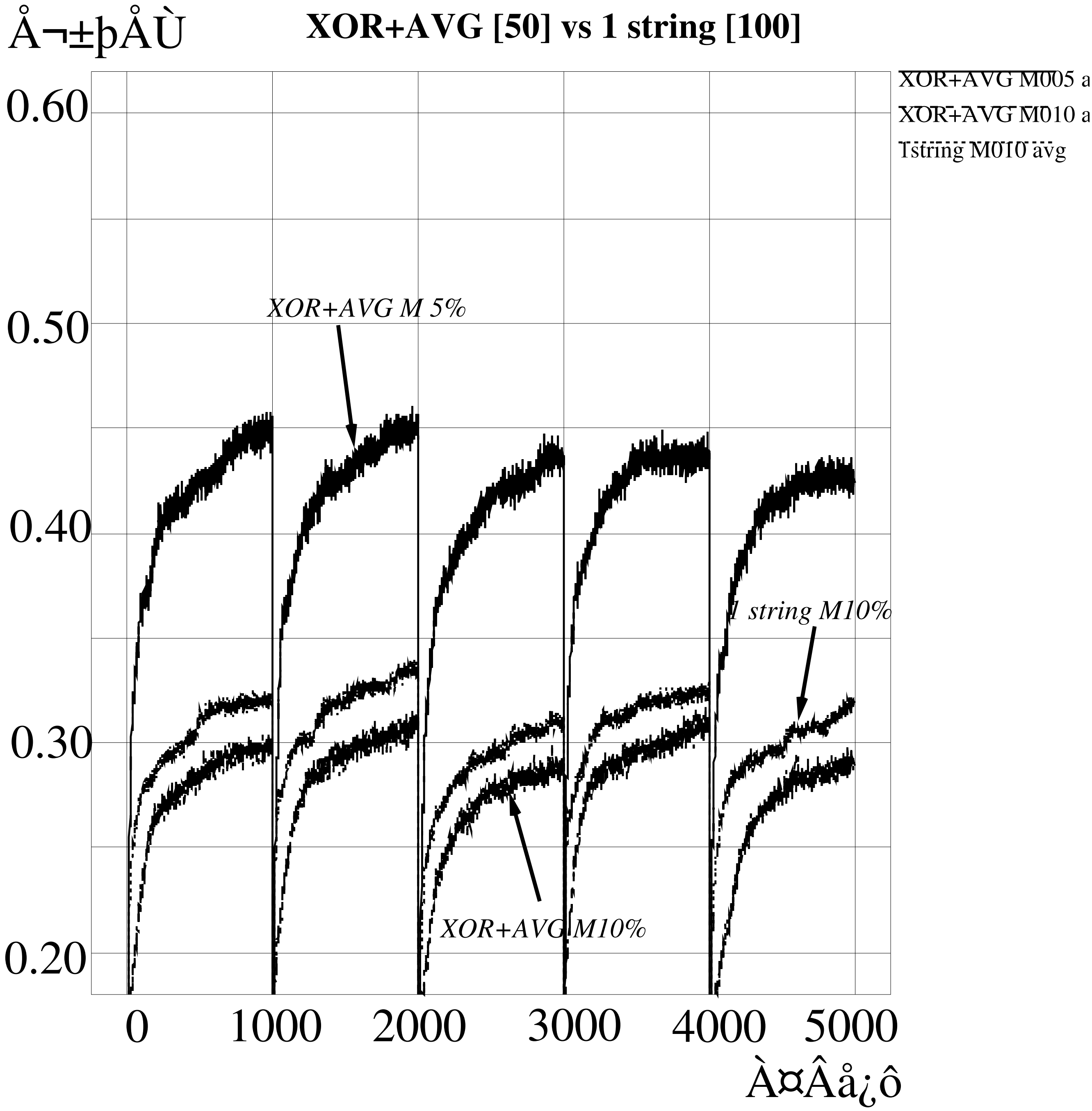
01K\:?$N GA hj9%@.@S$rG<a? FsK\:? (XOR)GA!$FsK\:? (AND)GA G"k,!$$h$jE,1~
E*K9k?aKH/8=7hDj$N5,B'<+BN$r?J2=E*$K@)8f·3MF@$7!$M-8z$J%k!<%k$r4D6-$K1~8FA*
J];}$7B3$1$?$$$H$$$&MW5a$,9M$(il$k!%$D$^$j!$$;C+$/M-8z$J%S%C%HNs$rA*Br$7$F$$$F$
8=7hDj%k!<%k$, XOR N_G"k?aKJQ2=7F7^$&$3H,9M$($ilkNG!$$=lr4KOB$
M-8z$J%S%C%HNs$rA*Br7DE1$?$$!%$^$?!$%k!<%k$, AND $@$1GOFCDj$N4D6-$KN_E,1~$,
9%KJCF7^$&798~$,$"$k!%

$=$3$GJ#?t$NH/8=7hDj%k!<%k$N;XDjK!$r:#$^$G$N%b%G%k$N2~NIH7$F9M$(F_$k!%

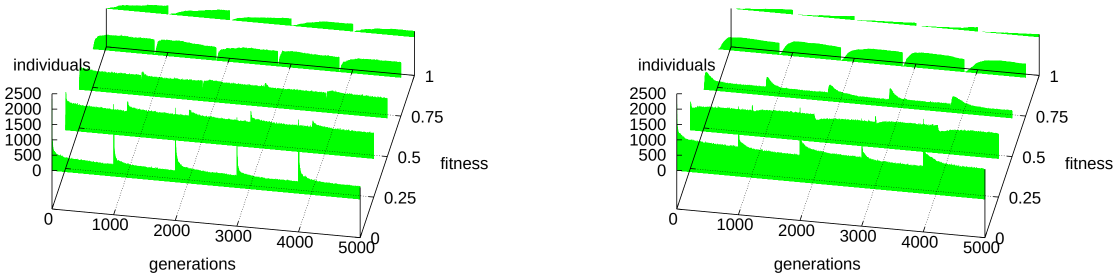
3N%k!<%k%;%C%H$NA@$$$O!$%9%H%j%s%0A*BrItJ,$K?7$?$K AND!$OR $rMQ$$$k3HKh$j!$A
Br5l$k%S%C%HNs$K$D$$$FA*BrE*$J;X8~@-$rO+k3HK$"$k!%D^$j!$AND $r%k!<%k$H$7
J];}7F$$$l$P!$%9%H%j%s%0A*BrItJ,$, 11 $N>l9g$N$_ string 0 $rA*Br$7!$$=$NB>$N>l9g$O string
1 $rA*Br$9k3HKJk!%D^$j!$%9%H%j%s%0A*BrItJ,$NJQ2=$KBP$7!$string 0 $rA*Br$7d9
$H$$$&0UL#$G;X8~@-$r;}$D;v$KJk!%3lKh$j!$$b$7 string 0 $KM-8z$J=E$_$,$"$C$?>l9g!$



?^ 3.16: FsK\:? GA(XOR+average) $N:GBgE,1~EY$N5sF0 (1000 @Be4HKJQ2=)

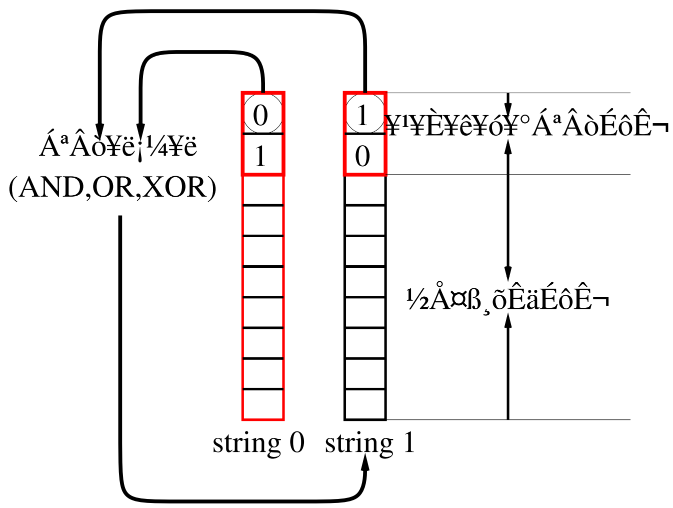


?^ 3.17: FsK\:? GA(XOR+average) $NJ?6QE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



(i) FMA3JQ0[N(5%　　　　(ii) FMA3JQ0[N(10%

?^ 3.18: FsK\:? GA(XOR+average) $N8DBN?t$NJ,I[



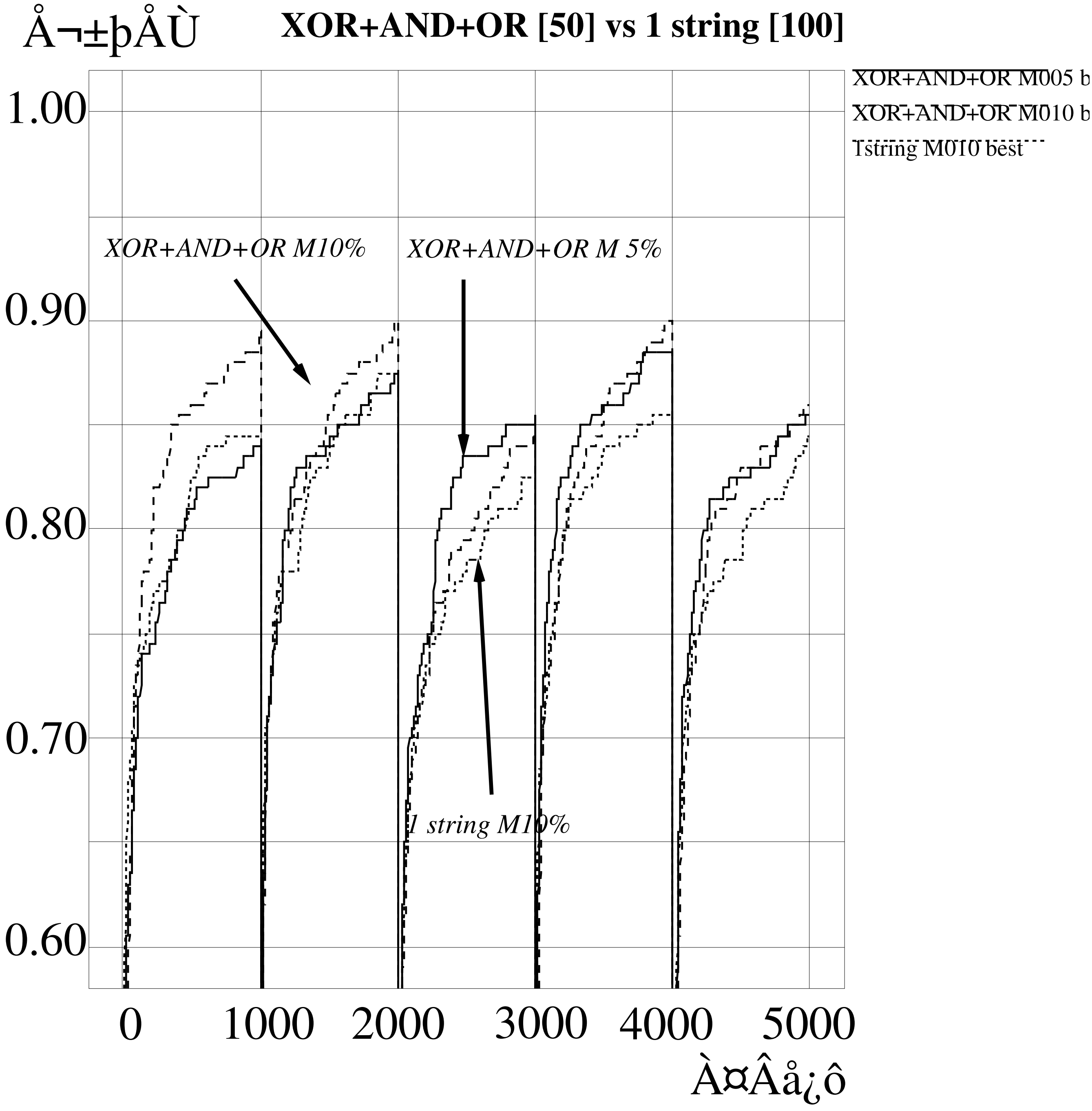
?^ 3.19: J#?t$N%k!<%k$r;}$DFsK\:? GA

I= 3.2: J#?t$NA*Br%k!<%k

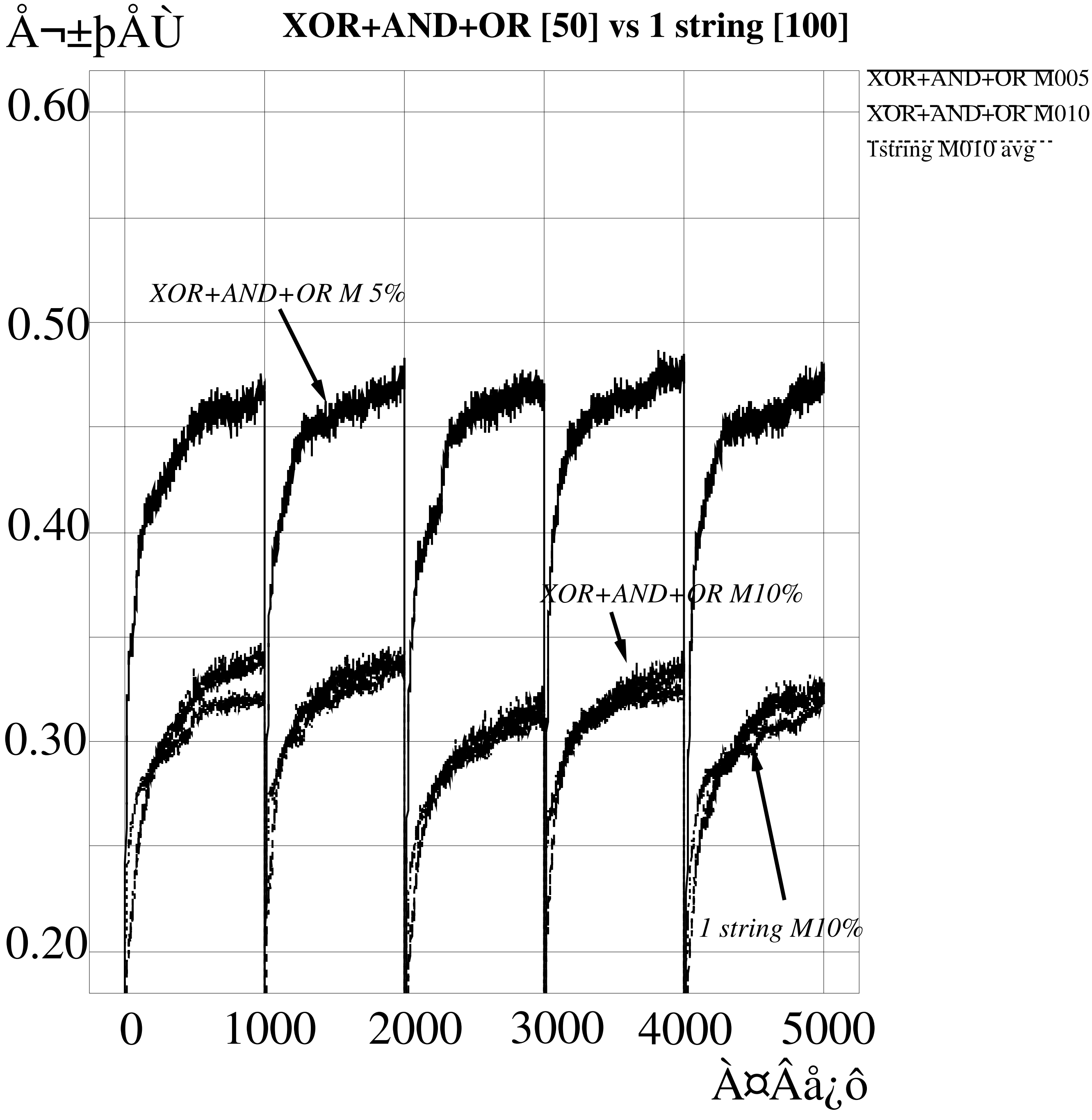
rule	rule bit	F~NO 00 $K BP$9$k=PNO	F~NO 01 $K BP$9$k=PNO	F~NO 10 $K BP$9$k=PNO	F~NO 11 $K BP$9$k=PNO
AND	11	0	0	0	1
XOR	10	0	1	1	0
XOR	01	0	1	1	0
OR	00	0	1	1	1

