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Summary of M. S. Thesis

Major	Student No.	SURNAME, Firstname
Computer Science	89423839	SASAKI Takahiro

Title

A Study on the Effect of Learning and Genetic Mechanisms toward the Evolution of Agents

Under an open-distributed environment, we cannot take account of all situations that certain problem-solving systems, what we call agents, will be confronted with, when designing and constructing those systems. Therefore a notion of *evolutionary agents* becomes more and more important. On the analogy of biological evolutionary theory, the adaptational process of such agents under a certain environment can be viewed as the mixture of the following two complementary phases, each taking place at different levels: 1) *learning*, occurring within each individual lifetime, and 2) *evolution*, occurring beyond successive generations of the population. Due to the biological background, most of the previous researches on these two processes were based on the models of Darwinian-style evolution. From the viewpoint of engineering, though some previous work have shown the increase in the speed of adaptation for Lamarckian-style evolution, they have not make thorough comparison with the Darwinian-style. And what is worse, these work have considered only the static environment where certain rules that agents had to learn were permanent, and they have not discussed the dynamic situation that is one of the most important characteristics of the real-world. In this thesis, we regard an abstract *neural network* as a learnable agent and use *genetic algorithms* to evolve the populations of such agents. And we evaluate the characteristics of two different mechanisms of genetic inheritance, that are *Darwinian-style* and *Lamarckian-style*. Particularly taking the dynamic characteristic of environment into consideration, we evaluate the effect of learning on adaptability, speed of adaptation, and robustness of agents under each genetic mechanisms.

We mainly show the following results. Firstly, we show that *Baldwin effect*, addressing that individual learning indirectly guides the evolutionary process, does not always occur especially when agents must learn difficult rules, while the effect has been confirmed by many previous work. Secondly, we show the results of comparison between the two different genetic mechanisms. In static settings, Lamarckian-style mechanism is more effective than Darwinian-style one. However, in dynamic settings, Darwinian-style mechanism functions successfully, while Lamarckian-style one perform poorly.

Although we use many biological terms in this thesis, the most essential matters are the processes of "*collecting*", "*exploiting*", and "*transmitting*" information. Therefore, the results of this thesis can give some useful suggestions, when we design and construct certain intelligent systems such as multiple-agent systems that will be used under the open-distributed environment.

Graduate School of Science and Technology, KEIO UNIVERSITY

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

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2.1 ?M9)@8L? (*Artificial Life*)

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2.1.1 ?M9)@8L?8&5fH=$NL\;X$9bN

?M9)@8L? (*Artificial Life*) $O!$%5%s%?%U%'8&5f=j$N Langton KhCFDs>'5l$?Hf3SE*?7$7$$ 8&5fNN0hG"$j!$$=$NL\E*!$<jK!JI$K4X$7$F9-$/9g0U5l$?$bNO8=:_NH3m3NN)7F$ $$!%Langton $OEv=i!$?M9)@8L?$r!V@8L?$NM-$jF@$k;Q (*Life-as-it-could-be*)!W$N8&5f$H7F0J2<$N h&$KDj5A7? [Lan89]!%

> ?M9)@8L?$O!$<+A3$N@8L?7O$NFCD'$rM-$9$k?M9)%7%9%F%`$K4X9k8&5fG"$k!%$3lO!$ @8L?Nh$&$J?6$kIq$$$r7W;;5!d=$NB>$N?M9)E*$JG^BN>e$G9g@. (*synthesize*) 7h$& H9k3HrDL8F!$=>Mh$NJ,@O (*analysis*) E*$J<jK!$rCf?4H7F-$?@8L?2J3X$rJd 40$9$kbNG"$k!%<B83$NEZBf$r!$CO5e>e$G?J2=$7F-$?C:AG:?%Y!<%9$N@8L?$+$i3H Bg9k3HKhCF!$?M9)@8L?$N8&5f$O!$M}O@@8L?2J3X$r!V2f!9$NCNCF$$$k@8L?!W (*Life-as-we-know-it*) $+$i!V@8L?$NM-$jF@$k;Q!W(*Life-as-it-could-be*) XH9-2k3H $K9W8%$7$F@$k!%

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$rCj>]2=$7!$$=3K$"$kK!B’$rH/8+$9k3HG@8L?$K4X$9$kM}2r$NB%?J$rL\;X$9bNG"$k!

J}!$9)3X;X8~$N?M9)@8L?8&5f$O!$?J2=$N%a%+%K%:%`$d@8L?%7%9%F%`$N86M}$KCeA[$rF@$??J2=E

;;!$AOH/<jK!$JIN7W;;5!9=$r<B5!>e$K<BAu$7!$?J2=!&E,1~7?%7%9%F%`$N9=C[<jK!$r3NN)9

Hr<g4cH9$k!%

2.1.2 ?M9)@8L?%b%G%k$NFCD’

$+$D$F!‼$V@8L?BNH=$&$G$J$$J*BNHNAj0c$O!$$=NCfK@85$$,=ICF$$$k$+H]$+K"$k!W$

$&%"%j%9%H%F%l%9$Khk!V@85$O@!W$N35G0$N;YG[$,D9$/B3$$$?;~4|$,$"C?!%D^$j!$@8L?$

L@9kNK!$DL>o$NJ*<AHO0[Jk!V@85$!W$J$kIT2D;W5D$J%(%M%k%.!<$"$k$$$ONONh$&$JF

$J<BBN$rI,MWH7$?$NG"$k!%

7+$74T85<g5AE*$J6aBe$*$h$S8=Be$N2J3XKhCFJ,;R!$86;R$N2rL@$,?J$‘KDlFMM!9$

L?8=>]$,J,;R@8J*3XE*$J8+CO$+$i@bL@2DG=HJ$j!$:#F|$N@8J*3X<T$N4V$G@85$O@$r;Y;}$9$k<

$$$J$/$JC?!%$$$^$d@8L?BN$O!$C1$J$kJ#;($J@82=3XE*$J5!3#$K9.$J$$$H$$$&;v<B$,9-$/<

F~lilF$$$k!%$?$@$7!$5!3#$H8@$CFbF|>oE*$J0UL#$G$N5!3#$HOBg-$/0[$J$k!%!V(<+A3

L?!W$O!$$=$l<+?H$O@8L?$r;}$?$LC1$J$kJ,;RB??t4V$NAH?%N)C?Aj8_:nMQNCf+$iAOH/(emer

7F$/$k!%J,;6$5$l$?$=l>lNItJ,$N?6$kIq$$$rCf1{=88"E*$K@)8f$9$kBg0hE*$J5!9=$OB8:

$:!$$‘7mA4FNItJ,$,?6$kIq$$$=NbNG$"$k!%@8L?HO!$$3$&$7$?ItJ,ItJ,$N?6$kIq$$4

6I=jE*$JAj8_:nMQ$+$iA4$F$,AOH/$9$kA4BNE*$J?6$kIq$$$K2a$.$J$$!%D^$j@8L?BN$OC10l$N@

3XE*$J5!3#$JNGOJ$/!$Hf3SE*C1=c$J>.$5$J5!3#B??t$+$i@.$k=8CDH7$F[1]$FB*$($ilk

?M9)@8L?$NCf?4$rJ935G0$b!$$3$NAOH/E*?6$kIq$$ (*emergent behavior*) K"$j!$$3Nh$&$J

%\%H%‘%"%C%WE*$J<jK!$GbC$F@8L?$N7W;;O@E*B&LL$r%b%G%k2=$9$k!%5!3#$K@8L?8=>]$r<B8=$

k?aK!$5!3#$K!V@8L?!W<+BN$r?a$-9~$‘$3HO7J$$!%$‘$7$m!$9=@.MWAG4V$N6I=jE*$JAj8

MQ$N%@%$%J%_%/%9A4BNKhCF5!3#$,!V@8L?!W$i7/?6kIq&h&$K!$9=@.MWAG(>.5!3#)$N=

$r9*L/$KAH?%N)F9$kJ}K!$r<hkNG"$k!%$3$N%\%H%‘%"%C%WE*$J%b%G%k2=$O!$%_%jICC10L$

>.$J;~4V%9%1!<%k$K$*$1$kJ,;R=8CD$N%@%$%J%_%/%9$+$i?t@iG/C10L$NCO<A3XE*;~4V%9%1!<%k$

1k@8J*$N?J2=$N%@%$%J%_%/%9^$G!$<+A3@8J*3&$K$*$1$kG!2?$J$k3,AX$N%l%Y%kK*$$$F$bE

[1] C1:YK&@8J*K*$$$F$b!$0lDN:YK&FbK*$$$FJ#?t$N2=3XE*<BBN$,Aj8_:nMQ7F$$$k!%

9k3H$,2DG=$G$"$k!%$$$:lN%l%Y%kGN%b%G%k2=$r9T$&K;$h!$7W;;5!%Y!<%9$N?M9)@8L
%G%k$O0J2<$Nh&$J<gMW$JFCD'$rM-$9$k [Lan89]!%

1. C1=c$J9=@.MWAG (%W%m%0%i%`!$;EMM) $N=89g$+$i@.$k!%
2. B>$N9=@.MWAGA4$F$N@)8f$r9T$&9=@.MWAG$OB8:_7J$$!%
3. 3F!9$N9=@.MWAG$O!$B>$N9=@.MWAGHNAj8_:nMQ$r4^$aF=NCV+l?6I=jE*4D6-NbH
   G!2?$KH?1~$9k+$NDj5A$r;}$D!%
4. %7%9%F%`Fb$K$O%7%9%F%`A4BN$N5sF0$r7hDj9k5,B'OJ$$!%
5. 7?$,$C$F!$$$$+Jk%l%Y%kK*1kA4BNE*$J9TF0$bAOH/E*JbNG$"$k!%

3l$O@8J*$N?6$kIq$$$NG!2?Jk3,AX$N%l%Y%k$K$b6&DL$9$k7W;;5!9=>e$NFCD'$H8@$($k!%

2.1.3 ?M9)@8L?$N8&5fNc

5F!$$3$3$G?M9)@8L?$N8&5f$K$*$1$kCf?4E*<gBj$r5s2k$H0J2<$Nh&KJ$k!%

- 7ABV7A@. (H/@8) $N%b%G%k
- ?J2=$N%b%G%k!$3X=,$N%b%G%k
- :YK&4V$N%3%_%e%K%1!<%7%g%s!$@8BNFb$NJ,;6JBNs=hM}
- LH1V7O!$<+8J=$I|

Nc$($P!$RNA JI$N@8J*$N0dEA;R$NMWAG$HJk2J3XJ*<A$r%7%_%e%l!<%H$7!$@8J*H/@8$N%a
%K%:%`$rI=8=$9$k%b%G%k$N9=C[$r;n$_$?8&5fNc$,$"$k [Ras89]!%F1MMNNcH7F$O!$%;%k%*!<
%^%H%s$rMQ$$$F:YK&$N<+8JA}?#$r%7%_%e%l!<%H7?bN [TH89] $d!$C1=c$J5,B'$K=>CF:YK&
Nv$r7+$jJV$9$3HG?F$HF1$87A>u$r:n$j$"$2k3H,=PMhk3Hr<(7?bNb"$k [dBFP92
$^$?!$%K%e!<%i%k%M%C%H%o!<%/$r;}$D?M9)5B$N=8CD$r0dEAE*%"%k%4%j%:%`$rMQ$$$F?J2=5
<B83 [CJ92] JI$N@8J*?J2=$N%7%_%e%l!<%7%g%sKD$$$F$N8&5f$b@9sKJ5lF$$$k!%?J2=
?@7P:YK&$HH/@8$N;0<T$r7k$SD1$?$bNH7F$O!$%0%i%U@8@.J8K!$H0dEAE*%"%k%4%j%:%`$
$_$KAH$_9g$o$;$F%K%e!<%i%k%M%C%H%o!<%/$NH/@8$N5,B'$r?J2=$5$;$k$H$$$C$?6=L#?<$$8&5
[Kit90, KLLn 93] b"$k!%$5iK%0%i%U@8@.J8K!$H$$$C$?%H%C%W%@%&%sE*$J%"%W%m!<%AGOJ
:YK&4V$N%3%_%e%K%1!<%7%g%s$HBe<UKhCF?@7P2sO)LV$r%\%H%`%"%C%WE*$KH/@8$5$;$k5!9=$
2=5;$k;n$_ [Kit94] b"$k!%0J>e$Nh&$K!$?M9)@8L?$K4X$9$k8&5f$OB?4tKEOC$F$$$k!%

2.2 0dEAE*%"%k%4%j%:%` (*Genetic Algorithms*)

0dEAE*%"%k%4%j%:%` (*genetic algorithms, GA*) $O!$@8J*$N?J2=$N86M}$KCeA[$rF@$?%"%k%4%j%:%`G"$j!$Holland KhCFDs>'5l$? [Hol75]!%GA $O!$@8L?%7%9%F%`$N8=>]$r7W;;$HB*$($k?M9)@8L?$N8&5fK*$$$F!$?J2=$N%b%G%kH7$FMM!9$J2r@O$KMxMQ$5lF$$$k!%$^$?!$@8J*=8CD$6-$KE,1~?J2=$7$F$$$/2aDx$r%R%s%H$K!$DL>o$NJ}K!GOG|Bg$J7W;;NL$rMW9k$?$a$K2r$/3:FqG$"$kh&JAH_9go;LdBjJIKBP9$k2r$NC5:w$*$h$S:GE,2=!$$"$k$$$O%m%\%C%HJ3X=,$N<jK!$H7F!$9)3XE*$K$b?tB?$/$N1~MQ$,J5lF$$$k [Dav91]!%