$N9=B$$rJ]Ad9/Jk!%

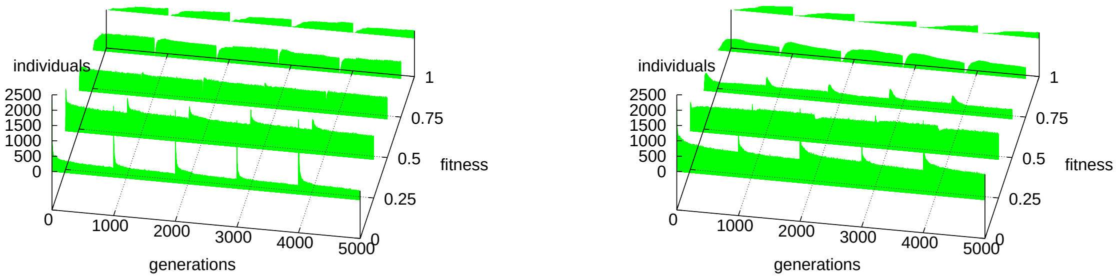
?^ 3.19!$I= 3.2$G<(7?2~NI$r<BAu$7!$<B83$r9TC?!%$=$N7k2L$r?^ 3.20!$?^ 3.21!$?^ 3.22 $K
<($9!% ?^ 3.20$r8+kH!$FMA3JQ0[N(5%$,:G=i$N 1000 @$Be$^$G$O0lK\:? GA hj$bE,1~EY$ODc
$/$JCF$$$k$,!$$=$l0J30$O0lK\:? GA hj$b9b$$E,1~EY$r<($7$F$$$k!%$@$,FsK\:? GA(XOR
$HHf3S$9kH!$$=lhjb7k2L$OA4BNE*$K0-$$!%:G=i$K0U?^$7$?$H$*$j$N7k2L$OF@ilJ+$



?^ 3.20: FsK\:? GA(XOR+AND+OR) $N:GBgE,1~EY$N5sF0 (1000 @Be4 HKJQ2=)



?^ 3.21: FsK\:? GA(XOR+AND+OR) $NJ?6QE,1~EY$N5sF0 (1000 @Be4 HKJQ2=)



(i) FMA3JQ0[N(5%   (ii) FMA3JQ0[N(10%

?^ 3.22: FsK\:? GA(XOR+AND+OR) $N8DBN?t$NJ,I[

3.3.3 =E$_A*BrItJ,$N8r49N"$k0lK\:? GA

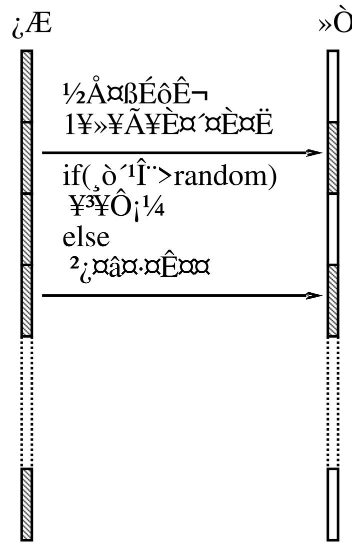
$3$3$^$G$O!$C1=c$J%9%H%j%s%0$, 1 K\$N GA $H!$MM!9$JA*Br%k!<%k$N%9%H%j%s%0$, 2 K\$N G
$r8!F$$7F-$?!%%9%H%j%s%0$, 2 K\$N GA $O!$8DBN?t$,H>?t$JNKb+$+$oi:!$1 K\$N GA $
jb9b$$E,1~EY$r<($9$3$H$,B?$+C?!%$3$3$G%9%H%j%s%0$, 2 K\$N GA $N7k2L$,NI$$M}M3$r9M
9k!%$=$N:GBg$NM}M3$H7F!$=E$_8uJdItJ,$r 2 K\$+$i 1 K\A*Br$7$F$$$k3H$GB?MM@-$,J]$
$F$$$k$+$i$H$$$&2DG=@-$,$"$k!%0lJ}$G!$=E$_A*BrItJ,$r0l$D$N%f%K%C%H$H$$$&C10LG^k
<h$j49$(ilk3HKhC$F@-G=$,>e$,$k!$$H$b9M$(il$k!%$D$^$j!$%9%H%j%s%0$, 1 K\$N
Gb=E$_A*BrItJ,$r$^$k4H<h$j49$(ilkh$&$J5!9=$,$"lP!$$o6o$6%9%H%j%s%0$r 2 K
7J$/$Fbh$$$N$+$b7l$J$$!%

$=$3$G!$$3$N2>@b$r8!>Z9k$?$aK,!$0lK\:? GA $G=E$_A*BrItJ,$r<h$j49$[1]$Nil$kJ}K!
F3F~$r;n$_!$$=$N%7%_%e%l!<%7g%s$HI>2A$r9T$C$?!%8r49$NJ}K!H7FO!$8r49N($r@_Dj$7!
lK=>CF$=$N;~E@$G:G$b$h$$8DBN$+$i$=$NItJ,$N=E$_ItJ,$r<h$j49$($k!%hj>\:Y$J%W%m%
$r0J2<$K<($9!%

[1]3l$O$$$o$P GA K*1k8r:5$KAjEv9kA`:nG"$k!%($?$@$787L)KO0[Jk!%)

1. E,1~EY$N9b$$=g$KA48DBN$rJB$YD>$9!%
2. >e0L 20 8DBN$r 4 2s%3%T!<$7!$$=lr;RH9$k!%
3. ;R$N=E$_ItJ,4H$K8r49$rE,MQ9k!%Nc$($P!$0l8DBN$KD-=E$_ItJ,$, 10 8D$"$k (8 %S%C%H!_10) Ji!$$=l>lN=E$_ItJ,$4HKMp?trH$j!$$=l,8r49N(0J2<Ji$=$N @BeN:GBgE,1~EY$r;}$D8DBNN=$N>l=j$K3:Ev9k=E$_ItJ,$r;R$N8DBN$KF~lk!%Nc $($P!$2 Da$N=E$_ItJ,$G8r49$r9T$&$3HKJC$?NJiP!$?F$N 2 Da$N=E$_ItJ,$r%3%T!<$7!$;R$N 2 Da$N=E$_ItJ,$KBeF~$9$k!%
4. FMA3JQ0[N($K=>$$;R8DBN$KFMA3JQ0[$NA`:n$r9T$&!%

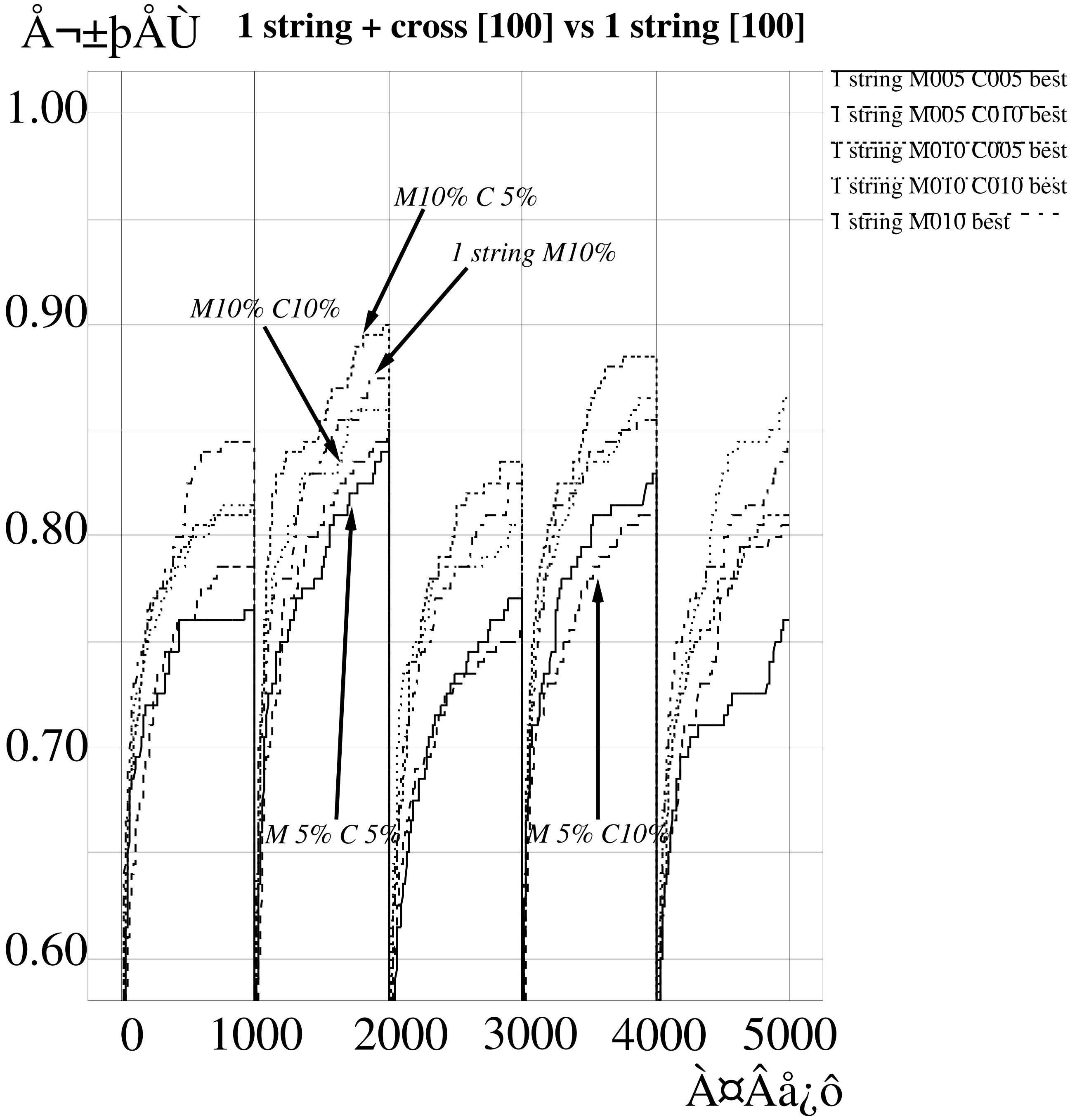
>e5-$N 3. $NItJ,$r?^ 3.23$K<($9!%$3$3$G 3. $N%3%T!<85$N?F$O8=@$Be$G:G9b$NE,1~EY$r;}$D8DBN$r5$7!$2. GN%3%T!<85$N?FHOI,$:7b0lCW7J$$!%



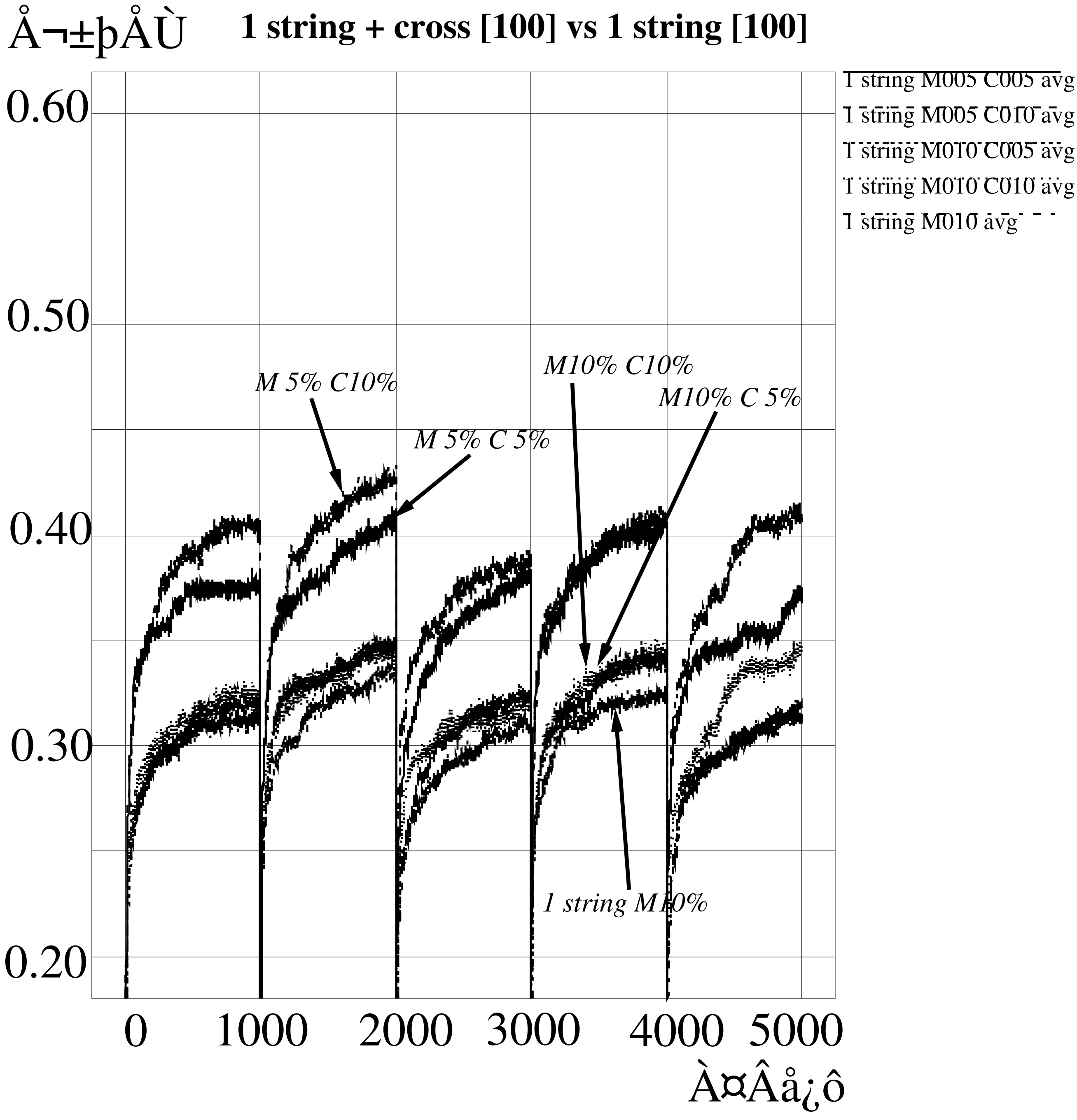
?^ 3.23: 8r49$N;EJ}

?^ 3.24K=$N7k2L$r<($9!%$3$3$G!$FMA3JQ0[N($O 10%$H 5%!$8r49N($O 10%$H 5%$rMQ$$$?!%J*!$?^Cf$N!VC!W$O8r49N($N3HG"$j!$C010 Ji8r49N($, 10%$G$"$k3H$r<($9!%