2.2.1 @8J*K*1k0dEA$H?J2=

Darwin $NM}O@

Darwin (1809 - 1882) $O!X<o$N5/8;!Y[Dar59] NCfG!$8=B8$9$kA4$F$N@8J*$O!$(30 2/G/$r1[$($k) 1s$$2a5n$NCO5e>e$K@8$^$l$?0l$D$"$k$$$O4/>/?t$NC1=c$JAD@h$KM3Mh$7!$$=l,JQ7lFG-$?Kvjc$G$"$k$HO@$8$?!%H`$O$^$?!$$3$N?J2=E*JQ2=$r$b$?$i$7$?<gMW$JNO$O<+A3E(*natural selection*) $G$"$k$H=R$Y$F$$$k!%$b$78DBN?t$,;`$KhC$F@)8B$5lk3H$,$J1l$P@8J*$O:]8BJ/A}$(B3$1k3HKJk$,!$<B:]KO5o=;0h$d?)NH$JIN;q8;$,8B$ilF$$$k$?$8DBN?t$NL5@)8B$NA}2C$,5v$5lk3HOJ$$!%0lJ}!$@8J*$O?F$+$i;RXH$=$NFCD'$,0z$-7Q$k0dEA$H$$$&FC@-$r;}$D$,!$A4FN;R$,?F$HA4$/F1$8@-<A$r;}$Do1GO$J$$!%3&7F@8$JQ0[$N>/J/Hb$$$/i+$O@8B8$HHK1IN7d9$5$K1F6A9k!%@8B8$dHK?#$KM-Mx$J7A<A$r;@8J*$O!$$h$jB?$/$N;RB9$r;D9@1GJ/!$0dEA$KhC$F;RB9$K<+J,$N7A<A$rEA$($kG"$mDarwin $O!$<+A3EqBA$N05NO$N2<GN0dEAE*$JJQ0[$NC_@Q$N7k2L$H7F!$@8J*$N=8CD$O?J2=$9G"m&$H=R$Y$F$$$k!%3N<+A3EqBA@b$O!$?J2=E*JQ2=$,5/$3k3H@1GJ/!$$=$NJQ2=$$Nh&JbNG$"$k$+$bM=B,9k!%FC$K!$@8J*O=l,@83h7F$$$k4D6-NCfG!$$hj&$^$B8$7HK1I$G$-$kh&$J7A<A$r@BerDL8F3MF@9kO:JNG"$k!%$D$^$j<+A3EqBA@b$O@8J4D6-$X$NE,1~$rM=B,9k!%

0dEA;R$N<BBN$H7F$N **DNA**

0lJ}!$7A<A$r?F$+$i;RXHEA$($k@8J*$N0dEA$N;EAH$_$O!$Ev;~!$$^$@Ff$KJq$^$l$?$^$^$G$"$0dEA>pJs$N2Y2r$-$H$$$C$?35G0$,B8:_7J$+$C$?$Ok+8E$$;~BeKO!$A0@8@b!W(*preformationism*KhCF@8J*$NH/@8$rM}2r9khj$[$+J+C?!%A0@8@bHO!$@.BN$N?HBN$N7ABV$,G[6v;RN"i+8a4^$^$lF*$j!$$3l,@.D9$7$F@8J*$N8DBN$HJk$H$$$&9M$($J}G"$j!$$"$k<T$O!$6@$G4Q;!9l$P@:;R$NF,It$K>.$5$J?M4V$,=L3^CF$$$kN,G'ailk$H9M$($F$$$? [D9LnH3m,!$Mendel $O 1850 G/$+$i 1860 G/Be$K$+$1$F9T$C$?%(%s%I%&F&$N<o;R$N0dEA$K4X9k

<B83Kh$j!$@8J*$NFCD’$OJ#?t$N2>A[E*$JN3;R>u$NJ*<A$H$$$&7A$G?F$+$i;R$K7Q>5$5$l$F$$$
$$$&2>@b$rN)$F$?!%$3$N0dEAE*7A<A$r;YG[9k0x;R$O8e$K0dEA;R (*gene*) $HL>IU$1il!$$5$i
1910 G/Be$K Morgan iKhC$F!$$=l>lN0dEA;R$O:YK&$N3KFbK"$k@w?’BN (*chromosome*)
>e$N8GM-$N0LCV$K:B$r@jaF$$$k3H$,L@$i$+$KJC$?!%$=7F!$1953 G/$K Watson $H Crick
KhCF%G%*%-%7%j%\3K;@ (*DNA*) $NFs=EMf@{9=B$$,L@i+K5$l!$DNA $,!V0dEA;R!W$NJ*<
E*<BBNG"k3H,FM$-;_$ail$?!%$=$N8e!$0dEA>pJs$r;}$D DNA J,;R$NFs=E:?$O$[$I1F
K\$:DKJj!$$=l>l,Cr7?HJCF!$<+J,$HAjJdE*$J?7$7$$$b$&0lK\$NJ,;R:?$r7A@.$9$
J]B8E*$J2aDx$G<+8JJ#@=$r9T$&3H$,<B>Z$5l?!%$^$?0dEA>pJs$O!$%3%I%s (*codon*) $H8F$P$l
%"%G%K%s (A)!&%0%"%K%s (G)!&%A%_%s (T)!&%7%H%7%s (C) $N 4 <oN`$N DNA $N1v4pG[Ns$N 3 $DAH
$G7hDj$5lk3H$,L@$i$+$K5l!$$=$N0E9f2=$NJ}K!$OA4$F$N@8J*$K6&DLNbNG$"$k3H$
$+$C$? [BgEg 81]!%@8J*$O DNA >e$K1v4pG[Ns$N0E9f$N7A$G9o$^$l$?0dEA>pJs$N2Y2r$-$r9TC
@8J*BN7A@.$K4X$o$k%?%s%Q%/<A$N9g@.$r9T$&NG$"$k!%

2.2.2 :GE,2=K!H7FN **GA** $H<+A3?J2=$NE,1~2aDx

<+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 $O!$3NN(E*C5:w$N0l<jK!$H7FB*$($k3H$,=PMh$k$,!$=>Mh$+$i$
EAE}E*$JC5:w$N<jK!HHfY$F0J2<$NE@$KFCD’$,$"$k [Gol89]!%

1. %Q%i%a!<%?%;%C%H$=$NbNGJ$/!$$=lrId9f2=7?BP>]$rA`:n$9$k!%
2. C10lCm;kE@$K4p$E$/C5:w$GOJ$/!$B??t$NCm;kE@=8CD$KhkB?E@C5:w$r9T$&!%
3. C5:w$rM6F3$9kN$K8zMQ>pJs (L\E*4X?t) $@$1$rMxMQ$7!$%R%e!<%j%9%F%#%C%/$JINGI@8
   $*$h$SJd=uE*$JbN$OMQ$$$J$$!%
4. 7hDjO@E*KGOJ$/!$3NN(O@E*$J5,B’$K4pE->uBV$rA+0\$5$;$k!%

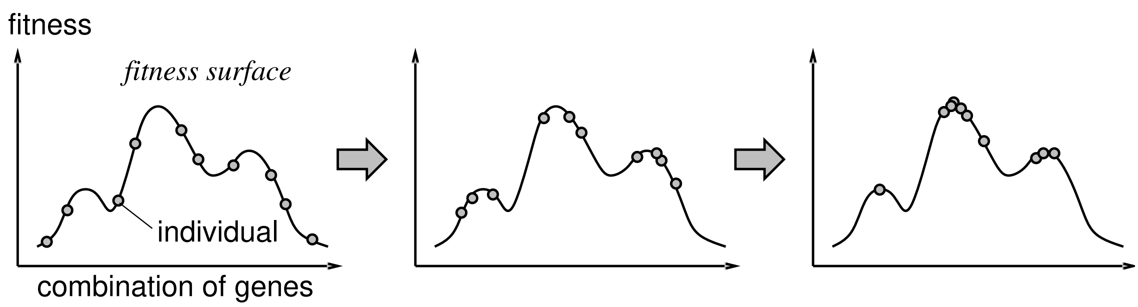
$"$kM?$($il?LdBjKBP9$k%Q%i%a!<%?%;%C%H$O!$($7P7$P 0!$1 $N%S%C%H$+$i@.$k) 0l<!85
Ns (%9%H%j%s%0) H7$FId9f2=$5lk!%3lOAg&$I!$DNA $N1v4pG[Ns$Khk0dEA;R72Kh$C
@8J*$N@w?’BN$,7A@.5lk3HKBP1~9k!%@w?’BN>e$N0dEA>pJs$,@8J*8DBN$N9=B$$r7hDj9
$&$K!$$3$N%9%H%j%s%0$OM?$($il?LdBjKBP9$k2r$N8uJd$rI=8=$9$k!%GA GO@8J*3XK*1
8l$HF1MM$K!$$3Nh$&$J0dEA;R$NAH9g$;H7FN%9%H%j%s%0$r0dEA;R7? (*genotype*)!$%9%H%j%s%
$NI=8=$9$k2r$rI=8=7? (*phenotype*) $H8F$V!%$^$?@w?’BN>e$N0dEA;R$N0LCV$r0dEA;R:B (*locus*) $H8F
$V!%GA $O!$$3$N0dEA;R7?$H7F$N@w?’BN=8CD$KBP7F7+jJV70dEAE*A`:n (*genetic operations*)
$r;\$9!%0lHL$K GA K*1k0dEAE*A`:nH7FO!$A*Br (*selection*)!$8r:5 (*crossover*)!$FMA3JQ

0[(*mutation*) $N;0$D$,<g$KMQ$$$ilk!%3liK$D$$$F$O 2.2.3 @a$G!$$h$j>\:Y$K=RYk!%J*
0J2<GOFCKCGoiJ$$8B$j!$@w?'BN!$8DBN!$2r$N8uJd$H$$$&8@MUr[$\F1$8 0UL#$GMQ$$$k

J#@=$N2aDx$G$O!$8zMQ — E,1~EY (*fitness*) $H8F$Plk3H$,B?$$ — $K4p$E$-!$$$$/D+$NM-
K>$J@w?'BN$r4{B8NbNNCf$+$iA*Br$7!$$=li$NItJ,%9%H%j%s%0 (0dEA;RNs) $r8r:5$KhC
AH$_49$(k3HG?7$7$$2r8uJdHJ$k@w?'BN$rF@$k!%$3$NA*Br$N2aDx$O!$%@!<%&%#%sM}O@$N<
EqBA$N2aDx$KBP1~9k!%9JoA!$$h$j4D6-$KE,1~7?8DBN$OE,1~$K<:GT7?8DBNKHfY$F!
$jD9@8$-r7!$7k2L$H7FhjB?$/$N;RB9rb$&$1$k!%

@w?'BN (b7$/$O2r) $NE,1~EY$O!$LdBj$KhC$FMM!9$JJ}K!$GI>2A$5lk!%Nc$($P!$M?$($i
$?LdBj$,$"$k?t<0$N2r$r5aakh&JbNG$"$C$?>l9g$KO=$N@w?'BN$NI=8=9k2r8uJdK
<+>h8m:9$N5U?t$,E,1~EYKJ$jF@$k$7!$=d2s%;!<%k%9%^%sLdBjJI$N>l9g$KO=$N@w?'BN$,I
9k7PO)$N9g7W5wN%$N5U?t$rE,1~EY$NI>2AH7$FMxMQ=PMh$k!%$3$3$G GA <+BN$O!$2r8uJd$,I
2=5l$F$$$k@w?'BN%9%H%j%s%0$N0UL#$ObAmsE,1~EYNCMN0UL#$=$NbNKD$$$F$N2r<a$
oJ$$!%GA $O!$M?$($il?LdBjKBP9$k%R%e!<%j%9%F%#%C%/$JINJd=uE*$JCN<1$rMxMQ$;$:
$?$@E,1~EYNCM=NbNKN_CmL\$9$k!%?^ 2.4 ONcH7F!$10 8D$N@w?'BN$H GA $,MxMQ$7F
$kA4$F$N>pJs$rI=7F$$$k!%

%i%s%@%`$K=i4|2=$5l?8DBN=8CD$N=i4|@$Be$+$i=PH/$7!$0J>e$K=R$Y$?8E$$@Ber?7$7$S
BeKCV-49$($kA`:n$r<!!9$K7+$jJV$7$F$$$/!%$9$k$H@$Be$,?J$`KDlF!$8DBN=8CD$OJ?6QE
hj9b$$E,1~EY$r;}$D=8CDXH?J2=9k!%D^$j7k2L$H7F!$M?$(il$?LdBj$KBP9khjE
$?2r$rI=$9@w?'BN$,@8$8$F$/$k3HKJ$k!%GA $NF0:n$rD>4QE*$KM}2r$9kK$O!$@w?'BN$N
EA;R:B$N?t$KAjEv9k<!85$ND6J?LL$rDj5A0hH9$kE,1~EY4X?t$GM?$($ilkE,1~EY6JLL (*fitn*
surface) $N35G0$r9M$($k$HNI$$!%GA $O!$$=l>lN8DBN$,E,1~EY6JLL$N;3D:$rL\;X$9B?E@C5:
$N2aDx$HB*$($ilk (?^ 2.1)!%



?^ 2.1: GA $HE,1~EY6JLL

5F!$$3$3$G GA $NF0:n$r$^$Hak$H0J2<$Nh&KJ$k!%

1. =i4|=8CD$N@8@. ($g = 1$)
2. Bh g @BeN=8CDFb$N8DBNA4$FKBP7$FE,1~EY$rI>2A
3. Bh $g+1$ @BeN=8CD$r@8@.
   (a) E,1~EY$K1~$8$F!$?FHJ$k8DBN$rA*Br
   (b) 8r:5!&FMA3JQ0[KhCFBh $g+1$ @BeN=8CD9=@.0wHJ$k;R8DBN$r@8@.
   (c) $"$k7hail??t$N;R$,@8@.5lk^$G!$3.(a) KLak
4. $g = g+1$ H7$F!$2. KLak

:GE,2=LdBjJI$N2rK!$H7F9)3XE*$K GA $rMQ$$$k>l9gKO!$>e5-$N<j=g 2.!A4. $^$G$r=*N;>
7o$,K~$?5lk^$G7+$jJV7F!$:G=*E*$KF@il$k8DBN(2r)$KCmL\$9$k!%0lJ}!$?J2=$N%b%G%
7F?M9)@8L?E*$J2r@O$r9T$&$N$KMxMQ$9$k>l9g$K$O!$FC$K=*N;>r7o$JIr@_1:$K!$>e5-$N<
$,7+$jJV5l$F$$$k4V$K8+$ilk%@%$%J%_%/%9$KCmL\$9$k!%

2.2.3 GA K*1k0dEAE*A`:n

A*Br (*Selection*)

A*BrHO!$8DBN$N=8CDNCf+$i<!@$Be$N?F$HJkY-8DBN$rA*$S=P$9A`:n$G$"$k!%%@!<%&%
M}O@$N<+A3EqBA$N86M}$K4p$E$-!$E,1~EY$N9b$$8DBN$[$I9b3NN($GA*$Plk3HKJ$k!%$7$+
$"$^jKM%=($J8DBN$,M%@h5l9.kHB?E@C5:w$NMxE@$,<:ol!$=i4|$NCJ3,$G6I=j2r$K4Y$
9/Jk3H$,$"kN$G!$:GE,LdBjJI$N2rK!$H7FFC$K9)3XE*$K GA $rMQ$$$k:]KOA*Br
(*selection pressure*)$,$"$^$j6/$/3]$+j9$.$J$$$h$&$KCm0U9kI,MW$,$"$k!%MM!9$JA*Br$NJ}K!
$,Ds0F$5lF$$$k$,!$BeI=E*JbNH7F$O0J2<$NFsDNbN$,$"$k!%

- E,1~EYHfNc@oN, (*fitness proportionate selection*) [Gol89]

  %k!<%l%C%H@oN, (*roulette wheel selection*) $^$?$O%b%s%F%+%k%m%b%G%k (*monte carlo model*) Hb8FPlkbNG!$8DBN$OE,1~EY$KHfNc$7$?3NN($GA*Br5l$k!%

- %i%s%/@oN, (*rank selection*)[WH89]

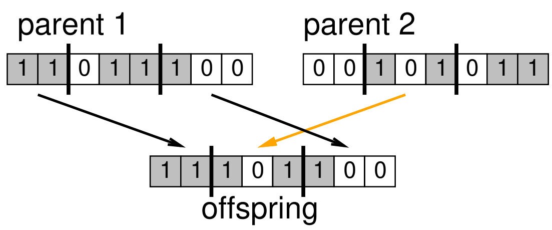
  3F8DBN$rE,1~EY$N=g$K%i%s%/$E$1$7!$8DBN$O$"$i$+$8$a%i%s%/Kh$K7hail?3NN($GA*Br$5lk!%

E,1~EYHfNc@oN,GO!$3F8DBN4V$NE,1~EY$N:9$,Bg$-$$=i4|$NCJ3,$G$OM%=($J8DBN$[$IA*Br$
d9$$ (A*Br05$,9b$$)!%7+$7 GA $,?J$`KDlF3F8DBN4V$NE,1~EY$N:9$,>.$5$/$JkH!$

hj$b>/$7M%=($J8DBN$G$"$CFbA*Br5l$k3NN($,B>$N8DBN$HBg:9$J$$ (A*Br05$,Dc$$) >u6
4Y$j!$2r$N<}B+B.EY$,Cx7/Dc2<9k [WH89]!%01J}!$%i%s%/@oN,$G$O!$E,1~EYNCM=Nb$N
0MB8$7$J$$$h$&$KA*Br3NN($r:NMQ$9k3HKhC$F GA $N$$$:lNCJ3,K*$$$F$b!$>/7G$k
=($J8DBN$KBP7FM-MxKJkh$&$JA*Br05$,3]$1i1$k!%$^$?%i%s%/@oN,$K$O!$6KC<$K9b$$E
EY$N8DBN$,=8CD$rFH@j$7$F6I=j2r$X$HAa4|<}B+$9k3HrHr1k8z2Lb"$k!%

8r:5 (*Crossover*)

8r:5HO!$A*Br$5l?FsDN?F8DBN$N@w?'BN>e$N0dEA;RrAH_49$($F?7$7$$;R8DBN$N@w?'B
:n$kA`:n$G$"$j!$M-@-@8?#$r9T$&@8J*$NM:$H;s$,G[6v;R$r7k9g$5$;$F?7$7$$0dEA;R$NAH9g$;$
$D;R8DBN$r;:$`2aDx$KBP1~$9$k[2]$:$O$8$a$K!$$$$/$D$+$N8r:5E@$,%i%s%@%`$K7hDj5l!$$=
li$r6-$K@w?'BN$,ItJ,%9%H%j%s%0$KJ,3d5l$k!%Fs$D$N?F$+iNItJ,%9%H%j%s%0$r8r8_$K@
9k3H$G?7$7$$@w?'BN$,:n$ilk!%?^ 2.2 $K!$FsE@8r:5KhCF;R$N@w?'BN$,:nil$kMM;
Nc$r<($9!%

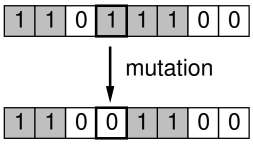


?^ 2.2: 8r:5

FMA3JQ0[(*Mutation*)

FMA3JQ0[HO!$@w?'BN>e$N0dEA;Rr"$k3NN($GJQ2=5;$kA`:n$G$"$k (?^ 2.3)!%$3$NA`:n$,
ol$J$$$>l9g$O!$=i4|$N0dEA;R$NAH$_9g$o$;0J30$N6u4V$rC5:w$9k3HOG-$J$$$N$G5a$a$
$k2r$N<AKb8B3&$,@8$8$k!%FMA3JQ0[$KhC$F@w?'BN=8CD$NB?MM@-$,J]$?$l!$$h$j9-$$2r6u4
C5:w9k3H$,2DG=$HJk!%$?$@$7!$$3$NA`:n$rMpMQ$9$k$HC1$J$k%i%s%@%`%5!<%A$K4YCF$
$&$N$G!$DL>o$OFMA3JQ0[N($ODc$$CMrH$k!%

[2]<B:]$N@8J*$G$O!$8DBN$O<+?H$NIc?F$HJl?F$KM3Mh9kBPrJ$9AjF1@w?'BN>e$K0dEA>pJs$rJ];}$7F*$j!$3F8
$,<o$KhC$F7h$^C??tNAHNAjF1@w?'BN$r;}$C$F$$$k!%G[6v;R7A@.NH$-$K$=$1$>$1NAHNAjF1@w?'BN$,01K\
JL!9$NG[6v;R$KF~$j (8:?tJ,Nv)!$G[6v;R$N9gBN (<u@:) KhCF:FSBPrJ9AjF1@w?'BNNAH,7A@.5l$k!%$3$N<
;~$K@w?'BNC10L$GM:8DBN$H;s8DBN$H$N4V$N0dEA>pJsNAH_49$((%7%c%C%U%k) $,5/$3ko1G$"$k$,!$$=$NA0$K?F$
FbKF@8?#:YK&$,8:?tJ,Nv$r7FG[6v;R$r7A@.$9$k:]$K$b0dEA;RC10L (1v4pC10L) $GAjF1@w?'BN$N4V$G0dEA>pJs$NA
49$($,5/3k!%



?^ 2.3: FMA3JQ0[

2.2.4 ?J2=E*7W;;H7FN **GA** $NC5:wG=NO:!V0EL[E*$JJBNs=hM}!W

$3$3$^$G!$A0=R$7$?$h$&$JC1=c$J0dEAE*A`:n$rAH$_9g$o$;$?$K2a$.$J$$ GA $,!$2?8N$+$/6/NO$G4h7r$JC5:w<jK!HJ$jF@$kN+KD$$$F8@5Z7F3J$+$C$?!%K\@a$G$O GA K*1k4pE*86M}$r=RYF!$GA $N;}$D@x:_E*$JC5:wG=NO$K$D$$$F2r@b9k!%

%9%-!<%^ (*Schema*)

8r:5Kh$k9=B$E*$J0dEA>pJs$N8r49$O!$E,7?8DBN$r7A@.$9kN$KM-MQ$J0dEA>pJs$r;}$DIE*>.JR$N;X?t4X?tE*$JA}2Crb$?$i$9!%$^$:$O!$0J2<$NNc$rMQ$$$F4JC1$K35G0E*$J@bL@r9

Chromosome	Fitness
0 0 0 0 1 1 0 1	169
1 0 1 1 0 1 0 0	32400
0 0 1 0 1 0 1 1	1849
1 1 0 1 1 1 0 0	48400
0 1 0 0 1 1 0 0	5776
0 0 1 1 0 1 0 1	2809
1 1 1 1 0 0 0 0	57600
0 1 1 0 1 0 1 0	11236
0 0 0 0 0 1 0 1	25
1 1 1 1 0 0 1 0	58564

?^ 2.4: @w?’BN=8CD$HE,1~EY

4X?t $F(x) = x^2$ $r:GBg2=$9kh$&$J x $(0 \leq x \leq 255)$ $r5a$a$?$$$bNH$7!$2r$N8uJd$rD9$5 8 $N 2 ?J%S%C%HNs$N@w?’BN$GI=8=$9$k!%$3NH$-$K!$GA $N<B9T<T$O@5$7$/2r$,5a$^kh$&$K!$$($P 4X?t $F(x)$ $=$NbN$rE,1~EY$H7FDj5A9k!%$3$3GNcK5s2?LdBj$N:GE,2r$OL@i+Gk$,!$0lHLE*KO!$M?$(il$?LdBj$N:GE,2r$,L@$i$+$G$"$ko1GO$J$$!%$=$3$G!$GA <+BN4X?t $F(x)$ $N0UL#$^GOCN$jF@$J$$$bNH9k!%D^$j!$GA <+BNKO!$?^ 2.4 Nh$&$K@w?’B

=8CD$HE,1~EY$NCM$@$1$,M?$(il$k!%$3Nh$&$J>u67$N2<$G!$$h$jE,1~EY$N9b$$?7$7$$@w?'B
@8@.7h$&$H7?>l9gKO!$4{B8$N@w?'BNNCfGE,1~EY$N9b$$$bNN4V$NN`;w@-$KCeL\$9k
$O9gM}E*$G$"$k!%?^ 2.4 KhkH!$:G$b:8$N0LCV$K 1 $,$"k3H,9b$$E,1~EY$r@8$_=P9h$&
8+$($k!%7?$,$C$F!$?7$7$$@w?'BNK*$$$F$b:G$b:8$N0LCV$r 1 K9k3HOM-K>$J@oN,$G$"
3Nh&$KE,1~EY$N9b$$@w?'BN$r9=@.$9$kN`;w$7$? (>.) ItJ,$rMQ$$$F?7$7$$@w?'BN$r@8@.$9
2aDx$O!$%9%-!<%^ (*schema*!$J#?t7A$O *schemata*) $N35G0$rMQ$$$Fhj87L)$K@bL@$5lk [Hol75]!%

%9%-!<%^HO!$@w?'BN=89gA4BN$N$"$kItJ,=89gFb$KB0$9$k8DBN4V$G6&M-9k%9%H%j%s%0$N%Q%
%s$rI=$9%F%s%W%l!<%HG"$k!%@w?'BN$,D9$5 l $N 2 ?J%S%C%HNs$GI=8=5l$k>l9g$K$O!${0, 1, *
$N 3 DN5-9f$N l 8DNJBSKhCFI=8=5l$k%9%H%j%s%0$,%9%-!<%^HJ$k!%$"$k%9%-!<%^>e
A4FN0LCVKD$$$F!$BP1~$9$k0LCV$N5-9f$,A4$F0lCW9kh&$J@w?'BN$O$=$N%9%-!<%^$K!VE
(*match*) 9k!W$H8@$&!%$3$3$G!$"*"(*wild card* b7$/$O *don't care symbol* $H8F$Plk) $O!$"0"
$H "1" $N$$$:lK$b0lCW$9$k!%Nc$($P!$D9$5 8 $N 2 ?J%S%C%HNs$r@w?'BNI=8=H9kH!$%9%-!<
"10*011*1" $O 4 DN@w?'BN {10001101, 10001111, 10101101, 10101111} $HE,9g$9$k!%

$^$:!$D9$5 l $N@w?'BN n 8D$+$iJk=8CDFb$K@8$8F@$k%9%-!<%^$N<oN`$NAm?t$r9M$($k!%@w
BN>eN=l>lN0LCV$, k 8D$N5-9fCM$r<h$jF@$kbNH9$k (2 ?J%S%C%HI=8=$N>l9g$O!$$k =$
$H!$Am?t $(k+1)$<oN`$N%9%-!<%^$,B8:_$7F@$k!%2?8NJi$P!$$=l>lN l 8D$N0LCV$O k 8D$N
5-9fb7$/$O * $N$$$:l+$0l$D$r<h$k3H$,$G$-$k$+$iG"$k!%A0=R$NNc (D9$5 8 $N 2 ?J%S%C
NsKh$k@w?'BNI=8=) GO!$@w?'BN$N<oN`$O$?$+$@$+ $256 (= 2^8)$ $G$"$k$,!$%9%-!<%^$N<oN`$O
$6561 (= 3^8)$ KbN\$k!%$^$?0lJ}!$0l$D$N@w?'BN$O 2^8 DN%9%-!<%^$KB0$9k3HK$J
$k!%2?8N$JiP!$0l$D$N@w?'BN$O!$A4$F$N0dEA;R:B$K$*$$$F$=$N0LCV$N5-9fCM$=NbN+$"$
$O "*" 5-9f$N$$$:l+$r<h$k%9%-!<%^$K0lCW$9k+iG$"$k!%D9$5 l $N 2 ?JI=8=$Khk@w?'BN
>l9g$O!$0lDN@w?'BN$O 2^l 8D$N%9%-!<%^$KB0$9$k3HKJ$k!%7?$,CF!$=8CD%5%$%:$, n $G
$"$kh&$J@w?'BN=89gFb$KB8:_9k%9%-!<%^$N<oN`$NAm?t$O 2^l $+$i $n \cdot 2^l$ 8D$N4V$NCM$r<h$k
NG$"$k!%3N3H$O!$Hf3SE*>.5J=8CDFbK*$$$F5($bN`;w@-$K4X9kB?NL$N=EMW$J>pJ
4^$_F@$k3H$r0UL#$7$F$$$k!%GA K*$$$F$O%9%-!<%^$KCeL\$9k3HKhC$F!$@w?'BN<+BN$
$_CeL\$7$?>l9g$KHfYFhjB?NL$N>pJs$r3hMQ9k3H$,2DG=$KJkNG$"$k!%

%9%-!<%^DjM} (*Schema Theorem*)