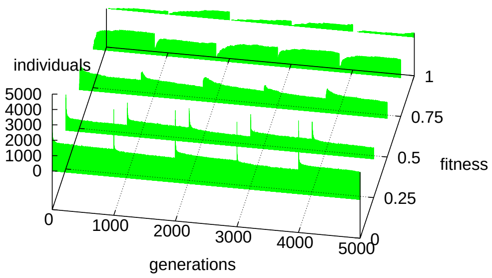
7k2L$r8+$k$H!$FMA3JQ0[N(10%!$8r49N(5%$NH-N_$,>o$KC1=c$J%9%H%j%s%0$, 1 K\$N GA hj$b9b$$:GBgE,1~EY$r3MF@$7F*$j!$$=$NB>$OC1=c$J%9%H%j%s%0$, 1 K\$N GA hjbAm8$F$$:GBgE,1~EY7+3MF@G-J+C?!%$^$?!$%9%H%j%s%0$, 2 K\$N GA $HHf3S$7F_$?$,!XOd AND $HHf3S$7F=lhjb9b$$:GBgE,1~EY$rF@$ilkHO8BiJ$+$C$?!%$3lh$j!$%9%H%s%0$, 2 K\$N GA $O!$=E$_8uJdItJ,$r8r49G-$k5!G=$N$_$N$?$a$K9b$$E,1~EY$rF@$ilko1OJ$$/!$I=8=BN$KH?1G5l$J$$!$$D$^$j;HMQ5l$J$$=E$_8uJdItJ,$,B8:_9k3H$,@-G=$N8KBP7FBg-$J4sM?$r7F$$$k$H8@$($k!%



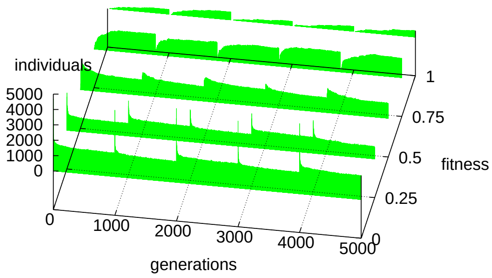
?^ 3.24: 01K\:? GA(8r49D-) $N:GBgE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



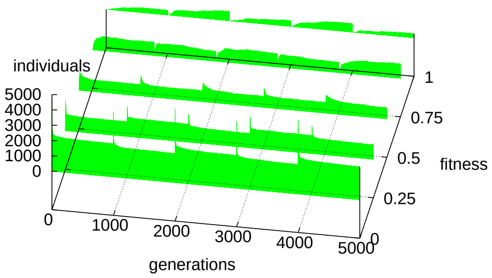
?^ 3.25: 0lK\:? GA(8r49D-) $NJ?6QE,1~EY$N5sF0 (1000 @Be4HKJQ2=)



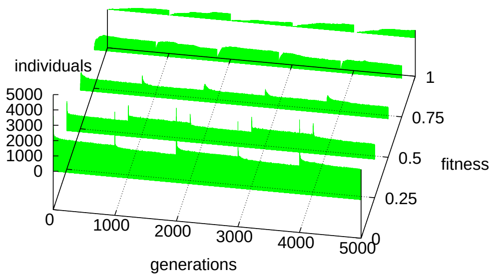
(i) FMA3JQ0[N(5% 8r49N(5%



(ii) FMA3JQ0[N(5% 8r49N(10%



(iii) FMA3JQ0[N(10% 8r49N(5%



(iv) FMA3JQ0[N(10% 8r49N(10%

?^ 3.26: 01K\:? GA(8r49D–) $N8DBN?t$NJ,I[

3.4 $^$H$a

$^$HaH7F!$K\>O$G$"$2$?%b%G%k$N:GBgE,1~EY$HJ?6QE,1~EY$r$^$Ha??^$r?^ 3.27!$?^ 3.2 $K<($9!%$^$?!$2000!$3000!$4000!$5000 @Bea$N:GBgE,1~EY!$J?6QE,1~EY$rJ?6Q$7$?$bNrI= 3.3$K<($9!%1000 @Bea$NE,1~EY$rF~1J$+$C$?$N$O!$4D6-JQF08e$N%G!<%?$N$_$rBP>]H9$k aG$"$k!%?^ 3.29$OE,1~EY$,JQ2=7?H-$N01<4:w (8%S%C%H) $"$?jN?F8DBN$H;R8DBN$N0c$$?^K7$?$bNG$"$k!%<B:]$K<4:w$N=E$_$r5,Dj7?!$$D$^$jI=8=BNHJC?%S%C%HNs$rBP>]$ $F$$$k!%50 ;n9T$NAmOB$r@]$j!$$=lrI4J,N(K7F^Ha$?!%$J$*FsK\:? GA(XOR+avg) KD $$$F$OAj0c$rFCDj9kN,:FqJ$?$a?F$H;R$N%S%C%H$NAj0c$OHC$F$$$J$$!%

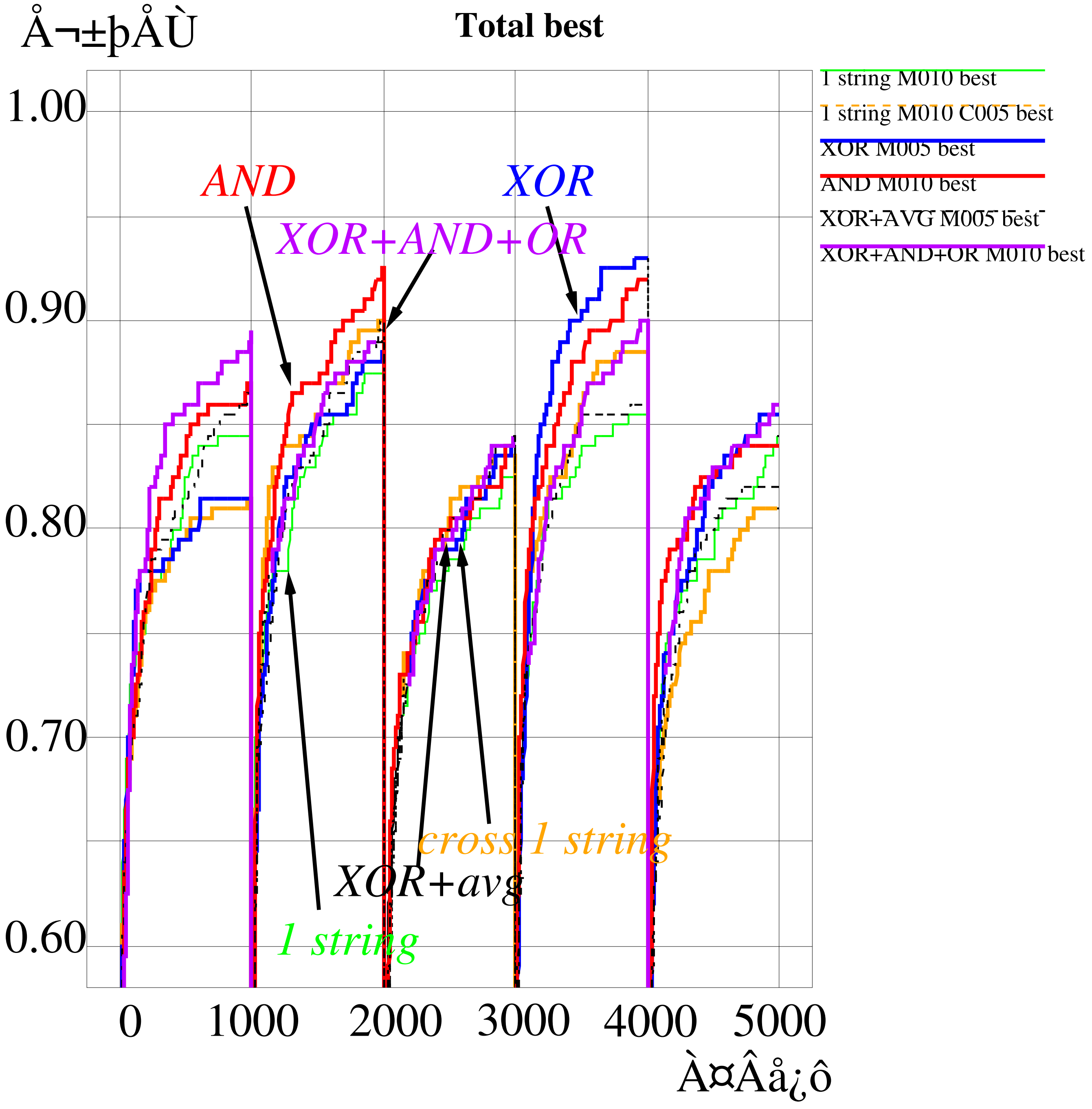
I=3.3hj!$F0E*$J4D6-2<K*$$$F!$4D6-1$G:G$b9b$$:GBgE,1~EY$r3MF@$7$?$N$O XOR+AND+C G"$j!$4D6-2GO AND G"C?!%$^$?!$%9%H%j%s%0$r 2 K\MQ$$$? GA $G!$XOR $HJ?6Q2=$r MQ$$$? GA $,4D6-1$G$OC1=c$J%9%H%j%s%0$r 1 K\MQ$$$? GA $K!$4D6-2GO8r49D-$N%9%H%j% %0$r 1 K\MQ$$$? GA $K!$$=l>$l:GBgE,1~EY$O2<2sCF$$$k!%$=$l0J30$N%9%H%j%s%0$r 2 K\MQ $? GA $O!$$I$N%9%H%j%s%0$r 1 K\MQ$$$? GA hj$b4D6-1!$2 Hb$K:GBgE,1~EY$O>e2sCF$$$?

$^$??^ 3.29hj!$FsK\:? GA N[$&$,4!$5%S%C%H$NJQ2=$,B?>/B?$$$3H,o+k,!$$=l IN:90[$O8+<u$1il$J$$!%3l$O!$FsK\:? GA K*$$$FA*Br5l$k%9%H%j%s%0$,JQ2=7F$ $=$3K"$k%S%C%H$,b&0lJ}$N%9%H%j%s%0Cf$N%S%C%HH"$^$jJQoiJ1lP!$0UL#$,$J$$$ $&$3Hr0E$KJ*8l$C$F$$$k$H$$$($k!%

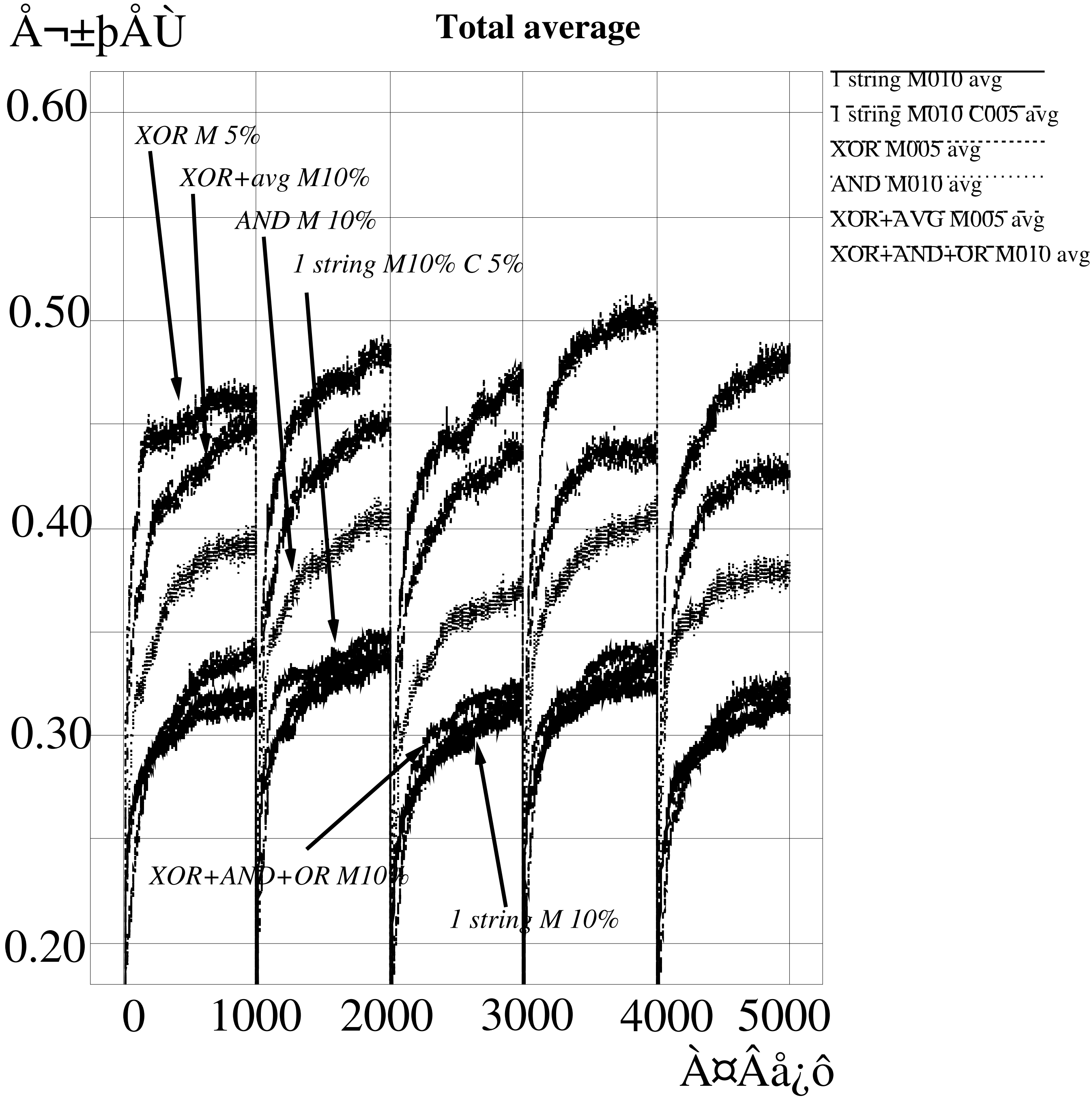
0J>eNh$&$K!$$3$3$G$OA*Br%k!<%k$5$(E,@Z$K7hDj9l$P!$%9%H%j%s%0$r 2 K\MQ$$$k GA $O K\$N GA hj$b4D6-JQF0$KBP7FDI?o@-$,$"$j!$4h6/G3H,8!>ZG-$?!%

I= 3.3: 4{B8%b%G%k$NHf3S (Best $O:GBgE,1~EY!$Avg $OJ?6QE,1~EY)

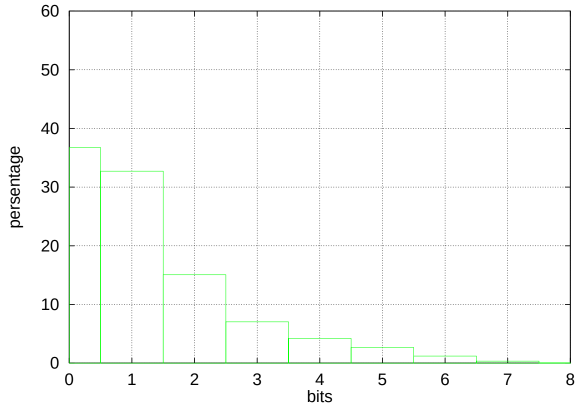
rule	Best(4D6-1)	Best(4D6-2)	Avg(4D6-1)	Avg(4D6-2)
1 string (M010)	0.8350	0.8650	0.3164	0.3269
1 string + exchange (M010 C005)	0.8225	0.8925	0.3190	0.3486
XOR (M005)	0.8475	0.9075	0.4744	0.4966
AND (M010)	0.8400	0.9225	0.3711	0.4019
XOR + average (M005)	0.8300	0.8775	0.4301	0.4423
XOR + AND + OR (M010)	0.8525	0.9000	0.3226	0.3362



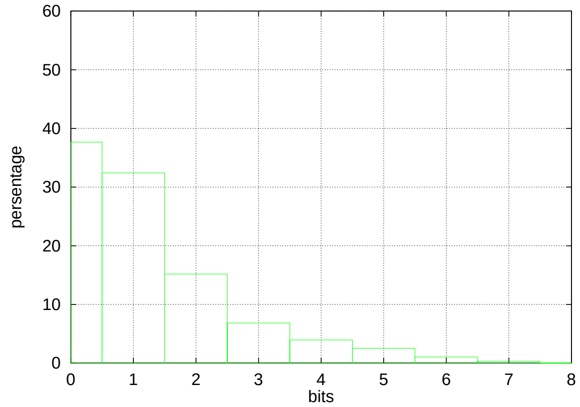
?^ 3.27: :GBgE,1~EY$N5sF0 (1000 @$Be4H$KJQ2=)



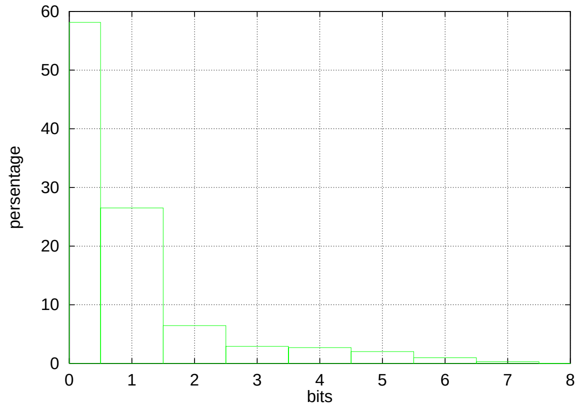
?^ 3.28: J?6QE,1~EY$N5sF0 (1000 @$Be4H$KJQ2=)



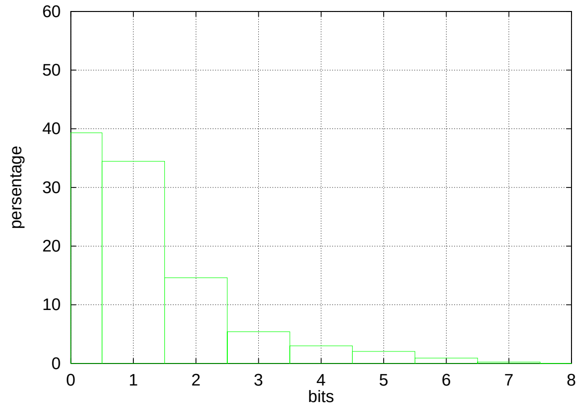
(i) 01K\:? GA (FMA3JQ0[N(10%)



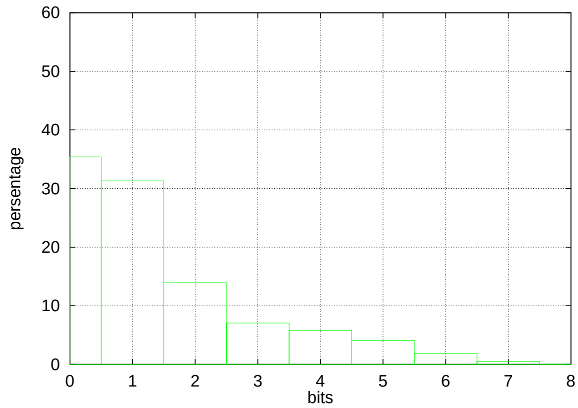
(ii) 01K\:? GA (FMA3JQ0[N(10% 8r49N(5%)



(iii) FsK\:? GA (XOR, FMA3JQ0[N(5%)



(iv) FsK\:? GA (AND, FMA3JQ0[N(10%)



(v) FsK\:? GA(XOR+AND+OR, FMA3JQ0[N(10%)

?^ 3.29: E,1~EYJQ2=;~$N01<4:w$"$?$j$N%S%C%HJQ2=$N2s?t

Bh 4 >O

Ds0F

4.1 F@il$?CN8J$K$D$$$F

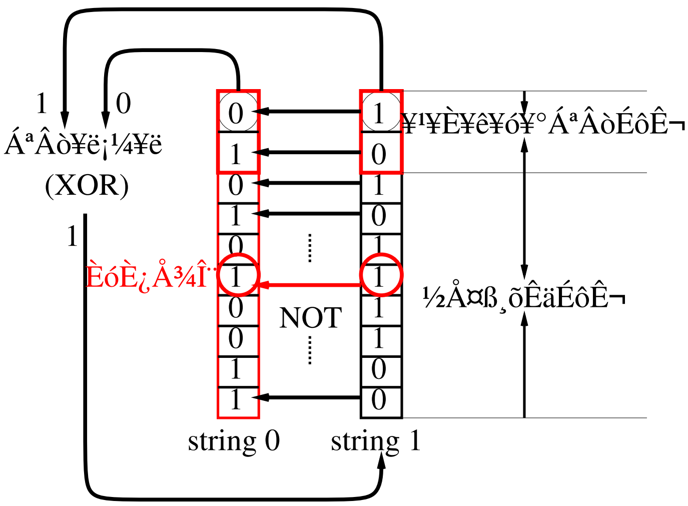
A0>O$GMM!9$JFsK\:? GA $rMQ$$$F%7%_%e%l!<%7%g%s$r9T$CF-$?!%$=$N7k2L!$8DBN?t$,0lK\
GA $NH>J,$Kb+$+$oi:!$$[HsINFsK\:? GA $,0lK\:? GA hj$b9b$$:GBgE,1~EY$r3MF@$
k3H,J,$+$C$?!%FsK\:? GA $N4D6-JQF0$KBP9kDI=>@-!$4h6/@-$N85$O!$EqBA$K3]$+iJ$
$_8uJdItJ,$rJ];}7F$$$k$+$iG"k3HO!$A0>O$N%7%_%e%l!<%7%g%s$+$i$b3N$+a?!%

7+$7!$@h$NFsK\:? GA $N%7%_%e%l!<%7%g%s$rDL7F!$0J2<$Nh&$J5?LdE@$,Ib>e7?!%$I
h&$J%S%C%HNs$rJ];}9lPh$$$N$@$m$&$+$H$$$&E@G"$k!%$D$^$j!$FsK\:? GA GO=E$_8u
ItJ,$rA*Br$G$-$k5!9=$,$"k,!$N>J}$N%9%H%j%s%0Cf$KB8:_$9$k=E$_8uJdItJ,$N%S%C%HNs$,F
G"kJiP!$$=$N5!9=$OA4$/0UL#$r@.5J$/$J$k!%$hCF!$EqBA$KGx5lK/$$=E$_8uJdI
$N%S%C%HNs$K2?i+$NM-8z$J%S%C%HNs$r3MF@!$J];}G-kh$&$K9k5!9=$,$"lP!$$5iK4
$NJQF0$KBP7F4h6/KJkNGO$J$$$+$H9M$(il$k!%

4.2 Ds0F:**Complemental GA - DNA** $N9=B$$r85K7$?AjJdE*$JFsK\:? **GA**

0J>eG"2?9M;!7k2Lhj!$0J2<$Nh&$J GA $r9M0F$7$?!%

?^ 4.1KD$$$F@bL@9k!%K\ GA $O!$%7%_%e%l!<%7%g%s$N0dEAE*A`:n$r9T$&CJ3,$G!$0J2<$N$
$&$J3H$r9T$&!%



?^ 4.1: Complemental GA (CGA)

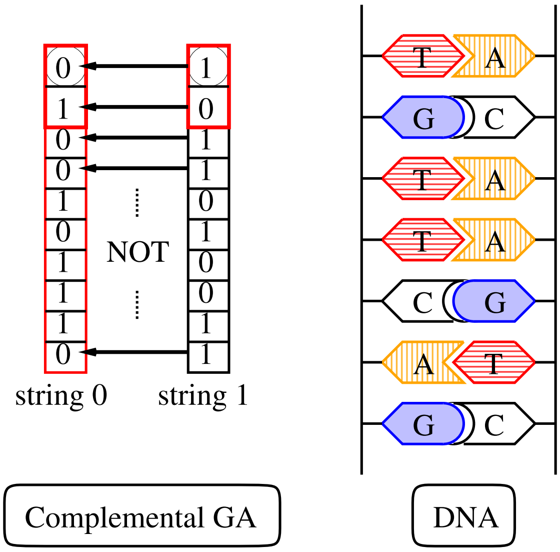
1. I>2ACM$,>e0L 20%$N8DBN$r 4 2s%3%T!<$7!$;RB9$N8DBNH9$k!%
2. ;RB9$KFMA3JQ0[N($K1~8?FMA3JQ0[$NA`:n$r2C$($k!%
3. string 1 $N%S%C%HNs$N NOT $r<h$j!$$=1r string 0 H9$k!%$3$NA`:n$rH?E>$H$$$&$3 $H$K$9$k!%$3$N$H$-!$$"$k3NN($G NOT $NA`:n$r2C$($J$$%S%C%H$r:n@.$9kh$&$K$9 $k!%$3$N3NN($rHsH?E>N($H$$$&3HK9$k!%
4. GA $N%k!<%k7hDjItJ,$rFI$_!$string 0 $,A*Br$5lkh&Ji!$string 1 $H string 0 $r F~$149$($k!%

%7%_%e%l!<%7%g%s$NI>2A2aDx$G$O!$string 1 $N%S%C%HNs$N$_$rI>2A9k3HKJk,!$$"$kIQ
$G string 0 $H string 1 $,F~$149ok!%

K\Ds0F$N:GBg$NL\E*$O!$EqBAK5i5lJ$$NN0hK"$k%S%C%HNs$K!$$Jsi$+$N;X8~@-r
i9$3$HK"$k!%$3$3$G$O!$$=$N;X8~@-$r%S%C%H$NH?E>$H$$$&A`:nKh$j<B8=$7$?!%

Complemental GA $H$$$&L>A0$NM3Mh$O!$2 K\$N%9%H%j%s%0$N%G!<%?$NFbMF$,AjJdE*$J4X78$r
@.7F$$$k$+$iG[1]"!$k(?^ 5.1)!%<B:]$N@8J*$N DNA GO!$%"%G%K%s (A) KBP7$F%A%_%s (T)!$
%0%"%K%s (G) KBP7$F%7%H%7%s (C) NAH_$GAjJdE*$JFs=E:?$r7A@.7F$$$k!%3l$O!$CGA $
$$$& 0 $H 1 $,AjJdE*$J4X78G"k3HKBP1~7F$$$k!%3Nh&$K CGA $H@8J*$N DNA HK$O
N`;wE@$,$"$k!%

[1]Complemental = AjJdE*!$JdB-E*



?^ 4.2: CGA $H<B:]$N DNA

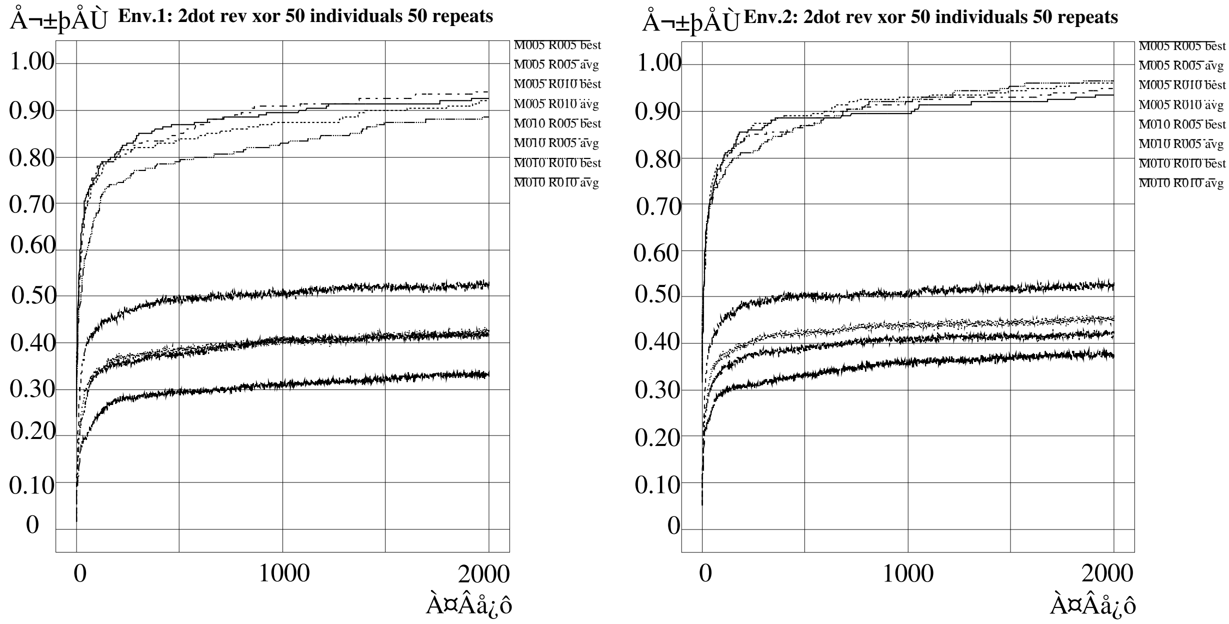
4.2.1 @EE*$J4D6-$G$N7k2L

CGA $NFC@-$r3NG’9k$?$a$K!$@EE*$J4D6-$GFMA3JQ0[N(!$HsH?E>N($N$=$1$>$1$r0J2<$NAH 9go;Nh$&$K@_Dj7?H-$NI>2A$r9TC?!%$=$1$>$1 50 ;n9T9T$$!$$=$NJ?6QCM$rHC$?!%