$"$k%9%-!<%^ H $NE,1~EY $f(H)$ $r!$$=$N%9%-!<%^$KB0$9$kA4FN@w?'BN8DBN$NE,1~EY$NJ?6Q
$H9M$($k!%3F%9%-!<%^$NE,1~EY$+$i!$A*Br$N8z2LKh$k3F%9%-!<%^$N@BeKEO$kA}8:$r2r@O$
3H$,2DG=$G$"$k!%$m(H, t)$ $r@$Be t K*$$$F=8CDFb$KB8:_$9$k%9%-!<%^ H $N8D?t ($"$k$$$O%
%-!<%^ H $KB0$9$k@w?'BN8DBN$N8D?t) $rI=$9H9$k!%$3$3$G f_{avg} $r=8CDFb$N8DBNA4BN$NJ?6QE,

1~EYH9kH!$@$Be $t+1$ $KB8:_$9$k%9%-!<%^ H $N8D?t$N4|BTCM$O0J2<$N<0$GI=8=$5lk!%

$$m(H,t+1) = m(H,t)\frac{f_s(H)}{f_{\mathrm{avg}}} \tag{2.1}$$

<!$K!$8r:5$dFMA3JQ0[$KhC$F%9%-!<%^$,GK2u5l$k1F6A$b9MN8$KF~$lkI,MW$,$"k,!$$ $O$$$/D+$NMQ8l$r@bL@9k!%%9%-!<%^ $H$$N!$:G=i$N8GDjItJ,$H:G8e$N8GDjItJ,HN4V$N5w $rDj5AD9 (*defining length*) $\delta(H)$ $H8F$S!$%9%-!<%^Cf$N8GDjItJ,$N?t$r%*!<%@ (*order*) $o(H)$ $H8F $V!%Nc$($P!$%9%-!<%^ "*1*1**01" $ODj5AD9 6!$%*!<%@ 4 G"$j!$%9%-!<%^ "***101**" $ODj5A D9 2!$%*!<%@ 3 G"$k!%$5F3$3$G!$8r:5E@$,%i%s%@%`$KA*$PlkbNH9kH!$EvA3Dj5AD9 D9$$%9%-!<%^$[$I8r:5KhCFGK2u5ld9$$798~K"$k!%0lE@8r:5$r9M$($?>l9g$O!$%9%-! "*1*1**01" $O 86% (= 6/7) $N3NN($G!$%9%-!<%^ "***101**" $O 29% (= 2/7) $N3NN($GGK2u$5 lk!%D9$5 l N"$k%9%-!<%^ H $, (0lE@) 8r:5$"$k$$$OFMA3JQ0[KhCF@8$-;D$k3NN((*surviva probability*) p_s $N2<8B$O!$8r:53NN($r p_c FMA3JQ0[N($r p_m H9kH0J2<$N<0$GI=8=5l$k!%

$$p_s \geq 1 - p_c\frac{\delta(H)}{l-1} - o(H)p_m \tag{2.2}$$

>e<0$NN>JU$,Ey9f (=) GJ$/ITEy9f ($\geq$) $G7k$PlF$$$kNO!$8r:5$"$k$$$OFMA3JQ0[KhC $"$k%9%-!<%^$,GK2u$5l?H7Fb!$8r:5$NAj<jKhCF$O:F$S85$N%9%-!<%^$,@8$8F@$k$+$ $"$k!%

(2.1)!$(2.2) <0$r$^$Hak$H0J2<$Nh&$J<0$GI=5l$k%9%-!<%^DjM} (*schema theorem*) $rF@$k!%

$$m(H,t+1) \geq m(H,t)\frac{f_s(H)}{f_{\mathrm{avg}}}\left(1 - p_c\frac{\delta(H)}{l-1} - o(H)p_m\right) \tag{2.3}$$

>e<0$O!$8DBN=8CDNCfG!VJ?6Qhj$bM%$l$?!W%9%-!<%^$r;}$D8DBN?t$,@Ber=EMkKh$K;X? ?tE*$KA}2C9k3H$r<($7$F$$$k!%$^$?!$GA $N<B9T$K$*$$$F%9%-!<%^DjM}$O "*exploitation*"(= 4{$KNI$$$HH=CG5l$?%9%-!<%^$r4^$`8DBN$N@8@.) $N2aDx$H "*exploration*"(= ?7$?$JL$CN$N%9%-!< %^$r4^$`8DBN$N@8@.) $N2aDx$N%P%i%s%9rDja$F$$$k$H2r<a$5lk!%Nc$($P!$2.2.3 @a$G5s$2 GA $N@)8f%Q%i%a!<%?$OA4$F!$(2.3) <0$N$$$:l+$N9`$K1F6A$rM?$(F*$j!$GA K*1k%9%-! %^=hM}$N@-<A$K?<$/4X78$7$F$$$k!%$?$@$7%9%-!<%^DjM}$O!$$"$k%9%-!<%^$K$D$$$FCmL\$7$?$ $K!$$=$N8D?t$,=8CDFbGINh$&$KJQ2=9k$+$K4X9kM=B,$rM?$(kK2a$.$:!$8r:5$dFMA3J KhCF@8@.5l$k?7$7$$%9%-!<%^$K4X$7FNJ,@OOJ5l$F$$$J$$$JIN5?LdE@$b;XE&$5$ $$$k!%

0EL[E*$JJBNs=hM} (*Implicit Parallelism*)

$$$:lK$;$h (2.3) <0$N%9%-!<%^DjM}$O!$E,1~EY$,9b$/$+$DDj5AD9$NC;$$%9%-!<%^$[$I5^B. =8CDFb$K9-$,CF$$$/3H$rI=$7$F$$$k!%3Nh&$JDj5AD9$NC;$$%9%-!<%^N3Hr!FC

%k%G%#%s%0%V%m%C%/ (*building block*) $H8F$V!%8r:5$H$$$&0dEAE*A`:nKhCF!$GA O3Nh$&
$J%S%k%G%#%s%0%V%m%C%/ (ItJ,2r) $r8+$D$1=P$7!$$5iK$=$lir7k9g9k3HGh$jE,1~EY
9b$$A4BN2r$rF@$k3H$,2DG=$KJk!%3N9M$(J}$O!$%S%k%G%#%s%0%V%m%C%/2>@b (*building bloc*
hypothesis) [Gol89] $H8F$Plk!%

3Nh&$KC;$$Dj5AD9$N%9%-!<%^ (%S%k%G%#%s%0%V%m%C%/) $,;X?t4X?tE*$KA}2C7F$$$/2a
$O!$IU2CE*$JFCJL$J=hM}$r;\$9$3$HJ7$K!$$=l>lN%9%-!<%^4H$KJBNs$K?J$`!%Goldberg $
$=$l$>$l$N@$BeKh$K GA KhCF=hM}5l$k%9%-!<%^$N8D?t$O8DBN?t n $N=8CD[3)]$K$*$$$F $O(n$
$H35;;$7$F$$$k [Gol89]!%<B:]KO!$$=l>lN8DBNKBP7FNE,1~EYI>2A$,0lEY9T$olk$@
G"kN$G!$1@$BeEv$?jN<B:]$N;~4V7W;;NL$*hS6u4V7W;;NL$O $O(n)$ KJ$k!%$D$^$j!$<B
KO $O(n)$ $N7W;;$7$+9T$C$F$$$J$$$NKb4Xoi$:!$<B<AE*KN7W;;$O $O(n^3)$ $r9T$C$F$$$k$N
$HF1$88z2L$r@8$`NG$"$k!%3Nh&$J GA $KFCD'E*$J@-<A$O!V0EL[E*$JJBNs=hM}!W(*implic*
parallelism) $H$$$&8@MU$GI=8=$5lF$$$k!%

2.3 %K%e!<%i%k%M%C%H%o!<%/ (*Neural Networks*)

<B:]$N@8J*$NG>$N@8M}3XE*$J%a%+%K%:%`$K3X$s$G!$7W;;5!>e$GG><+BN$N9=B$$*hSF0:n86M
%b%G%k2=$7!$?M4V$,9T$C$F$$$kh&$J=@Fp$J>pJs=hM}$r9T$o$;$h$&$H9k;n$_$,J5lF$-
3N7W;;5!>e$K%b%G%k2=$5l?G>$O!$%K%e!<%i%k%M%C%H%o!<%/ (*Neural Networks*) $H8F$Plk!
G>$N4pK\E*$J9=@.MWAGG"$k%K%e!<%m%s (?@7P:YK&) $N0l$D0lDOHf3SE*C1=c$J5,B'$K=>C
$kIq$$$rDh9k$,!$$=lGbJ$*!$?M9)E*$J%K%e!<%i%k%M%C%H%o!<%/$K?M4V$NG>$r>\:Y$JItJ
;jk^$G40A4$KLOJo5;k3HOIT2DG=G"$k!%2?8N$JiP!$G>$NCfKOKDBg$J?t$N%K%e!<%
$,B8:_$7!$$7$+$b$=$liN%K%e!<%m%s4V$O8_$$$KJ#;($K@\B3$5lF$$$k$+$iG"$k!%$7$?$,$
7W;;%3%9%H$r8=<BE*$JHO0OFb$KM^$(k?aK!$%K%e!<%i%k%M%C%H%o!<%/$G$OB?$/$NCj>]2=$,$
lk!%$=$lGbJ*!$%K%e!<%i%k%M%C%H%o!<%/$N%G%6%$%s$O3l$^$G$K0Y$5lF$-$?%"%W%m!
NCfG:G$bG>$K6a$$$bNH8@$($k!%$^$?9)3XE*Kb!$%K%e!<%i%k%M%C%H%o!<%/$N9T$&6K$a$F=
$J>pJs=hM}$NFC@-$r3h$+7F!$%(%"%3%s!$@vBu5!!$?fHS4o$JIN2HEE@=IJ$+$i@=E46H$N8=>l!
$k$$$O0e3XNJ,LnH$$$C$?I}9-$$NN0hK*$$$F6C$/$Y$-@-G=$r<(7F$$$k [GO>l 94]!%

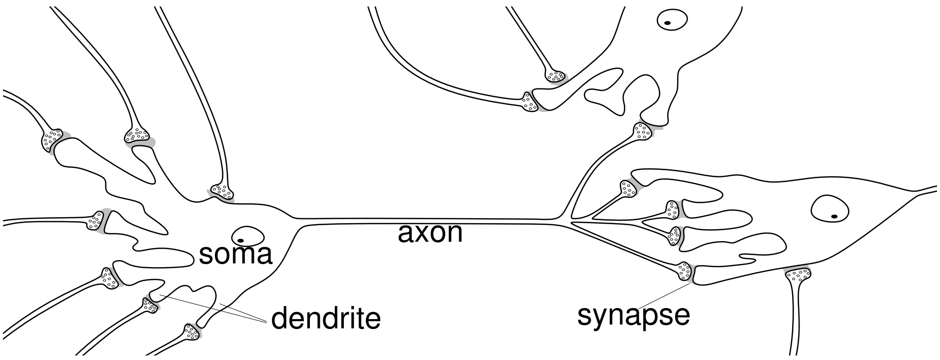
2.3.1 ?M4V$NG>$K$*$1$k?@7P2sO)LV

?M4V ($"$k$$$OF0J*) $NG>$O!$%K%e!<%m%s (*neuron*) $H8F$Plk6KaFB??t$N?@7P:YK&$,8_$$$
J#;($K@\B3$5l?2sO)LV (%M%C%H%o!<%/) $G9=@.$5lF$$$k!%3F!9$N%K%e!<%m%s$N3hF0$O!$J#;
EE5$E*!&@82=3XE*$J2aDx$K4p$E$$$?bNG"k,!$$=$N4pK\E*$J7W;;86M}$*$h$S?6$kIq$$$OC
G"kH9M$($ilF$$$k!%3F%K%e!<%m%s$O!$V<+J,$KF~$CF/$kF~NO?.9f$r2C$(>e$2$F!$ogCMS
Hf3S1i;;$N7k2L$K1~8F<+J,$N=PNO?.9f$r=PNO9k!W!%3Nh&$JHf3SE*C1=c$J?6$kIq$$$,?

$NCNE*3hF0$Nh&$JJ#;($J?6$kIq$$$r@8$_=P$9HkL)$O!$KDBg$J?t$N%K%e!<%m%s4V$NAj8_:nMQ$
$k!%$3$NKDBg$J%K%e!<%m%s4V$NF/$-KhCFAOH/9k?6$kIq$$$3$=$,@8J*$NCN@-$N:,8;G"$
8@ol$F$$$k [Cri94]!%

%K%e!<%m%s (*Neuron*) $N9=B$

E57?E*$J@TDGF0J*$N%K%e!<%m%s$N9=B$$r?^ 2.5 $K<($9!%%K%e!<%m%s$O5!G=>e!$F~NOC<;RG"
<y>uFM5/ (*dendrite*)!$=PNOC<;R$G$"$k<4:w (*axon*)!$$JiS$KK\BN$N:YK&BN (*soma*) NBg^$+$K;0
DNItJ,$KJ,$1il$k!%



?^ 2.5: %K%e!<%m%s

3F%K%e!<%m%s$O!$:YK&BN$d<y>uFM5/$KF~CF$/$kEE5$%Q%k%9$KBP7F!$6=J3@-!$M^@)@-!$D
@-$H$$$C$?;0<oN`$NH?1~r9$k!%6=J3@-$NH?1~$N>l9g$K$O!$2C$(>e$2il$?F~NO?.9f$,$"$kc
$r1[$(kJI7$F%K%e!<%m%s$,==J,$K6=J3$9kH!$EE5$;I7c$r=PNO%1!<%V%k$G$"$k<4:w$XAw=
kH$$$&7A$G!$%K%e!<%m%s$,H?1~ (H/2P) 9k!%EE5$?.9f$O<4:w$+$iJ,4t7?B&;^rEAoCF!
$N%K%e!<%m%s$KC#9k!%3Nh&$K%K%e!<%m%s$O!$B>$NB?$/$N%K%e!<%m%s$+$iEE5$%Q%k%9$N7
>pJs$r<u$1<h$j!$%@%$%J%_%C%/$J=hM}$r2C$($?>e$G!$$^$?EE5$%Q%k%9$N7A$GJL$N%K%e!<%m%s$
$k!%$H3m$G!$%K%e!<%m%s$H%K%e!<%m%s$N@\9gIt0LG"$k%7%J%W%9 (*synapse*) GOD>@\E*$JEE5
?.9f$N<x<u$,9Tolko1GOJ$/!$%J%H%j%&%`%$%*%s$d%+%j%&%`%$%*%s$N0\F0$H$$$C$?2=3
$J2aDx$r2p7F?.9f$,EA$(il$k[3]$Nh&$J%K%e!<%m%s$N3hF0N?aNJ,;R$NBe<U5!G=$J$I
$OI,MWIT2D7g$G$"$k$,!$%K%e!<%m%s$NK\<AE*$J5!G=$O?.9f$N<x<u$H$$$C$?!$$$$ofk>pJs$N=
G"$k!%