- FMA3JQ0[N(5%!$HsH?E>N(5%!%
- FMA3JQ0[N(5%!$HsH?E>N(10%!%
- FMA3JQ0[N(10%!$HsH?E>N(5%!%
- FMA3JQ0[N(10%!$HsH?E>N(10%!%

$=$N7k2L$r?^ 4.3$K<($9!%$J$*!$?^Cf$N!VM!W$OFMA3JQ0[N($r!$VR!W$O!$HsH?E>N($rI=$7$F $k!%(Nc !VM005!W$OFMA3JQ0[N(5%$r!$VR010!W$OHsH?E>N(10%$rI=$9!%)

4D6-1 $N:GBgE,1~EY$N6J@~$O!$FMA3JQ0[N(10%!$HsH?E>N(10%0J30$OF1$8$h$&$J<}B+$r8+$ $F$$$k!%J?6QE,1~EY$OFMA3JQ0[N(!$HsH?E>N($,Dc$$$[$&$,9b$$!%4D6-2 GO!$:GBgE,1~EY$N< $OFMA3JQ0[N($,9b$$$HCY$$!%$^$?!$:G=*E*$J<}B+$OHsH?E>N($,9b$$$bN,$h$$!%J?6QE,1~EY$ JQ0[N($,Dc$$$bN,9b$/$J$k!%$^$?!$FMA3JQ0[N(5%!$E><LFMA3JQ0[N(10%$N$[$&$,FMA3JQ0[10%!$HsH?E>N(5%Nh$j9b$$!%



(i) 4D6- 1

(ii) 4D6- 2

?^ 4.3: CGA $N5sF0 (2000 @$Be)

4.2.2 F0E*$J4D6-$G$N7k2L

<!$K4D6-$NJQ2=KBP9$k%7%_%e%l!<%7%g%s$r9TC?!%$=$1$>$l 50 ;n9T9T$$!$$=$NJ?6QCM HC$?!%

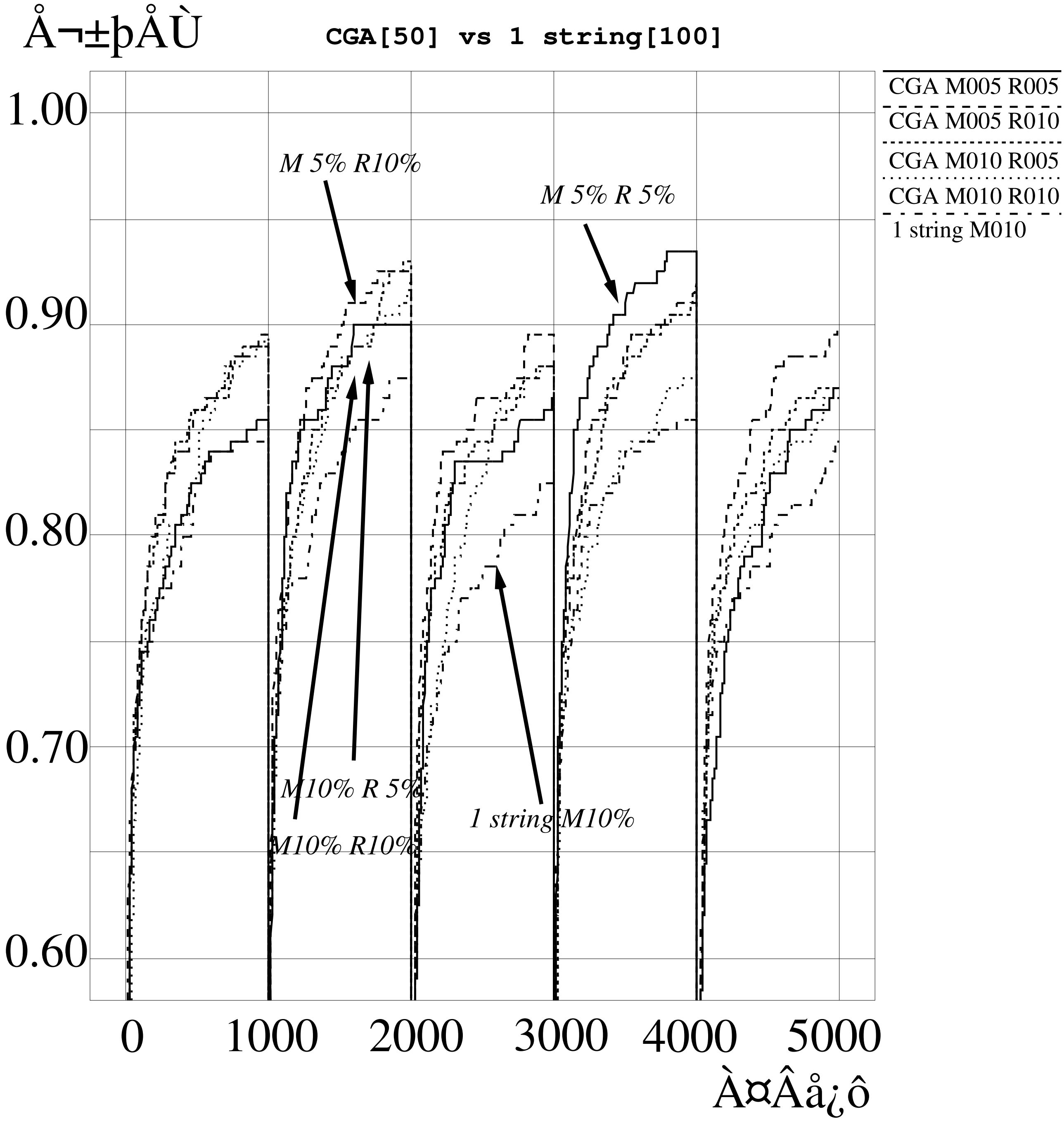
?^ 4.4!4.5,$=$N7k2LG"$j!$Hf3SN?$a0lK\:?$N7k2L$bF~$lF"$k!%FC$KCmL\$7$?$$$N$ FMA3JQ0[N(5%!$HsH?E>N(10%$NH-G"$k!%3000 $+$i 4000 @BeNH-$N:GBgE,1~EY$,NI$$J} $+$iFsHVL\$@C?0J30$O!$<}B+$NB.$5!$:G=*E*$J:GBgE,1~EY$N9b$5Hb:G$bNI9%$J7k2L$r<($ 3HG"$k!%

4.3 4{B8$N%b%G%k$H$NHf3S

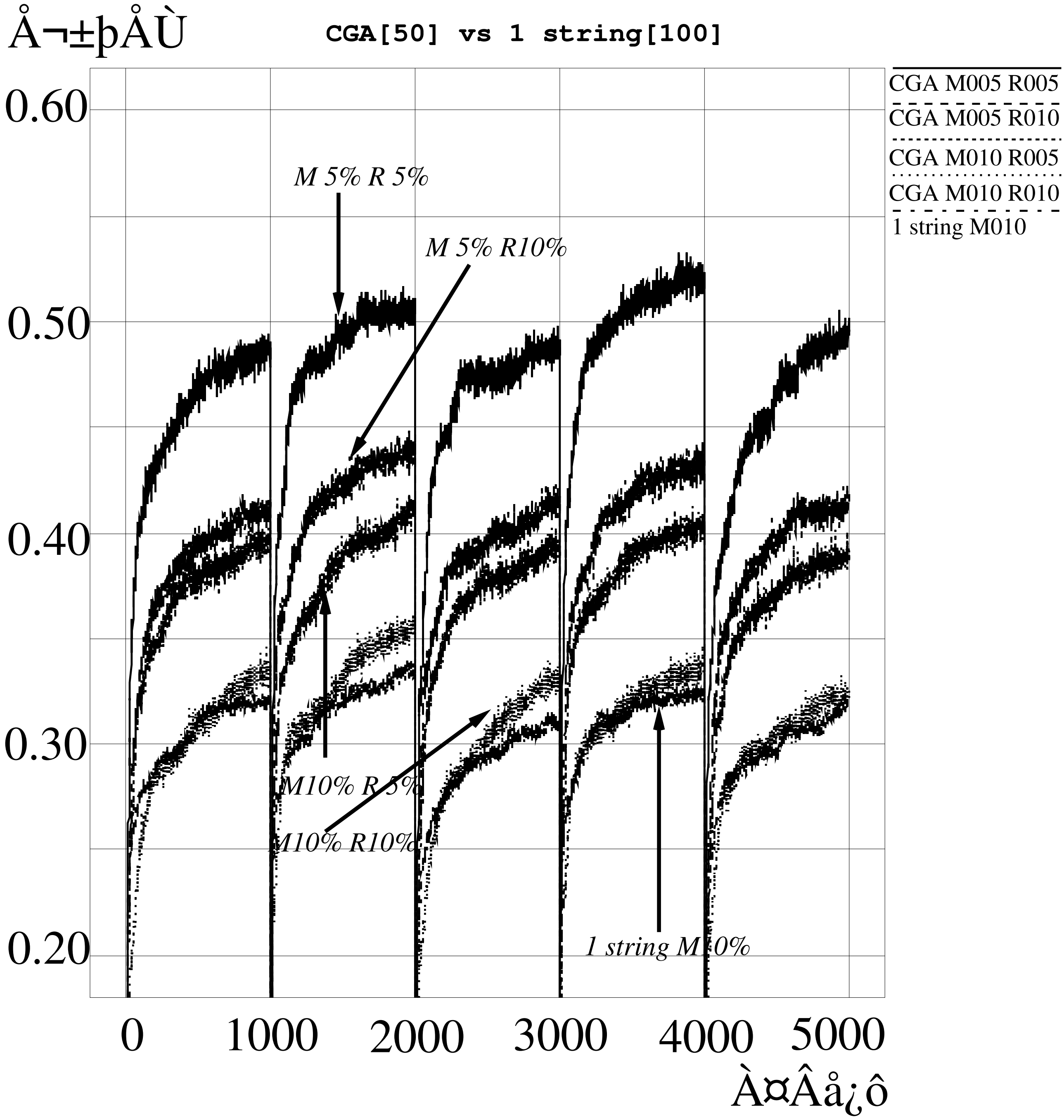
Ds0F7? CGA $H0lK\:? GA!$$5iKBh 3>O$N<B83$G!$4D6- 1 $G:G$b9b$$:GBgE,1~EY$r<($7$ XOR+AND+OR!$4D6- 2 $G:G$b9b$$:GBgE,1~EY$r<($7$? AND $N7k2L$rHf3S9k!%?^ 4.7K= 1>1N:GBgE,1~EY$r<($7!$?^ 4.8$KJ?6QE,1~EY$r<($9!%

$^$?!$2000,3000,4000,5000 @$BeL\$N3F7k2L$rJ?6Q$7$?$bNrI= 4.1$K<($9!%

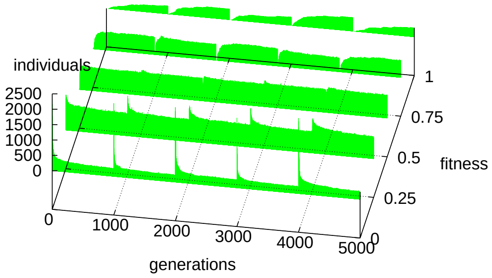
?^ 4.7$r8+$k$H!$4D6- 2 GO CGA $NE,1~EY$OB>$N GA!$FC$K AND %k!<%k$N;~$HF1$8$+>/!99b $$$0$i$$$G$"$k!%7+$7!$4D6-JQF08e$N4D6- 1 GOB>$N GA hj$bE,1~EY$O 0.4 $+$i 0.6 0i$



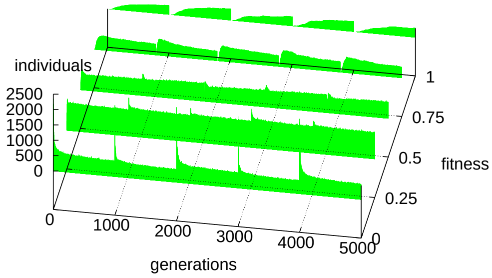
?^ 4.4: CGA $N:GBgE,1~EY$N5sF0 (1000 @BeGJQ2=)



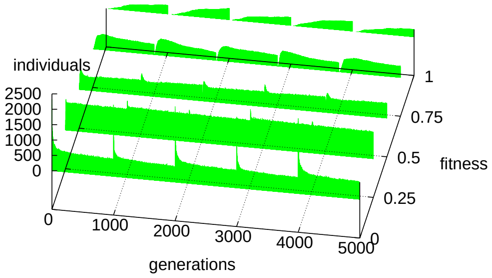
?^ 4.5: CGA $NJ?6QE,1~EY$N5sF0 (1000 @BeGJQ2=)