[3] <B:]!FsD$N%K%e!<%m%s$N4VKO 0.02 %_%/%m%s$[$I$N4V7d (%7%J%W%94V7d) $,$"$k!%EE5$%9%Q%$%/$,%7%J%W%9$K
Ce9k$H%7%J%W%94V7d$K2=3XJ*<A$N>.$5JJq_ (%7%J%W%9>.Jq) $,J|=P$5$l!$$3$N%7%J%W%9>.Jq$,<u$1F~$lB&%K%e!
%s$N%7%J%W%9$N%$%*%s%A%c%M%k$r3+$/!%$9kH%J%H%j%&%`%$%*%s$O%K%e!<%m%sFb$K?/F~$7!$%+%j%&%`%$%*%s$O%K%e
%s30$KJ|=P$5lk3H$G!$<u$1F~$lB&$N%K%e!<%m%s$N%7%J%W%9It$NEE0L$,>e>:$7!$%$%s%Q%k%9$NH/@8$r0z$-5/$3

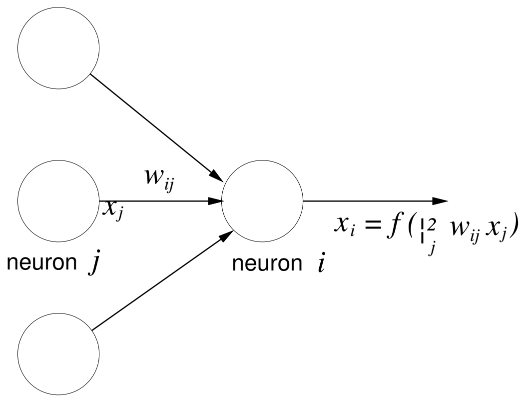
Dj>o;~$N%K%e!<%m%s$O!$Hf3SE*$fC/j7$?IT5,B'$JEE5$%Q%k%9$r<4:wKAwj=P7F$$$k!
$N<~GH?t$O 1!A5 Hz G"$j!$%P%C%/%0%i%&%s%I<~GH?t$H8F$Plk!%3N;}B3E*$JEE5$%Q%k%9$
%K%e!<%m%s$r0lDj$N6=J3>uBV$KJ]$A!I,MWH$"$iPh$j6/NO$KH/2PG-kh$&$K7F$*$/$?$
bNG"$k!%0lJ}!$%K%e!<%m%s$,6=J3$7$?>uBV$G$O?tB?$/$NEE5$%Q%k%9$,H/$;il!$$=$N:]$
GH?t$O 50!A100 Hz DxEY$G$"$k$,!$=V4VE*KO 500 Hz $KC#$9k3Hb$"$k!%0lIC4V$K 500 2s$N
%Q%k%9$H$$$($P!$$+Jj9bB.Nh$&$K;Wolk,!$:#F|$N%Q%=%3%s$N>pJs=hM}$NB.EY$HHf3S$
$H6C$/$[$ICY$$!%%Q%=%3%s$N>pJs=hM}$N%9%T!<%I$O!$%K%e!<%m%s$NB.EY$N%BKb$J[6]10
$k!%$7$+$7!$?M4V$NG>NCfK$O 10[11]$N%K%e!<%m%s$,B8:_$9$k!%100 Hz $N%Q%k%9$rH/7F$$$k
%K%e!<%m%s$N<4:w$r!$KhIC 100 %S%C%H$N?.9f$rEAC#$9$k%1!<%V%k$H$_$J7F35;;9k$H!$?M4V
G>A4BNGO!$KhIC 10[13] %S%C%H$N>pJs$N<x<u$,0Y5l$F$$$k3HKJ$k!%$3lOC1$K%G!<%?$NEA
C#NLN_$K4X$9$k35;;$G$"$k!%3F!9$N%K%e!<%m%s$,J?6Q7F$N 10[4] %J%W%9$+$iF~NO$r<u$1
<hCF$$$k3H!$$5iK3F%K%e!<%m%s$G<B:]$K9Tol$F$$$k7W;;$r9MN8$9kH!$G>$O6KaFK
JNLN%G!<%?$r=hM}$7$F$$$k3HKJ$k!%$3lO!$:#F|$N:GB.$N%9!<%Q%3%s%T%e!<%?$N?tI4K
0J>e$NB.EY$KAjEv9k!%3N;v<B$O!$D6JBNs7W;;5! (*massively parallel computers*) $N8&5f$NBg$-
$J86F0NO$N0lDHbJCF$$$k!%

G>$N3X=,$H5-21

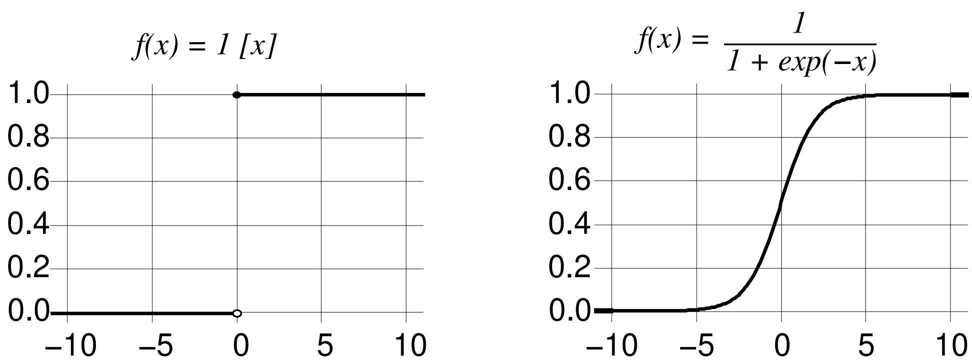
!VG>$N3X=,$d5-21$r<B8=$9$kJ*<AE*<BBN$O2?$+!)!W$H$$$&LdKBP7$F!$$"$k?M$OG>Fb$N2=
J*<A$N9=B$JQ2=KhkbNG$"$k$H9M$(!$$^$?$"$k?M$O0dEA;R$NG[Ns$NCf$K3X=,$7$?>pJs$,3
5lkNGO$J$$$+$H9M$($?!%$3lKBP7F?4M}3X<T$N Hebb $O 1949 G/$K!$?@7P7O$N3X=,$C
%K%e!<%m%s4V$N%7%J%W%92Y=E$NJQ2=KhkbNG$"$kHN9M$(J} (**Hebb** $N2>@b) $rDs>'$7$
Hebb $N2>@b$O!$?@7P:YK&$,%$%s%Q%k%9$r=PNO7?H-!$$=lK2YC4$7$?F~NOA!0]$+$i$N%7%J
%9$N7k9g$,6/2=5lkH$$$&bNG"C?!%Ev;~$O!$$3lOC1Jk2>@b$K2a$.J+C?$,!$$
8e$N@8M}3XE*$J<B83KhCF!$3N$+$K%7%J%W%9$N6/5O!$$=$NF~NO?.9f$NAj4XKhCFJQ2=$
3H$,<B>Z$5lF$-$?!%

FsDN%K%e!<%m%s4V$GEE5$?.9f$,$d$j<h$j5l$k:]$K!$N><T$r@\B3$9$k%7%J%W%9$N4V$G2=3
$J2aDx$,4XM?7F$$$k3H$OA0=R$7$?$H$*$jG"$k!%$3NH$-$KEE5$E*$J?.9f$N<x<u$K4XM?$
%J%H%j%&%`%$%*%s$d%+%j%&%`%$%*%s$N:YK&Fb30XN0\F0N[$+$K!$AjEvNL$N%+%k%7%&%`%$%*%
%K%e!<%m%sFb$K0\F~$7!$0lO"$NJ#;($J2=3XH?1~$r3+;O5;$k%7%0%J%k$NLr3d$r2L$?$9!%$3$N2
H?1~$K4X$7FO8=:_$OItJ,E*$K7+2rL@5l$F$$$J$$$,!$:G=*E*$Kb?i5lk8z2L$OD94|$
$?$C$F;}B3$9$k%7%J%W%9@\9g$N6/EY$NJQ2=$G$"$k$H9M$(il$F$$$k [Cri94]!%3Nh&$K!$%7%J
%97k9g6/EY$NJQ99$rDL8F3F%K%e!<%m%s$,B>$N%K%e!<%m%s$KM?$($k1F6A$rJQ2=5;$FG>A4BN$
Js=hM}2aDx$rJQ99$9k3H,!$3X=,$d5-21$KAjEv$9kH9M$($ilF$$$k!%

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



?^ 2.6: ?M9)%K%e!<%m%s



(a) Step Function (b) Sigmoid Function

?^ 2.7: %K%e!<%m%s$N=PNO4X?t

<B:]$N@8J*$NG>$N%a%+%K%:%‘$KCeA[$rF@$?%K%e!<%i%k%M%C%H%o!<%/$b?M9)E*$J%K%e!<%m%sB $rAj8_$K@\B3$7$?2sO)LV$G9=@.$5lk!%?M9)E*%K%e!<%m%s (0J2<!$C1$K%K%e!<%m%s$H5-$9) $O! ?t$NF~NO?.9f$r<u$1<h$j!$$=$N4X?t$H7F=PNO$r7hDj$9$k (?^ 2.6) !%

1943 G/$K!$McCulloch $H Pitts $O!$0J2<$N<0$GI=5l$k%K%e!<%m%s$N%b%G%k$rDs0F$7$? [MP43]!%

$$x_i(t+1) = 1\left[\sum_j w_{ij} x_j(t) - \theta_i\right] \tag{2.4}$$

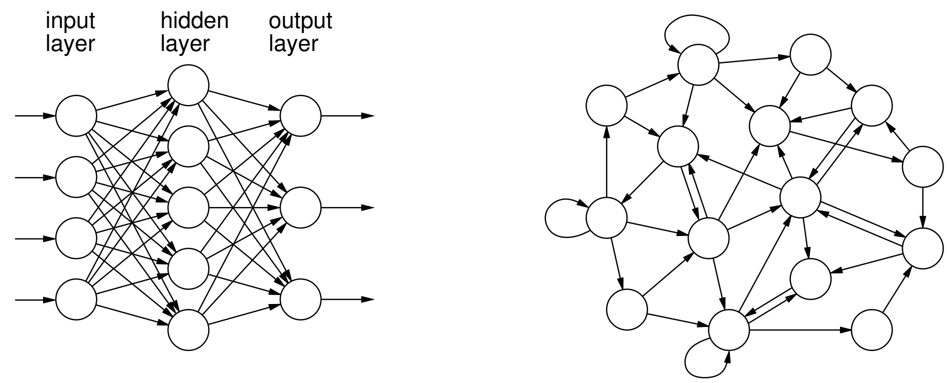
$3$3$G!$ $x_j(t)$ $O;~9o t K*1k%K%e!<%m%s j $N=PNOCM$, w_{ij} $O%K%e!<%m%s j $+$i%K%e!<%m%s i XN%7%J%W%97k9g6/EY$r!$ θ_i $O%K%e!<%m%s i $NogCM$rI=$9!%$^$?!$ $1[x]$ $O!?^ 2.7 (a) $,<($9h& $K!$ $x \geq 0$ NH$- 1!$ $x < 0$ NH$- 0 HJ$kC10L%9%F%C%W4X?t$rI=7F$$$k!%1 $r6=J3>uBV!$0 $r

@E;_>uBV$H9M$(kH (2.4) <0$O!$%K%e!<%m%s j $+$iEAoC$$x_j(t)$?$,9=E$_IU$1il$F2C;;$5 $l!$%K%e!<%m%s i $KC#$7!$$=l,$"$k$gCM θ_i (kH%K%e!<%m%s i $,6=J3$9k3Hr0UL#$7 $F$$$k!%(2.4) <0Kh$k%K%e!<%m%sI=8=$O:G$b4pK\E*$J%b%G%kH5lF$$$k$,$x$ $,[$x$]$G6aGO 1 $$$&C10L%9%F%C%W4X?tNBeojK?^ 2.7 (b) $K<($7$?%7%0%b%$%I4X?tGCV-49$($?0J2<$N%K%e %m%s$N%b%G%k$,;HMQ$5lk!%

$$x_i(t+1) = \frac{1}{1+\exp\left(-\left(\sum_j w_{ij}x_j(t)+\theta_i\right)\right)} \tag{2.5}$$

>e$K<($7$? (2.5) <0$O!$Hs@~7A$G$"$jJ,$iA4$F$NE@$K$*$$$FHyJ,2DG=G"$j!$$3$NFC@-$O<! $K=R$Y$k8m:95UEAGE3X=,K! (BP K!) K*$$$F6KaF=EMW$JLr3d$r2L$?$7$F$$$k [4]

%K%e!<%i%k%M%C%H%o!<%/$O!$9=B$>e$N4QE@$+$i?^ 2.8 $K<($9h&KFsD$KJ,N`$5lk!%(a) 3,AX9=B$$N%K%e!<%i%k%M%C%H%b%G%kGO!$?.9f$NN.lO0lJ}8~E*$J%U%#!<%I%U%)%o!<%I7?$G$ (b) $NAj8_7k9g9=B$$N%K%e!<%i%k%M%C%H%b%G%kGO?.9f$NN.$l$,=gJ}8~$N$_$H$O8B$i$J$$!%0 GO!$A0<T$N3,AX9=B$$N%K%e!<%i%k%M%C%H%o!<%/H=$N3X=,K!$K$D$$$FN_=RYk!%