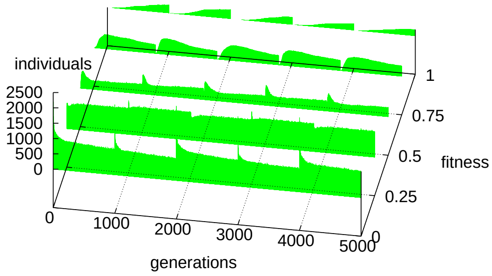
(i) FMA3JQ0[N(5% HsH?E>N(5%



(ii) FMA3JQ0[N(5% HsH?E>N(10%



(iii) FMA3JQ0[N(10% HsH?E>N(5%

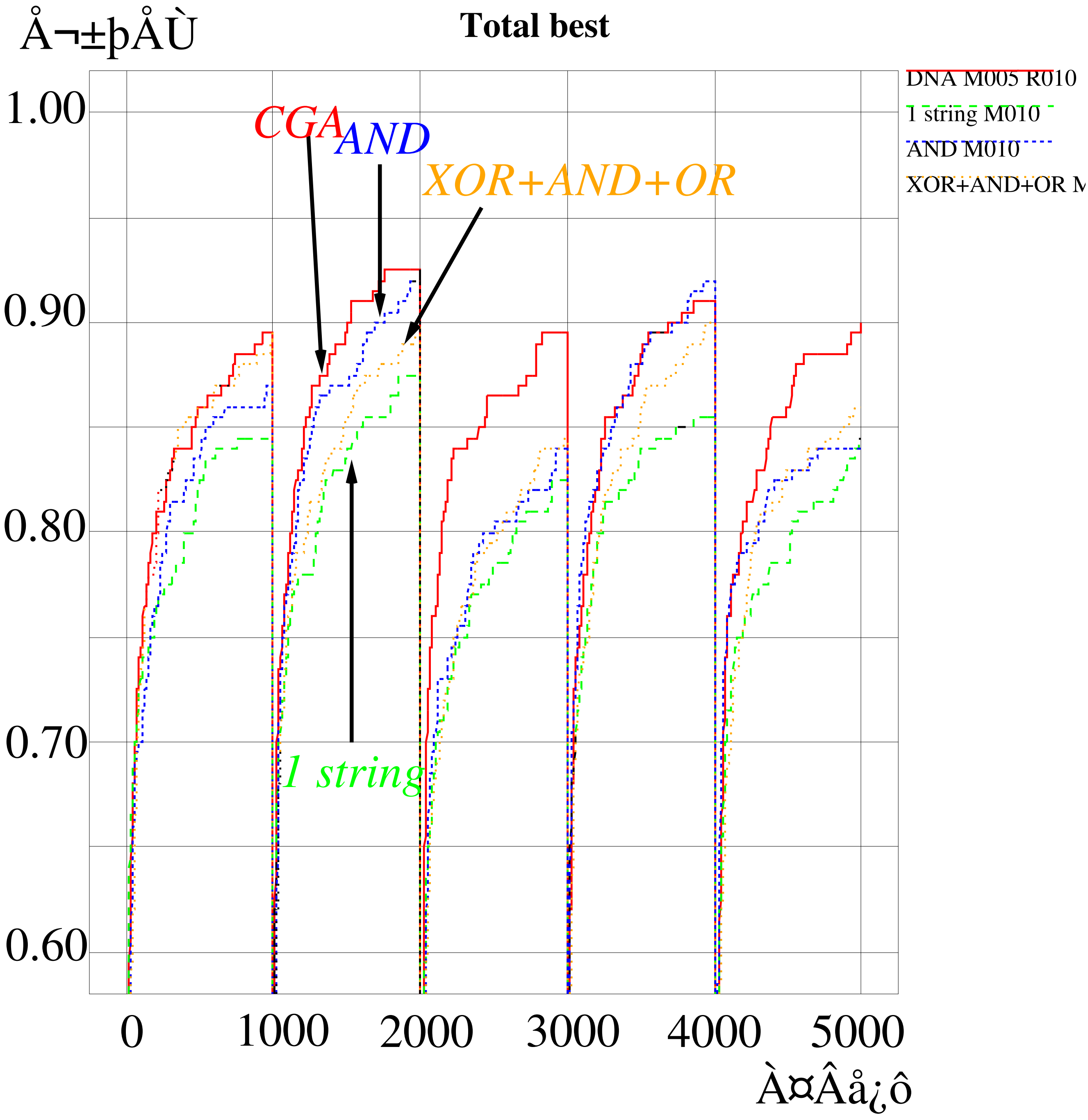


(iv) FMA3JQ0[N(10% HsH?E>N(10%

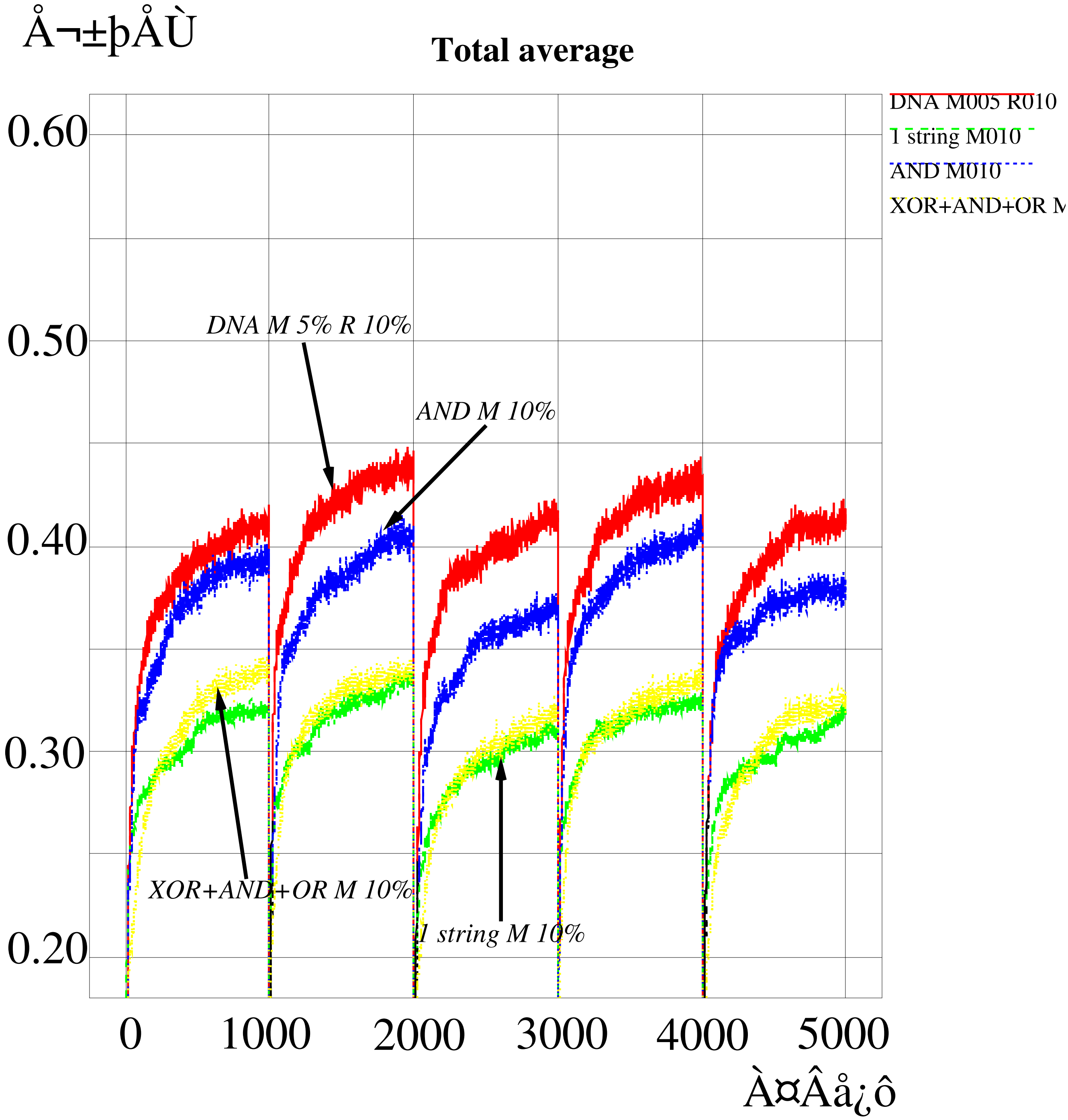
?^ 4.6: CGA $N4D6-JQF0$KBP9k8DBN?t$NJ,I[

I= 4.1: CGA HNHf3S (Best $O:GBgE,1~EY!$Avg $OJ?6QE,1~EY)

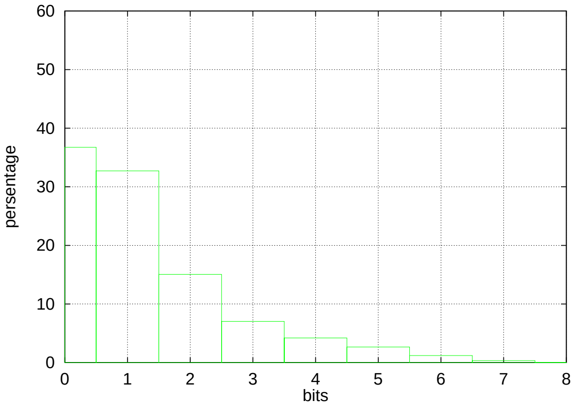
rule	Best(4D6- 1)	Best(4D6- 2)	Avg(4D6- 1)	Avg(4D6- 2)
1 string (M010)	0.8350	0.8650	0.3164	0.3269
AND (M010)	0.8400	0.9225	0.3711	0.4019
XOR + AND + OR (M010)	0.8525	0.9000	0.3226	0.3362
CGA (M005 R010)	0.8975	0.9175	0.4142	0.4374



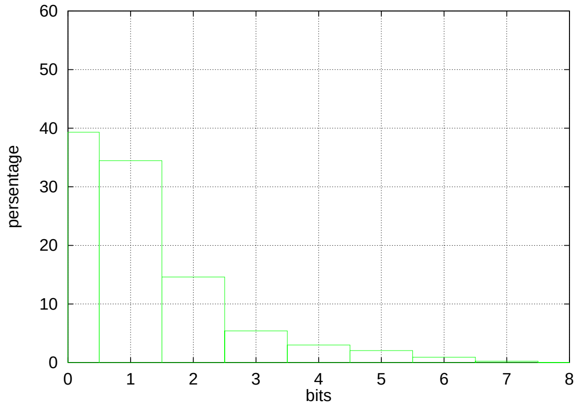
?^ 4.7: CGA HN:GBgE,1~EY$NHf3S (1000 @$Be$GJQ2=)



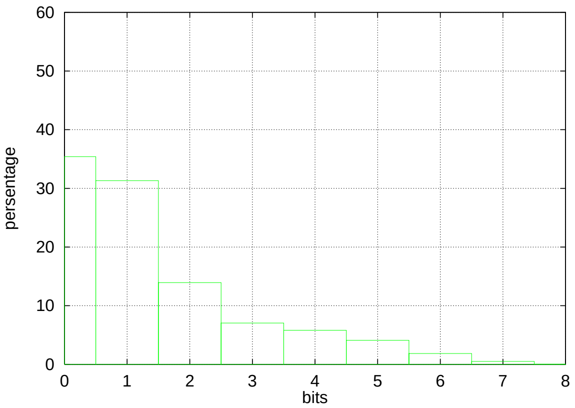
?^ 4.8: CGA HNJ?6QE,1~EY$NHf3S (1000 @$Be$GJQ2=)



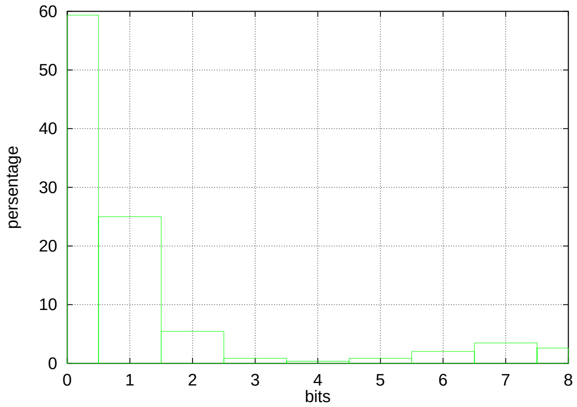
(i) 0lK\:? GA (FMA3JQ0[N(10%)



(ii) FsK\:? GA (AND, FMA3JQ0[N(10%)



(iii) FsK\:? GA(XOR+AND+OR, FMA3JQ0[N(10%)



(iv)CGA(FMA3JQ0[N(5%!$HsH?E>N(10%)

?^ 4.9: E,1~EYJQ2=;~$N0l<4:w$"$?$j$N%S%C%HJQ2=$N2s?t

$O9b$$!%3N%G!<%?$O 50 ;n9T$NJ?6QG"k3Hr9M$($k$H!$CGA $OBgJQDI?o@-$,h/!$4h6/ $"$k$H8@$($k!%$^$?!$?^ 4.8$r8+$k$H!$J?6QE,1~EY$bB>$N GA hj9b$$!%3l$O!$B>$N:GBgE, EY$N9b$$ GA $OHf3SE*9b$$FMA3JQ0[N($GC5:w$r9T$$!$$=$N7k2LJ?6QE,1~EY$rMn7F7^$&$N$ 3S9k$H!$CGA $O0[$JCF$$$k!%bAms!$B>$N GA $bFMA3JQ0[N($r2<2l$PJ?6QE,1~EY$O >:9k$,!$$=lG$O:GBgE,1~EY$,Dc2<7F7^$&$3H,!$A0>O$N<B83$+$i$b3NG'$5$1$F$$$k! $NE@!$CGA $O:GBgE,1~EY!$J?6QE,1~EY$NAPJ}$r9b$/0];}$G$-$k!%

?^ 4.9$O!$E,1~EY$,JQ2=$7$?$H$-$N0l<4:w (8 %S%C%H) $"$?jN?F8DBN$H;R8DBN$N0c$$$r%0% %UK7$?$bNG$"$k!%<B:]$K<4:w$N=E$_$r5,Dj7?!$$D$^$jI=8=BNHJC?%S%C%HNs$rBP> 7F$$$k!%50 ;n9T$NAmOB$r@]$j!$$=lrI4J,N(K7F^Ha$?!%$3lh$j!$4{B8$N0lK\:? G FsK\:? GA GO%S%C%H$N?t$,BgI}K+okh&$JJQ2=$O$[$HsIG-$J$$$3H,o+$k!%$7 $7!$CGA GO 1!$2 %S%C%H$NJQ2=Kh$k6I=jE*$JC5:w$H!$6!$7!$8 %S%C%H$NJQ2=$Khk9-0hE $JC5:w$,9Tol$F$$$k3H$,J,$+$k!%$3N3H,2r$NC5:w@-G=$KBg$-$/4sM?7F$$$k2DG=@-$,$

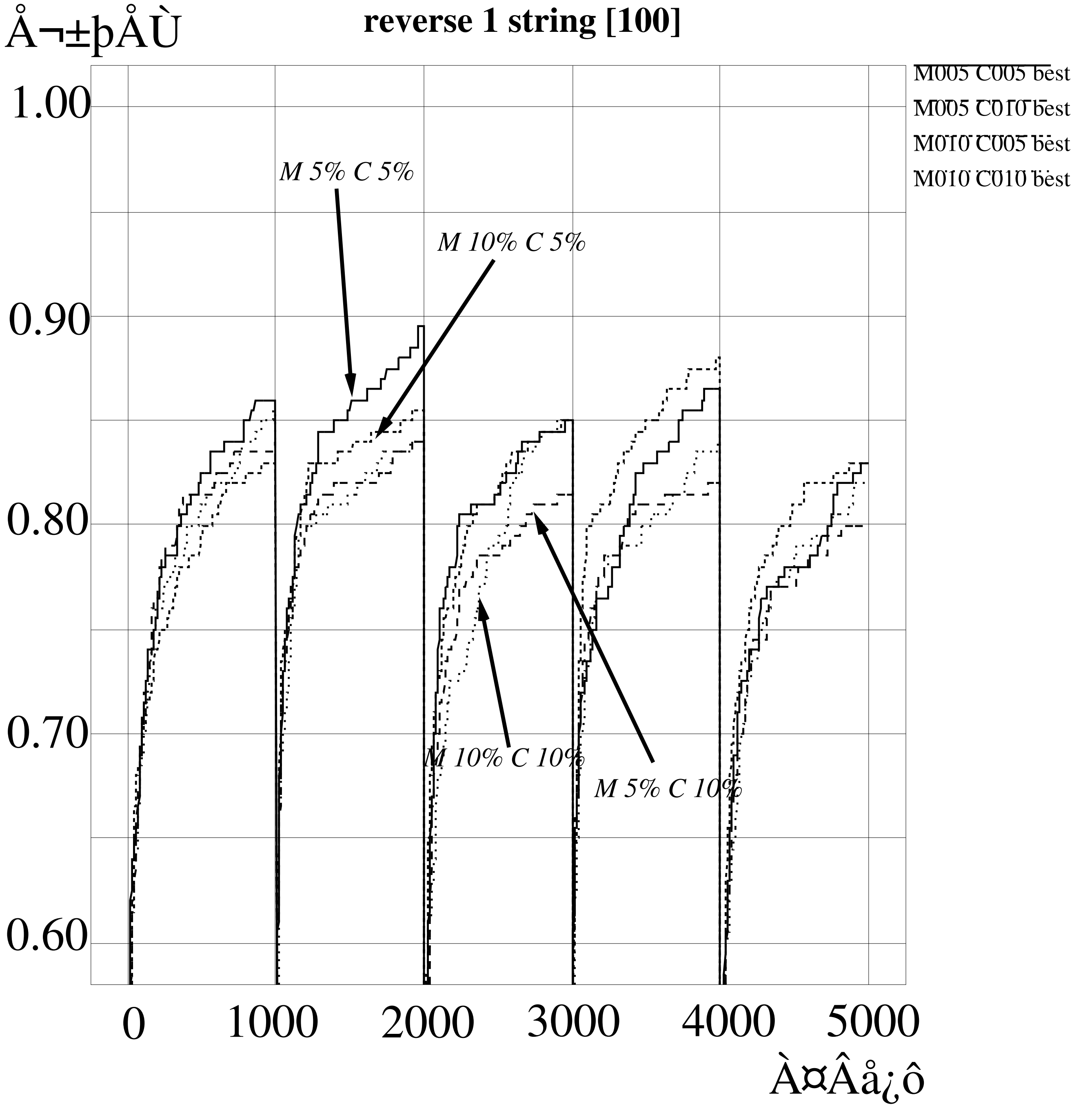
$=$N2DG=@-$r8!>Z$9k?$a!$0lK\:? GA $K CGA $G9T$C$?H?E>$K6a$$A`:n$rF3F~$7$FI>2A$r$H F_$?!%0J2<$N>r7o$G%7%_%e%l!<%7%g%s$r9TC?!%$=l>$l 50 ;n9T9T$$!$$=$NJ?6QCM$rHC

- FMA3JQ0[N(5%!$H?E>N(5%!%
- FMA3JQ0[N(5%!$H?E>N(10%!%
- FMA3JQ0[N(10%!$H?E>N(5%!%
- FMA3JQ0[N(10%!$H?E>N(10%!%

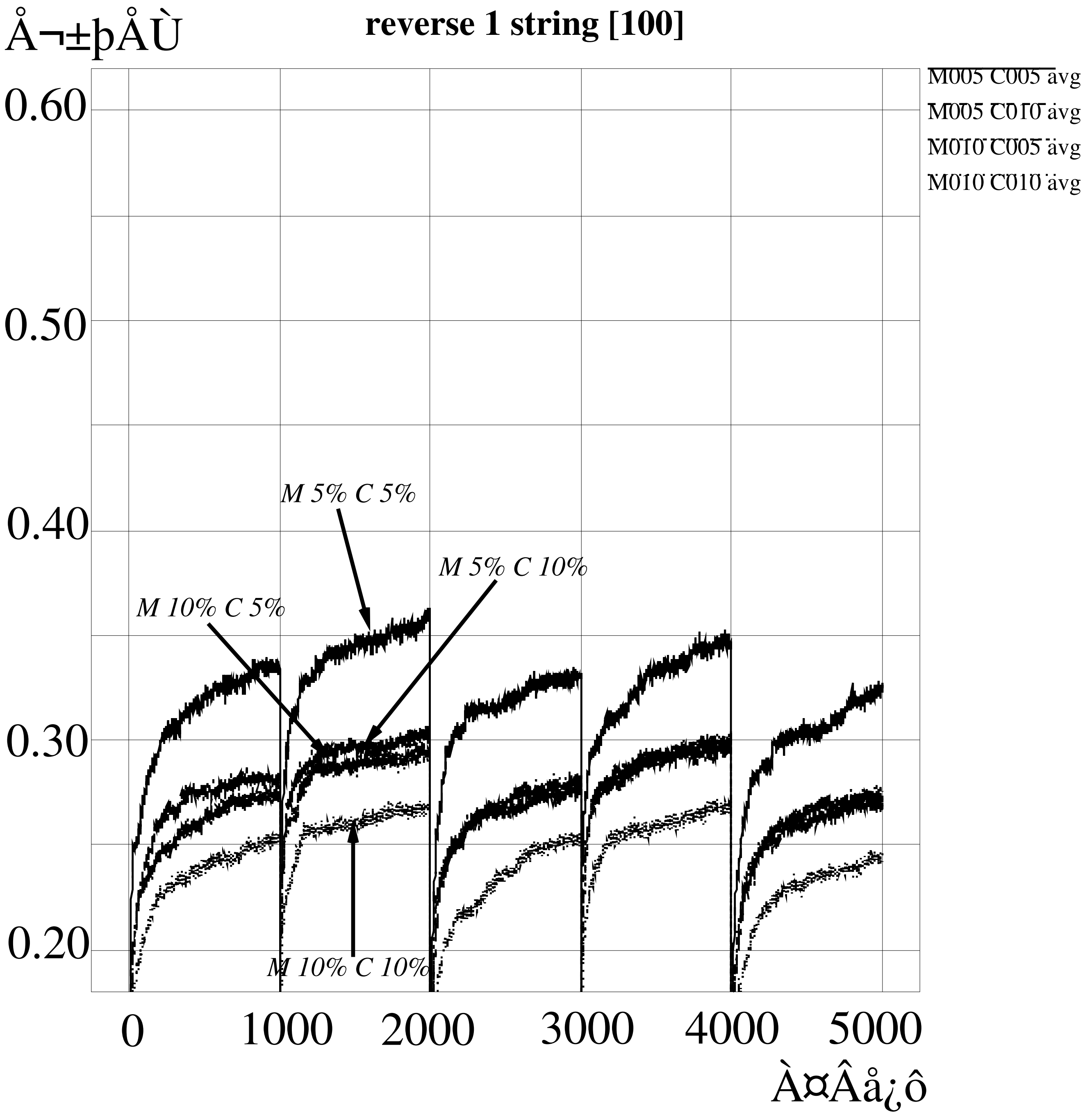
0lK\:? GA K*1kH?E>$O0J2<$Nh&$K9T$C$?!%

1. FMA3JQ0[$r9T$C$?8e!$=E$_ItJ,1 %;%C%H$4HK!$0 $+$i 1 $^$G$NMp?t$r@]$k!%
2. $=$NCM$,H?E>N(0J2<$JiP!$0J2<$NA`:n$r9T$&!%H?E>N(0J>eJi$P2?$b7J$$!%
   (a) =E$_ItJ, (8 %S%C%H) $N 1 %S%C%H$4HK!$0 $+$i 1 $^$G$NMp?t$r@]$k!%
   (b) $=$NCM$,H?E>N(0J>e$JiP!$%S%C%H$rH?E>5;$k!%
   (c) $=$&GJ1l$P!$2?b7$J$$ (%S%C%HO=N^$^)!%

?^ 4.10$H?^ 4.4$rHf3S7F$_$k$H!$0lK\:? GA(H?E>D-) $H CGA $N:GBgE,1~EY$N:9$O!$4D6- 2 $G 0.2!A0.3!$4D6- 1 $K;j$CFO 0.5!A0.8 G"C?!%3NHf3SKh$j CGA $N:GBgE,1~EY$N9b$5 $O!$%S%C%H$NH?E>A`:n$N$_$,860xJNGOJ/!$$=lHFsK\:? GA $NFCD'$G$"$kEqBAK5i5 $J$$NN0h$NB8:_$H$$$&!FsD$NMWAG$NB8:_$,860x$G$"$k$H8@$($k!%



?^ 4.10: 01K\:? GA(H?E>D-) $N:GBgE,1~EY$N5sF0 (1000 @BeGJQ2=)



?^ 4.11: 01K\:? GA(H?E>D-) $NJ?6QE,1~EY$N5sF0 (1000 @BeGJQ2=)

0J>e$N;vJA$h$j!$CGA $OFMA3JQ0[$Khk6I=jE*$J2r$NC5:w$H!$%S%C%H$NH?E>5!9=$Khk9-
E*$JC5:w$r7sMHw($?!$4D6-$NJQ2=$KBP7F4h7r$J!$?7$7$$FsK\:? GA G"k3Hr8!>ZG-
:#2s$N8!F$$G$O<g$K:GBgE,1~EY$K>GE@$r9JCF GA $N@-G=$rC5CF$-$?$,!$J?6QE,1~EY$,=EMW
LdBjGO!$CGA KO5iJk2DG=@-$,$"kH$$$(k@m&!%

Bh **5** >O

5DO@$H:#8e$N2]Bj

5.1 5DO@

Ds0F7? Complemental GA(CGA) $O!$@EE*$J4D6-2<$G$OI,$:7b0lK\:? GA hj@-G=$,NI
$+$C$?$o1GOJ$$$,!$F0E*$J4D6-2<GO0lK\:? GA $O8@$&$K5Z$P$:!$4{B8NI$NFsK\:? GA
jbDI?o@-!$4h6/@-$O9b$$$3H,<(5l$?!%$=$NMW0x$H7F!$<g$K0J2<$NFsE@$,5s2ilk

- EqBAK5i5lJ$$%S%C%HNs$rJ];}$G$-$k!%
- %S%C%H$NH?E>A`:n$r7F$$$k!%

hC$F!$$3$NFsE@$K>GE@$r9J$C$F!$$3$3$G$N9M;!$H7?$$!%

5.1.1 EqBAK5i5lJ$$$3HN0U5A

EqBAK5i5lJ$$NN0h$rFsK\:? GA $OJ]M-$7$F$$$k!%3NNN0h$NB8:_$KhkM-8z@-$OK\8&
K*1k%7%_%e%l!<%7%g%sKhCF==J,$K3NG'$G$-$?!%$"$k$^$H$^$C$?C10L$rGK2u9k3H$
$^$k4H<h$j49$(ilk3$H<+BN$,BgI}$J@-G=8~>e$K4sM?7F$$$ko1GO$J$$$3HO!$0lK
GA $K=E$_ItJ,$r<h$j49$($ilk5!9=$rF3F~$7$?<B83$KhC$F3NG'$7$?!%

GO!$$J$<EqBA$K>pJs$,$5i5lJ$$$H$h$$$N$@$m$&$+?

0lDNM}M3$O!$I=8=7?H7$F;HMQ$5lk>pJsH^C?$/0[$J$k>pJs$rC_@QG-kN$G!$0l
:? GA $HHf3S$7$FF10l;~4VFb$G$NC5:wNN0h$r9-$/$9k3H,G-k?aG$"$k$H9M$(il$k!
$?JL$NM}M3H7FO!$$=l^$GI=8=7?$H7F;HMQ5l$?=E$_8uJdItJ,$,!$I=8=7?H7$F;HMQ$
J/JC$?>l9g$K$O!$$=3K$"$C$?>pJs$O;DkN$G5-21AuCV$HF1$88=>]$,5/3k$+$iHb9M$
lk!%

FsK\$"$k%9%H%j%s%0$r!$$INh$&$JIQEY$GA*Br$9k+KD$$$F$O!$$=$NA*Br%k!<%k$rMM!9$
$($F<B83$r9T$C$?!%$=$N7k2L!$XOR JI$N%9%H%j%s%0 2 K\$r8xJ?$K07$&%k!<%kGOJ/!$AN
$H$$$&!$%9%H%j%s%0 2 K\$r:9JL2=9k%k!<%k$NJ}$,Hf3SE*7k2L$ONI9%$G$"$C$?!%$D$^$j!$C1=
%9%H%j%s%0$r 2 K\MQ0U$9k@1N GA hj$b!$%9%H%j%s%0$N 2 K\$N$&$AJRJ}$r%a%$%sKb$&

J}$r%5%V$H7FMQ$$$k GA $NJ}$,$h$$$H$$$&3H$,8@$($k!%$3lO!$GA $NFCD'$HJ;$;$F9M$(
$H!$%a%$%s$GFMA3JQ0[N(Kh$j6I=jE*$JC5:w$r9T$$!$%5%V$G6I=jE*$JC5:w$G$OC5:w$9$k2DG=@
Dc$$NN0h$rC5:w$G$-$k9-0hE*$JC5:w$r@.$7F@$F$$$k$+$iG"kH9M$($ilk!%

5.1.2 H?E>A`:n$NM-8z@-

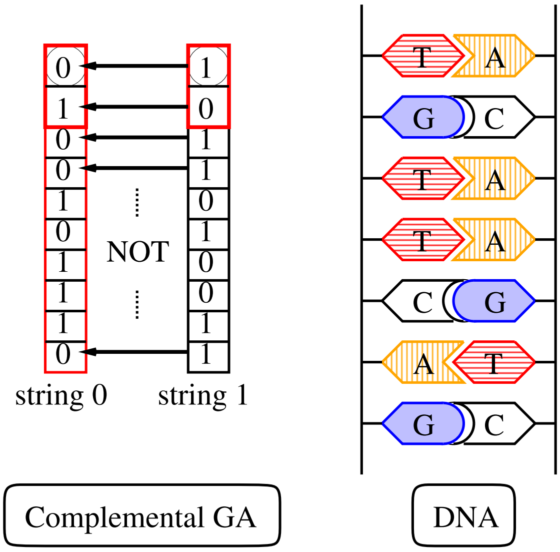
A0@a$N5DO@$G!$EqBA$K5i5l$J$$NN0h$,!$9-0hE*$JC5:w$r9k$?$a$KM-8z$G$"$k3H$OM
G-$k!%$7$+$7!$$=N;C+$/EqBA$K5i5l$J$$NN0h$K!$$b$7EqBA$K5i5l$?NN0h$H$^$
$/F1$8>pJs$,$"C?iI$&$JkG$"$m$&$+!%EvA39-0hE*$JC5:w$OIT2DG=HJ$j!$FMA3JQ0[K
6I=jE*$JC5:w$rCf?4$K@.$i6k$rF@$J$$!%