(a) Multi–Layered Feed Forward Network   (b) Mutually–Connected Network

?^ 2.8: %K%e!<%i%k%M%C%H%o!<%/$N9=B$

2.3.3 8m:95UEAGE3X=,K! (*Back Propagation Learning*)

$$$^$d!$%K%e!<%i%k%M%C%H%o!<%/$OCN@-E*$J%7%9%F%`$r9=C[$9k?aNM-NO$JF;6q$N0lD $FG'<1$5lDD"$k!%$=lO!$%K%e!<%i%k%M%C%H%o!<%/$,3X=,KhCFCNG=$r3MF@$9k3H $-$k$+$iG"$k!%!VCNG=$N3MF@!WHO!$6qBNE*$K$O!$3X=,KhCF0UL#N"$k>pJs=hM}$r9T$ $&$J%M%C%H%o!<%/$NE,@Z$J7k9g6/EY$r8+=P$9$3$HG"$k!%

[4](2.4) <0Nh$&$J%G%8%?%k$J:YK&%b%G%k$N%M%C%H%o!<%/GO!$3,AX7?%K%e!<%i%k%M%C%H$K$*$1$kCf4VAX$G$N:G5 2<3X=,$O=PMh$J$$!%$^$?!$@~7A$N:YK&%b%G%kGO!$$$$/$iB?AX$K7Fb=$NG=NO$OFsAX$N%M%C%H%o!<%/$HJQoi$ J*!$FsAX$N%M%C%H%o!<%/$N3X=,G=NO$K6KaF=EBg$J@)8B$,$"$k3H$O>ZL@$5lF$$$k [MP69]!%%"%J%m%0Hs@~7A :YK&%b%G%k$rMQ$$$k3HKhCF!$B?AX%M%C%H%o!<%/$G$NC1=c$+$D6/NO$J3X=,B'$r<B8=$9k3H,2DG=JNG"

8m:95UEAGE3X=,K! (*Back Propagation Learning*) HO!$3,AX7?$N%U%#!<%I%U%)%o!<%I%K%e!<%i %k%M%C%H%o!<%/$N7k9g6/EY$r71N}KhCF5aakJ}K!G"$k [RMtPRG86]!%8m:95UEAGE3X=,K (0J2<!$BP K!) $G71N}$5lkE57?E*$J%K%e!<%i%k%M%C%H%o!<%/$N9=B$$O!$?^ 2.8 (a) $K<($9h $K30It$+$i?.9f$r<u$1<h$kF~NOAX (*input layer*) $H30It$X?.9f$r=PNO$9$k=PNOAX (*output layer*) $N 4V$K1#$lAX (*hidden layer*) $,64$^l?;0AX$+$i@.k,!$0lHL$K$O1#$lAX$,J#?tB8:_$9$k;MAX0J> $N3,AX7?%K%e!<%i%k%M%C%H%o!<%/$r71N}$9k3Hb2DG=G"$k!%BP K!$G$O!$%K%e!<%i%k%M%C %o!<%/$K7+$jJV$7F~=PNO$N%Z%" (I, O) $,Ds<($5$l!$%K%e!<%i%k%M%C%H%o!<%/$OF~NO I $,M?$(l?H-$KM}A[=PNO O $r=PNO$9kh$&$K71N}5l$k!%$3liF~=PNO$N%Z%"$O$=$l$>$lF~NOA =PNOAX$N3hF0%Q%?!<%s$rI=7F$*$j!$%K%e!<%i%k%M%C%H%o!<%/$O3Nh&$JK>$^lkF~=PNO4 K7$?$,C??6$kIq$$$r9kh$&$JFbIt9=B$$r9=C[7F$$$/NG$"$k!%F~NOKBP7$FM}A[=PN M?$(ilkH$$$&0UL#K*$$$F!$BP K!$O65;U$"$j3X=, (*Supervised Learning*) $KJ,N`$5lk!%

BP K!$N3X=,$N2aDx$O!$0J2<NFsD$N6ILL$KJ,1ilk!%

1. F~NO?.9fEAGE%U%'!<%:

   F~NOAX$KM?$(il$?F~NO?.9f$K4p$E$$$F!$F~NOAX$+$i;O$a$F!$3FAXK*1k3F!9 $N%K%e!<%m%s$N=PNO$r<!!9$KNYNAXN%K%e!<%m%s$KEAGE$7$F$$$-!$=PNOAX$K$*$1 $k=PNO?.9f$rF@$k!%

2. 8m:95UEAGE%U%'!<%:

   <B:]$KF@$il?=PNO$HK>$`M}A[=PNO$N:9$+$i8m:9$r7W;;$7!$$=$N>pJs$r=PNOAX $+$iF~NOAX$K8~$+CFEAGE$7!$3F%K%e!<%m%s4V$N%7%J%W%97k9g6/EY$rHyL/$KD4@0 9k!%

71N}$N3+;O;~$K$O!$A4FN%7%J%W%9$N7k9g6/EY$K$O%i%s%@%`$JCM$,M?$($i$l$k$N$G!$%K%e!<% %M%C%H%o!<%/$X$N$$$+$J$kF~NO?.9f$KBP$7$F$b:G=i$NH?1~$OL50UL#$J$b$N$G$"$k!%BP K!$N%' %4%j%:%`$NE,MQKhCF!$%K%e!<%i%k%M%C%H%o!<%/$,A4BNH7FN8m:9$r:G>.$K9kh&$K: $/D4@0$5lF$$$-!$$3$N2aDx$r2?EY$b7+$jJV$9$3HG:G=*E*$KM}A[E*$J9=B$$r3MF@7F$$$/

0J2<$K!$$p$ 8D$N%K%e!<%m%s$rF~NOAX$K!$$q$ 8D$N%K%e!<%m%s$r1#lAXK!$$r$ 8D$N%K%e!<%m%s$r NOAX$K;}$D%K%e!<%i%k%M%C%H%o!<%/K*1k BP K!$N<j=g$rhj>\:Y$K<($9!%F~NOAX$N%K%e!< %s i $+$i 1#lAXN%K%e!<%m%s j XH@\B3$9$k%7%J%W%9@\9g6/EY$r w_{ij} $H!$1#lAXN%K%e!<%m%s i $+ $i=PNOAX$N%K%e!<%m%s j XH@\B3$9$k%7%J%W%9@\9g6/EY$r v_{ij} H9$k!%$^$?!$ $\boldsymbol{x} = (x_1, \cdots, x_p)$ $OF~NO%Q%?!<%s%Y%/%H%k$r!$ $\boldsymbol{o} = (o_1, \cdots, o_r)$ $O<B:]$N%K%e!<%i%k%M%C%H%o!<%/$N=PNO%Q%?!<%s %Y%/%H%k$r!$ $\boldsymbol{y} = (y_1, \cdots, y_r)$ $OM}A[=PNO%Q%?!<%s%Y%/%H%k$rI=$9bNH9$k!%

1. %M%C%H%o!<%/$NA4$F$N%7%J%W%97k9g6/EY$r%i%s%@%`JCMG=i4|2=9k!%

2. F~=PNO%Z%" $(\boldsymbol{x}, \boldsymbol{y})$ $rA*$S!$ $\boldsymbol{x}$ $rF~NOAX$KM?$($k!%

3. F~NOAX$N%K%e!<%m%s$N3hF0$r1#$lAX$N%K%e!<%m%s$KEAGE5;!$1#$lAX$N%K%e!<%m%s j $N3hF0 h_j $r (2.5) <0$K4p$E$$$F7W;;9k!%%K%e!<%m%s j $N2DJQ$N θ_j $O>o$K 1 $r=PNO$9$k%@%_!<%K%e!<%m%s$H%K%e!<%m%s j $r@\B3$9$k%7%J%W%97k9g6/EY$N7A$GI=8= 5l$k (Appendix B $N?^ B.1$r;2>HN3$H) !%

$$h_j = \frac{1}{1 + \exp\left(-\left(\sum_{i=1}^{p} w_{ij}^{1} x_i + \theta_j\right)\right)}$$

4. 1#lAXN%K%e!<%m%s$N3hF0$r=PNOAX$N%K%e!<%m%s$KEAGE5;!$=PNOAX$N%K%e!<%m%s j $N3hF0 o_j $r (2.5) <0$K4p$E$$$F7W;;9k!%

$$o_j = \frac{1}{1 + \exp\left(-\left(\sum_{i=1}^{q} w_{ij}^{2} h_i + \theta_j\right)\right)}$$

5. =PNOAX$N%K%e!<%m%s j K*1k=PNO8m:9 δ_j^o $r!$<B:]$N=PNO%Q%?!<%s%Y%/%H%k $\boldsymbol{o} = (o_1, \cdots, o_r)$ $HM}A[=PNO%Q%?!<%s%Y%/%H%k $\boldsymbol{y}$ $N:9$rMQ$$$F0J2<Nh$&$K5aak!%

$$\delta_j^o = o_j(1 - o_j)(y_j - o_j)$$

6. 1#lAXN%K%e!<%m%s i K*1k=PNO8m:9 δ_i^h $r!$A0CJK*$$$F5aa?=PNOAXK*1k=PNO8m:9 δ_j^o $rMQ$$$F0J2<Nh$&$K5aak!%

$$\delta_i^h = h_i(1 - h_i) \sum_{j=1}^{r} \delta_j^o w_{ij}^2$$

7. %K%e!<%m%s i $+$i%K%e!<%m%s j $K@\B3$9$k%7%J%W%97k9g6/EY$r0J2<Nh$&$K=$@5$9$k!%

$$w_{ij}^2(t+1) = w_{ij}^2(t) + \eta \delta_j^o h_i + \alpha \Delta w_{ij}^2(t)$$

$$w_{ij}^1(t+1) = w_{ij}^1(t) + \eta \delta_j^h x_i + \alpha \Delta w_{ij}^1(t)$$

$3$3$G!$ $\Delta w_{ij}(t) = w_{ij}(t) - w_{ij}(t-1)$ G"$j!$:G8e$N9`$O47@-9`$H8FPl$k!%$^$?!$ η $O3X=,N(!$ α $O47@-78?t$H8FPl$k!%

8. 0J>e$N 2. $+$i 7. $N<j=g$r=PNO8m:9$,==J,$K>.5/Jk$^$G7+jJV9!%

%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:94X?t$r!$%M%C%H%o!<%/Fb$N3F7k9g6/EY w_{ij} r^Ha$F;}$D7k9g6/EY%Y%/%H%k $\boldsymbol{w}$ $N4X?t$H7F!$0J2<$Nh&$KDj5A$9$k!%

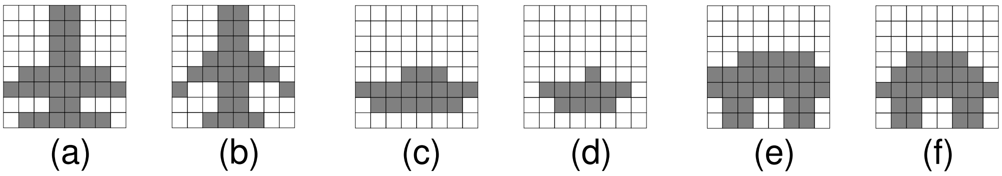
$$E(\boldsymbol{w}) = \frac{1}{2} \sum_{j=1}^{r} (y_j - o_j)^2 \tag{2.6}$$

3NH-$K!$3F%K%e!<%m%s$N3hF0$, (2.5) <0$K=>$&bNH9kH!$>e5-$N BP K!$N<j=g 7. $G9T$
$F$$$k7k9g6/EY$N=$@5$O0J2<$N<0$GI=$5lk!%

$$\boldsymbol{w}(t+1) = \boldsymbol{w}(t) - \eta \left. \frac{\partial E(\boldsymbol{w})}{\partial \boldsymbol{w}} \right|_{\boldsymbol{w}=\boldsymbol{w}(t)} + \alpha \Delta \boldsymbol{w}(t) \qquad (2.7)$$

>e$N (2.7) <0$O!$(2.6) <0$GI=5l$k%K%e!<%i%k%M%C%H$N8m:94X?t$N8{G[%Y%/%H%k$r7W;;$7!$$=$
5UJ}8~$K $\boldsymbol{w}$ $r2~NI$9kH$$$&$$$ofk:G5^9_2<K! (*steepest descent method*) $N<j=g$HEy2AG"
$k [GO>l 94]!%

BP K!$NE57?E*$J1~MQNc$O%Q%?!<%sG'<1$NLdBjG"$k!%Nc$($P!$?^ 2.9 $K<($9h&$J$$$/D
$N?^7A%Q%?!<%s$r%K%e!<%i%k%M%C%H%o!<%/$K7+$jJV$7Ds<($9kH!$%M%C%H%o!<%/$O3F!9$N%Q%
%s$NFCD'$KCmL\$7$F3X=,$r9T$&!%$=7F==J,$J71N}$,:Qs@8e$K!$N`;w7??^7A$,F~NO$5l
$=$l$rE,@Z$KJ,N`!$G'<1$9kh$&$KJk [0B@> 89]!%BP K!Kh$k%Q%?!<%sG'<1$NJ}K!$O!$Hs>o
6=L#?<$$$bNG$"$kNG!$KvHx$N Appendix B KF!$?^ 2.9 $K4X$7$F9T$C$?<B83$N7k2LKD$$$
4JC1$K=R$Y$k!%



?^ 2.9: %Q%?!<%sG'<1

2.3.4 %K%e!<%i%k%M%C%H%o!<%/$N2DG=@-$H8B3&

%3%s%T%e!<%?$,C1=c$J7W;;$r9bB.$K<B9T9k0J30Kb!$$"$k<o$NCNE*$J7W;;$r9T$&$3H,$
$k2DG=@-$K?M!9$,5$IU$$$F0JMh!$(?M4V$N) CN@-E*$J3hF0$rLOJo9k7W;;5!rAOj=P9Y$/MM!
;n$_$,J5lF$-$?!%7+$7!$$3N3HOEv=i9M$($ilF$$$?$[$I!$4JC1$J3HGOJ+$C
=>Mh$N8EE5E*$J?M9)CNG=$NJ}K!$G$O!$%A%'%9$r%W%l$$$9kH$+!$2?i+$N:GE,2=LdBj$r
2r7h9kG"kH$+!$$"$k$$$O0eNE?GCGr9kH$$$C$?FCDj$N69$$NN0h$K4X$7$FCNE*$JH=CG$
$k7W;;5!%W%m%0%i%`$OF@ilFb!$?M4V$,$$$ofkF|>o@83hK*$$$F9TCF$$$k!VCN@-E*!W$
CG$r9T$&%W%m%0%i%`$r:n$k3H$OE~DlIT2DG=$G$"$C$?!%!VCN@-E*!W$H8FYk?6$kIq$$$r9k$
KO!$MM!9$J0[JC$?;vJA$r07$&$3H,G-!$$^$?ITB,$N;vBV$KAx6x$7FbE,@Z$JH=CG$r9T$
=@Fp$KBP=h$G$-$kI,MW$,$"$k!%