$3$3$GL@3N$KJkNO!$EqBA$K5i5l$J$$NN0h$KB8:_$9$k>pJs$N<A$,LdBj$G$"$k3H$O
$k!%$3$NNN0h$KB8:_9k>pJsH7$F!$$INh$&$JbN$,M}A[E*$JNG$"$m$&$+!%3NNN0h$N>
$O!$9-0hE*$JC5:w$K;HMQ9k3H$rL\E*$H7F$$$kN@$+$i!$$G$-$k$@$1EqBAK5i5l
0hK"$k>pJs$H$O0[$J$kJ}$,K>$^$7$$!%Nc$($P!$$"$kJRJ}$N%9%H%j%s%0$N>pJs$, 11111111 J
$P!$00000000 $,:G$b0[Jk>pJsHJkG$"$m$&!%$3Nh$&$J9M$($K4pE-F3F~7? CGA G"$
$,!$$O$?$7$F7k2L$O4{B8$N0lK\:? GA!$FsK\:? GA hjNI9%G"C?!%FC$KF0E*$J4D6-K*$$
$OHs>o$KDI?o@-!$4h6/@-$HbKNI9%G"C?!%3l$O!$$b7"$k4D6-$K$*$1$k%S%C%HNs$N@52
11111110 Ji$P!$EvA3 11111111 $+$iFMA3JQ0[Kh$j6I=jC5:w$9kN$,H/8+$9$k2DG=@-$O9b$$!
7+$7!$00000001 Ji$P!$0lC6 11111110 $K<}B+$7F7$^$C$? GA $N%S%C%HNs$,FMA3JQ0[Kh$k
C5:wN_G3lrH/8+9k3NN($OHs>o$KDc$$!%7+$7!$CGA G"lP!$H/8+$9kN$OMF0W$G
m&!%

5.1.3 @8J*$N DNA HNN`;w@-

K\8&5f$GDs0F$7$? CGA $O!$:#$^$G$K=R$Y$?$h$&$K<g$K9-0hC5:w$r9T$&$?aK9M0F7?5!9=
$"$C$?!%$7$+$7!$$3$3$GCmL\$9Y-$O<B:]$N@8J*Gb;w$?$h$&$J5!9=$,$"k3HG$"$k!%$=$
DNA G"$k (?^ 5.1)!%<B:]$N@8J*$N DNA $O!$%"%G%K%s (A) $H%A%_%s (T)!$%0%"%K%s (G) $H%7%H
%7%s (C) NAH_GJCF$*$j!$$=l>$lAjJdE*$J4X78G"$k!%$3lO!$CGA $G$$$& 0 $H 1 $,A
JdE*$J4X78$G$"$kNHN`;w7F$$$k!%$^$?APJ}HbFs=E:?9=B$$G$"$k!%

<B:]$N DNA $,$3Nh$&$J9=B$$r7F$$$kM}M3KD$$$F$OL$$@$K2>Dj$N0h$rC&$7$J$$!%$@$
FsK\:?9=B$$r7F$$$k3H!$$=$N>pJs$OAjJdE*J3Hh$j!$DNA J#@=;~$K>pJs$,8mCFEAC#
lk3NN(rDc/9k3H$,2DG=$G$"$ki7$$ [Joh94]!%3Nh&J3HKhj!$DNA O=$NA4D
rIsI$sD9$/9k3H$,2DG=$HJj!$$h$jJ#;($J9=B$$rbD@8J*$N@_7W?^$r5,Dj9k3H$
G=HJC?i7$$!%3l$KBP$7!$0lK\:?$G$"$k RNA $r0dEA;R$H7FMQ$$$k0lIt$N%&%$%k%9G
RNA $OIQHK$K>pJs$,Be$o$j!$M-8z$J>pJs$NJ];}$,MF0W$GOJ$$!%hC$F RNA N_$r0dEA;R$



?^ 5.1: CGA $H<B:]$N DNA

7F;HMQ9kN_GOJ#;($J9=B$$r;}$D@8J*$r5,DjG-$k=j$^$G!$$=Nh$&$J>pJs$rJ];}$G$

MFNL$r3NJ]$G$-$kD9$5$^GOJi$J$$!%7+$75U@bE*$K$$$&$H!$>pJs$,IQHK$KBeok$?$a4D6

JQ2=KOBP1~7d9/!$MM!9$J0!<o$,=P8=$7d9$$!%

$^$?!$%9%H%j%s%0$NIAirA*V+!$$H$$$&OC$@$,!$<B:]$N DNA GINh$&$K7FA*Br$7

$$$k$+$O$^$@o+CF$$$J$$!%

INh&$J0dEA$N7ABVrHm&Hb!$$=1JjND9=j$,B8:_$9kN$G!$$I$NJ}K!$,:Gbh$$

$H$$$&C1=c$J5DO@$O@8J*GO$"$j$($J$$$h$&$@!%

5.2 :#8e$N2]Bj

K\O@J8$GDs0F$7$? CGA $OHf3SE*@EE*$J5!9=Cf$G;HMQ$7$?!%6qBNE*$K$$$&$H!$=E$_8uJdItJ,

8%S%C%H4H$KH?E>A`:n$rE,MQ9kh&K7F"C?!%$3$1rb$7A4%S%C%HNs$KBP7F0l2sM

kh$&$K;HMQ7?H9kH!$$"$^$j$KJQ2=$,7c$7$9$.$F!$<B:]>e$OH?E>$N8z2L$,8=1J$$$G$

$&!%H?BP$K:Y$+$/dj9.Fb$$$1$J$$!%hC$F!$:GE,$JE,MQNN0h$H$$$C$?$bN,B8:_9k$

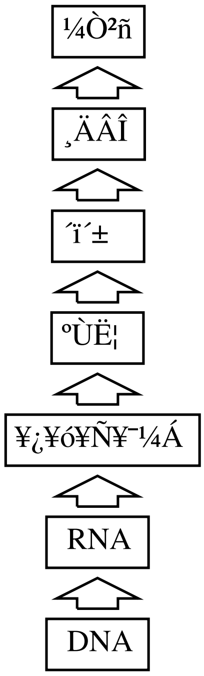
o1k,!$LdBj$K0MB8$9$kG"m&!%$^$?!$%K%e!<%i%k%M%C%H%o!<%/$N=E$_$r5,Dj9k$H$$$

3d$+$i9M$($k$H!$K\ CGA $O%K%e!<%m%s$N<4:w4V$N4X78$rA4$/9MN8$7$F$$$J$$!%3NE@KD$$

$O!$KLLn$,9T$C$?J8K!%(%s%3!<%IK! [Kit90, KLLn93b, Kit95] Nh$&$JJ}K!HAH_9go;kI,MW,

$"$k!%

:G8e$K!$@8J*$N?J2=%b%G%k$H7F9M$($F$_$?$$!%@8J*KO!$9=B$E*$K3,AX@-$,B8:_9k(?^ 5.



?^ 5.2: @8J*$N3,AX@-

K\8&5fGO!$<g$K DNA!$RNA $NItJ,$+$i8DBN$^GN%l%Y%kKD$$$F07C?3HKJk,!$@
J*$N%b%G%k$H7FO"$^$jKbIO<eG"k3HO4V0c$$$J$$!%DNA $N9=B$$rLO7?$@$1$GK\
5fNh$&$KNI9%$J7k2L$,F@il$?$3H+ib!$@8J*$N5!9=KO9)3XE*Kb7WjCNl$J$$B8:_2
$,B8:_$9$k!%@5LL$+i3$N@8J*$N3,AX@-KD$$$F07C?8&5fO^$@>/$J$$ [MNP96] $,!$8&5f%F
%^H7FOHs>o$K6=L#?<$$$bNG$"$k$H3N?.$7$F$$$k!%$$$El3Nh$&$J%F!<%^$r07$&H-
K\8&5f$,$=$N0lC6$KJlPh$$$H;W$&!%

Bh **6** >O

7kO@

K\O@J8GO4D6-JQF0KBP9$k?J2=%b%G%k$H7F!$FsK\:?$N GA $rCf?4$H7?bN$r07$C$?!% K\:?$N GA $O0lK\:?$N GA hjbAm8$F4D6-$NJQF0KBP9$kDI?o@-!$4h6/@-$ONI9%$G$"$C$?!% $K!$FsK\:?N&AIAi$rA*Br$9k+$r7hDj$9$k%k!<%k$KhjDI?o@-!$4h6/@-$OJQ2=7?!%$ 7k2L!$AND %k!<%k$JIN!$FsK\:?$rJ?Ey$K07$&NGOJ$/!$JRJ}$r%a%$%sH7$F!$$b$&JRJ} %5%V$H7FMQ$$$k%k!<%kN[$&$,FsK\:?$rJ?Ey$K07$&%k!<%k$hjb9%7k2L$r@8$_=P7?!%7 LdBjE@H7$F!$EqBAK5i5lJ$$NN0hK"$k>pJs$N<A$,$h$/$J1l$P!$$;C+$/$NFsK\:?$ B$$bM-8z$K:nMQ$7$J$$$3H,H=L@7?!%

$=$3$G!$EqBAK5i5lJ$$$b$&0lK\$N%9%H%j%s%0$KM-8z$J%S%C%HNs (>pJs) $r@8$_=P$9 Com plemental GA(CGA) $H$$$&?7$7$$FsK\:?$N GA $rDs0F$7!$0lK\:?$N GA!$4{B8$NFsK\:?$N GA NIlhjb4D6-JQF0KBP9$kDI?o@-!$4h6/@-$,9b$$$3Hr%7%_%e%l!<%7%g%srDL8$F<B>Z$ F@il$?7kO@$r$^$Hak$H!$Bg$-$/0J2<NDLjG"$k!%

- 0lHL$K!$FsK\:? GA $O0lK\:? GA hj8DBN?t$,>/J/$Fbh$$<}B+r_$;$k3H$r3NG 7?!%
- FsK\:? GA K*$$$F!$EqBA$K5i5l$J$$NN0h$NB8:_!$$*hS$=$N>pJs$N<A$,=EMWG"$ 3H$r<($7$?!%
- Complemental GA $H$$$&%9%H%j%s%0$r 2 K\;HMQ$9$k GA H7$F?7$7$$J}K!$rDs0F$7!$4{ B8$NFsK\:? GA hjM-8zG"k3Hr<(7?!%

<U<-

K\8&5f$N5!2q$rM?$($i$l!$$^$?:)@ZCzG+$J$4;XF3$r$$$?$@$-$^$7$?7DXf5A=NBg3XM}9)3XIt6

=j ??M}M: 5R0w65<x$K?4$+$i?<$/46<U$$$?7^$9!%

K\8&5f$K4X$75.=E$J$4<(:6$rD:$-!$$^$?$3$l0J>e$J$$$[IKF|:"$NLLE]$r8+$FD:$$$?!$7DX

=NBg3XL$Mh3+Bs%W%m%8%'%/%H >>NS 7D ;a!$7DXf5A=NBg3XM}9)3X8&5f2JGn;N2]Dx :4!9LZ 5.9(;a

?<$/46<U$$$?7^$9!%

F18&5f2J=$;N2]Dx%^%k%A%(!<%8%'%s%H%7%9%F%`(MAS)%0%k!<%W CSC+ D>5*;a!$7,@^ N4G7 ;a$

46<UCW7^$9!%F1$8%0%k!<%WH7$F?t!9$NM-1W$J5DO@$r7FD:$-$^7?!%

F18&5f2JGn;N2]Dx J!ED 7r2p ;a!$=$;N2]Dx%M%C%H%o!<%/%0%k!<%W>!Ln 63<# ;a!$5WA>?@ 9(;

G*59 CN9' ;a!$Pornchai Laohakulvathit ;a!$;0NX BY9' ;a!$Lp:j 7<G7 ;a$K46<UCW$7$^$9!%@lLg

J,Ln$,0[$J$kJ}!9$N8f0U8+!$A4BNE*$J7W;;5!$K4X$9$kJY6/!$;dNCNi$J$$CN<1JI!$=$;N$N4

rh$jM-1W$K2a$4$5$;$FD:$-$^7?!%

F18&5f<<$N3'MM$K?<$/46<U$$$?7^$9!%

7DXf5A=NBg3XM}9)3X8&5f2J7W;;5!2J3X@l96;3K\8&5f<< GOM\ 9@0l ;a!$H`$N:J$N??F`<B$5$s!$

$N<BM%$Acs!$OB??7/$K46<UCW7^$9!%$^$?!$AGE($J%?%l%s%H$NK\>e$^$J$_$5sK46<UCW7

3'5s$N@:?@E*$J;Y$($,J1lP4hD%j,8z$+$J$+$C$?$3HG7g$&!%

$=$7$F!$;d$K4X$ok9YF$NJ}!9$K46<UCW7^$9!%

=$;N$+$i8&5f<<$r0\F0$7$?;d$K!$3'MM$N6(NO$,J1lP:#$^$GdCF3l^$;$sG7$?!%

:G8e$K!$2f$,2H$K$F;d$N2fPV$rK\Ev$Kh/J9$$$F$/$@5C$?Ic$HJl$HADJl$HKe$K:GBg8B$N4

$r<($7$F!$<U<-H5$;$FD:$-$^$9!%

1998 G/ 2 7n

;2 9M J8 8%

[=j95] =j ! ??M}M:!%%^%k%A%(!<%8%'%s%H%7%9%F%'8&5f$NL\;X$9bN!%%3%s%T%e!<%?%=%U%H%&
%"!$12(1):78–84!$January ! !1995!%

[KLLn93a] KLLn ! 9(L@!%0dEAE*%"%k%4%j%:%'!%;:6H?^=q!$1993!%

[KLLn93b] KLLn ! 9(L@!%0dEAE*%"%k%4%j%:%'$H%K%e!<%i%k!&%M%C%H%o!<%/$NM;9g!%!$KLLn ! 9(I
JT=8<T!$0dEAE*%"%k%4%j%:%'!$235–262 %Z!]%8!$;:6H?^=q!$1993!%

[OBED93] OBED ! 7rG72p!%?J2=%7%9%F%'O@ 0dEAE*%"%k%4%j%:%'$N4pAC!%5;Js 47-53!$Computer
Today!$1992-93!%

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