[5] K\O@J8$N<9I.Cf (1996 G/ 2 7n) $K!$%A%'%9@$3&%A%c%s%T%*%s$N Kasparov ;a (%m%7%"?M) $HJF9q IBM <R$, 7 G/$K
EOCF3+H/7F$-$??M9)CNG= Deep Blue HN4V$G%A%'%9$NBP@o$,9T$ol?!%Deep Blue $O 3 J,4V$K 500 2/bN%2!<%`
$N6ILL$rC5:w$7I>2A$9$kG=NO$r;}CF$$$?Kb4Xoi$:!$7k2LH7FO 3 >! 1 GT 2 J,$G?M4VB&$K73G[$,>e$,C?!
$+$7!$@lLg2H$Khk$H Deep Blue $O%A%'%9$N@$3&$G 60 0L0JFb$N<BNO$r;}CF$$$k$HI>2A$5$l!$?M9)CNG=5;=Q$N?J
$,3NG'$5lkHHbK2]Bjb^$@;D$C$F$$$k3H$r<($97k2LHJC?!%

5,B'%Y!<%9$"$k$$$OCN<1%Y!<%9JI$NCN<19)3X (*knowledge engineering*) E*$J<jK!$K4pE/8E
E5E*$J?M9)CNG=$NJ}K!Kh$kLdBj$O!$%W%m%0%i%^$,A4FNCN<1$d5,B'$rM?$($FL@<(E*$J%W%m%
%`$G<jB3$-$r5-=R$9kI,MW,$"$k$H$$$&E@K"$k!%$3Nh$&$JCN<1$d5,B'$O!$35$7$F!$IT40A
$"$j!LCNG"$j!$$7$+$b8mCF$$$k>l9g5($"$k!%Nc$($P!$0eNE?GCG$K$*$$$F!$?M4V$N@lI
KHCFE,@Z$JH=CG<+BN$r9k3H$OMF0W$G$"$CFb!$!V2?8N!W$"$k$$$O!VINh&$JGX7JC
$K4p$E$$$F!W$=$Nh&$JH=CG$r9TC?N+$r@53N$K@bL@9k3H$O!$H=CG$r9T$C$?Ev?M$KH
5(MF0WJ3HGOJ$$!%35$7$F!$=8@Q$5lkKDBg$JCN<1$r$-$AsHDj5A5l$?5,B'$@1GI
9k3H$OIT2DG=$G!$3NN(E}7WE*$J?dO@J}<0$d%U%!%8%#O@M}$JI,I,MWKJCF$/$k!%$^$?!
@$3&$K$*$1k3$&$7$?CN<1$K$O!$B?$/$N%N%$%:$,4^$^$l$F$$$k!%3Nh&$JKDBg$+$D;(2;$,4
lF$$$k>pJs$+$i0UL#$"$k5,B'$rF3$-=P$9$3HN:FqO%K%e!<%i%k%M%C%H%o!<%/KhCF2r7
lk$H8@$olF$$$k!%$^$?!$%K%e!<%i%k%M%C%H%o!<%/$O!V@dBPE*$JCN<1!W$N$J$$LdBjNN0hK
FOFC$KM-8z$G$"$k!%2?8NJi$P%K%e!<%i%k%M%C%H%o!<%/$O3X=,KhCF!$KDBg$JNcNCf+$
F0E*$K5,B'@-$r8+=P$7!$J#;($JLdBjNN0h$K$*$1$kCN<1$rCj=P9k3H$,2DG=$@$+$iG"$k!%<
$K!$2hA|=hM}!&2;@<=hM}!&3t2AM=B,JI$NE57?E*$J1~MQNc [GO>l 94] $NB>$K$b!$;(2;$NB?$$>u
NCfGF0:n9k%m%\%C%HJI$N9TF0$r%K%e!<%i%k%M%C%H%o!<%/$rMQ$$$F3X=,5;$kJ}K!$rDs0I
$=$N8z2L$r3NG'$7$F$$$k8&5fNcb"$k [LM92, Lin93]!%

$^$?%K%e!<%i%k%M%C%H%o!<%/$N;}$D=EMW$JFCD'$H7F!$BQ>c32@- (*fault tolerance*) $KM%$lkH
$$$&E@$,5s$2il$k!%%K%e!<%i%k%M%C%H%o!<%/GO!$3X=,$KhC$F3MF@$7$?>pJs$O!$%7%J%W%
7k9g6/EY$H$$$&7A$G%M%C%H%o!<%/A4BN$KJ,;62=5l$FJ];}$5lk!%3N$?$a$K!$0lDN%f%K%
$d7k9g$,%@%a!<%8$r<u$1FbA4BNH7$F5^7c$K@-G=rMn9$3$H$,$J$/!$%@%a!<%8$NA}2C$KBP$
4Kd+$K@-G=$rDc2<5;k@1N798~$r;}$D [SR87]!%$^$?!$%@%a!<%8$+iN2sI|$b3X=,$r:G=i
id$jD>$9NKHfYl$PB.$/!$6K$a$F>c32$K6/$$%"!<%-%F%/%A%cG"kH8@$($k!%0lJ}!$8EE
$J?M9)CNG=$NJ}K!Nh$&$KL@<(E*$+$D5-9fE*$J7A$G>pJs$rJ];}$9$kJ}K!$G$O!$$?H($%@%a!<%
>.$5$$$H7Fb=lr<u1k2U=jKhCF$O!$%7%9%F%`$N=EBg$J5!G=Dc2<rb$?$i$9!%

0J>e$K=R$Y$?$h$&$K!$Hs>o$KC1=cG"jJ$,$i9bEY$J>pJs=hM}$N2DG=@-$*$h$SM%$l$?BQ>c3
$r;}$D%K%e!<%i%k%M%C%H%o!<%/$N35G0$O!$:#8e!$%(!<%8%'%s%HJIN5iK9bEY$JCNE*LdBj2
%7%9%F%`$N9=C[$N:]$N4pHW5;=Q$N0lDH7F=EMW$JLr3d$rC4$&$bNH9M$($ilk [9g86 93]!%

0lJ}!$%K%e!<%i%k%M%C%H%o!<%/$K$b<eE@$O$"$k!%Nc$($P!$=>Mh$N5,B'%Y!<%9$N%7%9%F%`$K$
FO!$Prolog JI$rMQ$$$FCN<1$rL@<(E*$K5-=R9k3H$G!$D>AK=jK>$N5,B'$K=>CFF0:n$9
%7%9%F%`$r9=C[$9k3H,G-$k!%$H3m$,!$%K%e!<%i%k%M%C%H%o!<%/K"$k5,B'$r3X=,5
$?$aKOB??tNNcrDs<(9kI,MW$,$"$j!$>l9gKhCF$O=jK>$NF0:n$r9=$kh&KJk^G
;~4V$N71N}$rMW9k3H$,$"$k!%=t5,B'$,L@3N$KDj5A2DG=$G$"$k "*well-defined*" $JLdBjNN0h$K$
$$$F$O!$=>Mh$NCN<19)3XE*$J%"%W%m!<%A$N%7%9%F%`$NJ}$,8zN(E*$G$"$k>l9g$,B?$$!%

2.4 3+J|7?J,;64D6-$H?M9)@8L?$N%"%W%m!<%A

K\@aGO!$3+J|7?J,;64D6-2<$K$*$1$k:#8e$N>pJs=hM}%7%9%F%`$r9MN8$7$F$$$/>e$G!$$3l
=RYF$-$?0dEAE*%"%k%4%j%:%`$d%K%e!<%i%k%M%C%H%o!<%/$JIrClH9$k?M9)@8L?E*$J>pJs=
$N%Q%i%@%$%`$,G!2?$K=EMWG"k+$H$$$&E@KD$$$F$^$Hak!%

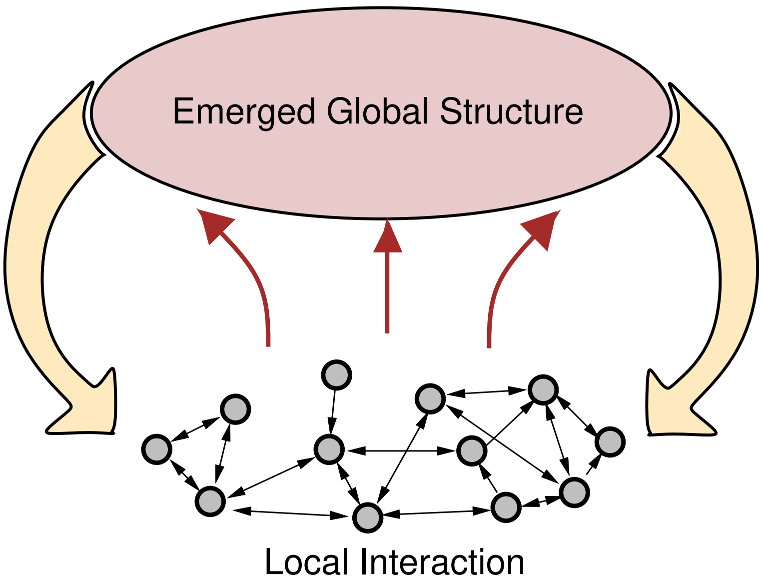
2.4.1 8EE5E*$J>pJs=hM}$N%"%W%m!<%A$N8B3&

=>Mh$+$i$N8EE5E*$JLdBj2r7h%7%9%F%`$N%"%W%m!<%A$O!$%7%9%F%`FbIt$K@$3& (4D6-) $N%b%G%k
J];}$7!$$=$NFbIt%b%G%k>e$G$NC5:w5;=Q [Pea84] $r4pAC$H9kJ#;($J%W%i%s%K%s%0$d?dO@Kh
LdBj2r7h$r9T$&$H$$$&bNG"C?!%%7%9%F%`$N@_7W<T$O!$%7%9%F%`$N9=C[;~$K4D6-$K4X$9$
EvNL$N>pJs$r$"$i$+$8$a%7%9%F%`Fb$KKd$a9~$`I,MW$,$"$k!%b7$/$O!$F0:n;~$K%7%9%F%`$,3
HNAj8_:nMQrDL8$FF0E*$K4D6-$N>pJs$r3MF@7F$$$/bN [SCT95] b"k,!$%7%9%F%`FbIt
$OHf3SE*%7%s%\%j%C%/$J9=B$$G4D6-$N%b%G%k$,9=C[5l$k!%!VCN<1%Y!<%9!W(*Knowledge-Based*)
$d!V5,B'%Y!<%9!W(*Rule-Based*) $H8F$PlkCN<19)3X (*knowledge engineering*) E*$J%"%W%m!<%A$K
4pE/%7%9%F%` [DL82] $,$=$NBeI=Nc$G$"$k!%7+$7!$$3Nh$&$JL@<(E*$J5,B'!$FbIt$N9E$$
<1I=8=%b%G%k$K4p$E$/LdBj2r7h$N%"%W%m!<%A$r<h$k%7%9%F%`GO!$F0E*$J@-<A$r;}$D<B@$3&$
BjNN0h$K=@Fp$KBP1~7-lJ$$$H$$$&LdBjE@$,;XE&$5lDD"$k!%FC$K!$M=B,$7F@J+C?>
$KD>LL$9kH!$%7%9%F%`$O=EBg$J4m5!$K4Yk3H,B?$$!%

B?<oB?MM$JMWAG$,6u4VE*$"$k$$$O;~4VE*KbB??t9-$,$CF*$j!$$=li$N4V$NL5?t$N6I=jE*A
:nMQ$N7k2L!$A4BNH7$FM=B,ITG=$JJ#;($J?6$kIq$$$r8+$;$k7O$O3+J|7?J,;64D6- (*open distribute*
environment) $H8F$Plk [Tok91, =j95]!%%3%s%T%e!<%?%M%C%H%o!<%/$N5^B.$JH/E8Kh$j6KEY$K
J,;62=$,?J$s$@:#F|$N7W;;5!4D6-$O!$%3%s%T%e!<%?%M%C%H%o!<%/$r2p$7$F8_$$$N7W;;5!$,J#;
1F6A$r5Z$\$79gCF$*$jM=B,$,:$Fq$JJ#;($J?6$kIq$$$rDh9kNG!$3+J|7?J,;64D6-$G$"$k!
$?7W;;5!4D6-$N$_J$i$:!$<B@$3&$N$"$ifk%l%Y%k$N7O$r9M$($F$_$F$b!$$=li$O6u4VE*$*$
;~4VE*$K9-$/J,;6$5$l$?9=@.MWAG4V$NJ#;($JAj8_:nMQ$KhC$F>o$KJQF0$r7+$jJV$7!$;~$H?7$
B,ITG=$JJ#;($J?6$kIq$$$r8+$;$kNG!$K\<AE*$K3+J|7?J,;64D6-G"kH8@$($k!%D^$j!$7
5!4D6-K*$$$FG"$l<B@$3&K*$$$FG"$l!$$h$j9bEY$J2?i+$NCNE*LdBj2r7h%7%9%F%`$r9
$78=<BE*$J1~MQ$rK>$`NG$"$l$P!$$=l,M=B,ITG=$J>u67$KD>LL9k2DG=@-$r9MN8$7F*$/$
$OI,?\$G$"$k!%7+$7!$$3Nh$&$JJ#;($J5sF0$r<($93+J|7?J,;64D6-$K$*$$$F!$Ax6x$7F@k
fk>u67KBP7$FE,@Z$J5sF0$r<($9h&$J%7%9%F%`$r$"$i$+$8$a40A4$K@_7W9k3H$O:$F
$"$k!%

2.4.2 @8L?8=>]$KCeA[$rF@$?>pJs=hM}7ABV$N=EMW@-KD$$$F

0J>e$NGX7J$r85$K6aG/@9$sKJ5lF-$?!$<+A33&$N%7%9%F%`$KFb:_9k%@%$%J%_%/%9$r%
%kH7$?=@Fp$J>pJs=hM}$N2DG=@-$rLO:w9k8&5f$N01$D$,!$$3l^GK=RYF$-$??M9)@8L?$
>N5l$k8&5fJ,Ln$G$"$k!%$^$?!$$=$N1dD9@~>e$K$"$j!$F0J*$N9TF0!&?6$kIq$$$NMM;R$+$iCeA[$
$F$$$k9TF0%Y!<%97? (*Behavior-Based*) AI $N35G0 [Mae92, PV92] KBP9$k4X?4$b9b$^CF$$$k!%
3liK6&DL$JFCD'$O!$"*Generate and Test*" 7?$NLdBj2r7h$N%"%W%m!<%A$rHk$H$$$&E@G"$k!
$^$?JL$N=EMW$JFCD'H7$F!$%7%9%F%`FbItKO5-9fH7FNM[$KI=8=$5l?@$3&$N%b%G%k$d9
5,B'$rJ];}$7$J$$$H$$$&E@$,5s$2il$k!%$`$7$m!$%7%9%F%`$r9=@.$9$kJ#?t$NC1=c$JMWAG$=$
l,B>$NMWAG$H$N4V$"$k$$$O4D6-HN4V$N6K$a$FC1=c$JAj8_:nMQ$r9T$&3HG=$NAmOB$H7
%9%F%`A4BN$N5sF0$,7hDj5lkH$$$&AOH/ (*emergence*) $N35G0$K=EE@$,CV$+lk [?M9) 94]!%AOH/
HO!$MWAG4V$NHs@~7AE*Aj8_:nMQKhCF>e0L3,AX$NFCD'$,@8$8!$3,AX4V$NAj8_:nMQ$HKh$
2<0LMWAG$N5sF0$,@)8B5lkH$$$&%@%$%J%_%C%/$J2aDxG"$k [Lew92]!%AOH/$O!$@8J*$N$"$i
$k3,AX$K$*$1$k@8L?8=>]$K6&DL$N35G0$G$"$j!$$3$3$G8@$&3,AX$H$O6u4VE*$JbNGb;~4VE*$
NG$b9=$o$J$$!%Nc$($P!$0dEAE*%"%k%4%j%:%`$O!$8DBN$NA*Br!&@w?'BN$N8r:5!&0dEA;R$NFMA
0[$H$$$C$?C;4|E*$J2aDx$,?J2=$H$$$&Nr;KE*$J%Q%?!<%s$rb?i9!VDL;~E*$JAOH/!W(*diachronic*
emergence) $K4p$E$/>pJs=hM}$N7ABVG"$k!%$^$?%K%e!<%i%k%M%C%H%o!<%/$O!01D01DN%K%e
%m%s$N%_%/%m$J%l%Y%kGN4JC1$J=hM}$,J#;($KAj8_:nMQ$7$"$C$F2?$i$+$N?6$kIq$$$r@8$8$5$
$H$$$&!V6&;~E*$JAOH/!W(*synchronic emergence*) $K4p$E$/>pJs=hM}$N7ABVG"$k [Cha90]!%



?^ 2.10: AOH/

AOH/7W;;$N35G0$N2<GO!$>pJs$*hS=hM}<gBN$OJ#?t$N9=@.MWAG4V$KJ,;6$5$;$ilk!%>p
$*$h$S9TF05,B'$r5-9fE*$JJ}K!$GCf1{=88"E*$+$DL@<(E*$KJ];}$9kBeojK!$3FMWAG4V$K9-$
;6$5$;$k7ABV$r<hkN$GBQ>c32@- (*fault tolerance*) KbM%$l!$=>Mh$N?M9)CNG=%7%9%F%`$,Jz$($
%U%l!<%`LdBj (*frame problem*) $H$bL51o$G$"$k$h$&$J=@Fp$J>pJs=hM}$,2DG=$H$J$k!%%7%9%F%`F
It$K9E$$9TF0%b%G%k$r;}$?$:$K!$Hs5-9fE*$G=@Fp$J%b%G%k$rMQ$$$k3N%"%W%m!<%AGO!$$"$
8a9M$(F@$kITB,$N;vBV$rA4$F9MN8$KF~lF%7%9%F%`$N@_7W$r9ToJ$/$H$b!$4D6-KBP9$kE
@-!&4h7r@-$KM%$l$?%7%9%F%`$r9=C[2DG=G"kH8@ol$F$$$k!%

0lJ}!3Nh&$J9=@.MWAG4V$NJ#;($JAj8_:nMQ$N7k2LH7$F!$%7%9%F%`A4BN$N0l4S$7$? (*coheren*
?6$kIq$$$,<B8= (AOH/) G-kN$+$H$$$&LdBjE@$b;XE&$5lDD"$k!%2f!9F0J*$rNcKHCF
@8L?5!G=$N0];}$K4X7F!$6a@\:YK&$N4V$N6I=jE*$JAj8_:nMQKh$kAOH/8=>]$N$[$+$K!$%[%k%
JIKh$k1s5wN%$Ko?$kBg0hE*$+$DHf3SE*Cf1{@)8fE*$J5!9=Kb0MB8$7$F$$$k3H$OL@$i$
$"$k!%6aG/GO!$%m%\%C%H$d%K%e!<%i%k%M%C%H%o!<%/$K@8J*$N%[%k%b%sJ,Hg$N;EAH$_$r<h$jF~$
3H$r;n$_$F$$$kNcb"$k [Bro94, Kit95]!%$"$k$$$O!$LdBj$,L@3N$KDj5A2DG=$G$"$k “*well-defined*
” $J4D6-$K$*$$$F$O!$$`$7$m=>Mh$NCN<19)3XE*$J%"%W%m!<%A$N%7%9%F%`$NJ}$,8zN(E*G"$k>
$bB?$$!%7?$,$C$F!$%7%9%F%`$NA4$F$NItJ,$r0J>e$K=R$YF-$?$h$&$J@8J*3XE*$J5!9=$KMj$
9=C[9k3H$,:GNI$G$"$ko1GOJ/!$=>Mh$+iNCN<19)3XE*$JL@<(E*$J5!9=$H$$$/i+$
9g7?7A$N%7%9%F%`$,8=<BE*G"m&!%

$$$:lK$;$h!$?M9)@8L?E*$JAOH/7W;;$NOHAH$@1rMQ$$$F%7%9%F%`$NA4$F$r9=C[$7h&$H;
k3HO$$$5$5$+6KC<G"kK7F$b!$HsJ?9U4D6-JI$NIT0BDj$J4D6-K*1k%7%9%F%`9=C
4pACH7F3$NOHAH$,:#8e$^$9$^$9=EMWKJCF$/$k$H9M$(il$k!%@8J*$O<B@$3&$H$$$&F0E
$+$DM=B,ITG=$J5sF0$r<($93+J|@-!&Hs@~7A@-$N6/$$4D6-KBP7$F6K$a$F=@Fp$KE,1~7F$$$k!
$+$b!$<+A33&$N%a%+%K%:%`$d?6$kIq$$$O$=$l<+BN$,L$2rL@G"C?$j?M9)J*$H$OA4$/0[Jk@
J}?K$K4p$E$/$bNHJC$F$$$kNG!$3+J|7?J,;64D6-$G$N1?MQ$rA[Dj7?:#8e$N%7%9%F%`$K$
$k?7$7$$>pJs=hM}%a%+%K%:%`$r9M;!$9$k>e$G!$$=3+$i3X$VY-3H$OB?$$!%FC$K!$@8J*$N3
$d?J2=$H$$$C$?E,1~E*$J2aDxKJoC$??J2=E*%7%9%F% (*evolutionary system*) $"$k$$$O?J2=E*%(!<
%8%'%s%H (*evolutionary system*) $H$$$C$?35G0$O!$:#8e$^9^$9=EMW$KJCF/kH;Wol$k!%

Bh **3** >O

3X=,$H0dEA!&?J2=

2f!9$,N>?F$+$i0z$-7Q$0 0dEA;R$O?tI4K|G/Ko$?$kAD@h$N7P83$N1F6A$r<u$1F*$j!$0dEA
$N;XNa$KhC$FG>$N9=B$$NBgItJ,$,=PMh>e$,C?>uBV$G2f!9$O@8$^$lF/$k!%G>$O!$@8J*$ND
!V?J2=!W$N2aDx$NCf$G;:$^$l0i$CF-$?$bNG$"$j!$AD@h$N7P83$r$$$/i+H?1G7?bNHJ$
$$$k!%D^$j!$@8$^$l$?=V4V$NG>$OGr;f$Nh&$J>uBV$GOJ$/!$@8B8$KI,MW($"$k$$$OM-Mx)$
$kIq$$$,$"$i$+$8$a%W%m%0%i%`$5l?>uBVKJCF$$$k!%Nc$($P!$%U%i%s%9$N$"$kCO<A3X<T$
M[$N8w!$5$29$NJQ2=!$;~7W!$%i%8%*!$%F%l%S$JIr0l@Z@Z$jN%$7$?F67"@83h$rB3$1$F?gL2$H3
$N<~4|$r4QB,7?H3$m!$F|<~%j%:%`$,Ls 25 ;~4V$G$"$k3H$,J,$+C?!%3N<~4|$O!$CO5e
<+E>Kh$k8w$H0G$N<~4|$K@8J*3XE*$KE,1~$7$F$$$k3H$rH?1G$7F*$j!$$3$N@-<A$O@8F@E*$
NG$"$k3H$,J,$+CF$$$k!%$^$?JLNNcH7F$O!$@8$^$lF+$i0lEY$b3<9|$r8+$?3HN
%A%s%Q%s%8!<Gb!$3<9|$r8+$;$ilk$HI]$,CFF(Hr9TF0$r5/$3$9$H$$$&3H$,Js9p$5lF$$
3<9|$N0UL#!$$D$^$j$=$l$,;`$KD>7k7F$$$k$H$$$&0UL#$r7P83E*$KCNCF$$$kO:$,$J$$$K$
oi$:F(Hr9TF0$r<hkH$$$&3Hhj!$3<9|$KBP9k62I]$N46>p$N5/F0$,0dEAE*$J>pJs$K>h$
EA$($ilF$$$k$+$Nh&$K;W$olk!%

0lJ}!$G>$O!$@8$^l?H-$N>uBV$N$^$^8GDj5l$F$$$ko1GOJ/!$CB@80J9_$N7P83$rD
$F!$@8B8$9$kNKM-MxKJkh$&$K5i$K4D6-$KE,1~7F$$$/!%2w3Z$dMx1W$rb?i9860x$
$k9TF0$G$"$lP=lr7+jJV7!$5U$K4m81$d6lDK$rH<$&9TF0$rHr1k798~$r6/$a$k!%$3$N2aD
!V3X=,!W$H8F$P$l!$2f!9?MN`$@$1GJ$/MM!9$J@8J*K*$$$F8+il$kIaJWE*$J2aDxG"$k!%6
Y-3H$K!$$"$k<o$N3X=,$OG>$,J/Fb2DG=G"$k!%2<Ey$J4,$-3-$K$OG>$b@T?qbJ$$$,!
$N%K%e!<%m%s$O!$(;I7c$,2?EY$b7+$jJV5l$?8e$G)<e$$;I7c$rL5;k$7$?$j!$6<0R$KJkh&$
7c$r<u$1$?8e$G$O!$$=$NH?1~$r6/a?j9k3Hr3X=,9k!%

0lHL$K@8J*$N4D6-XNE,1~$O!$0J2<$K5s$2kh$&$K;~4V$*$h$S6u4V$N%9%1!<%k$,0[$JkFs
B&LL$NAjJdE*$JbNH7$FB*$(k3H,G-$k!%

1. !V3X=,!W: 3F8DBN$N0l@8$H$$$&C;$$;~4V%9%1!<%k$NE,1~2aDx

2. !V?J2=!W: =8CDK*1k@Ber$^$?$$$@D9$$;~4V%9%1!<%k$NE,1~2aDx

A0>O$N:G8e$G!$:#8e$Nhj9bEY$J>pJs=hM}%7%9%F%`$J$I$r9M$($k:]$K$O!$?J2=E*%7%9%F%`$"$
$O?J2=E*%(!<%8%'%s%H$N9M$(J}$,=EMWKJk3Hr=RY?!%K\O@J8GO!$$3Nh$&$J?J2=E*%
%8%'%s%H$NE,1~$b!$?J2=O@$d@8J*3X$+$i$NN`?d$K4p$E$$$F!$>e=R$N!V3X=,!W$H!V?J2=!W$Kh
<B8=5lkbNG$"$k$H9M$(!$0J9_!$$3liFsDN4X78KD$$$FCmL\$7$F$$$/3HKJ$k!%

H3mG!$>e=R$NFsDN2aDx$O<B:]$N@8J*3&K*$$$F$O!$C1=cKN_2CE*K8r8_$K7+$jJV5
?J$`$o1GOJ$$!%K\>OGO!$$RH^$:@8J*3XE*$J8+CO$+$i!$3X=,$H?J2=KD$$$FD/ak!%$
3.1 @aKF!$K\8&5f$N5DO@$r?J$a$k>e$GI,MWHJ$k%i%^%k%-%:%`$H%M%*%@!<%&%#%K%:%`$N9M$
KD$$$F35@b9k!%<!$K 3.2 @a$K$F!$3X=,$H?J2=$NAj8_:nMQH7F%\!<%k%I%&%#%s8z2L$H8F$P

$k8=>]$K$D$$$F@bL@$7!$7W;;5!2J3X<TKhCF9Tol$?3X=,$H?J2=$NAj8_:nMQ$NI>2AKD$$$
2a5n$N8&5fNc$r$$$/D+>R2p9k!%

3.1 %i%^%k%-%:%`$H%M%*%@!<%&%#%K%:%`

?J2=O@$NNr;K$K$*$$$F!$?J2=$N86F0NO$K4X$9$kO@Ah$r=dCFBg$-$/FsDNN.l,B8:_9k!
%^%k%-%:%` (*Lamarckism*) $H%@!<%&%#%K%:%` (*Darwinism*) G"$k!%$7$+$7:#F|$N?J2=O@$K$*$$$F
<gN.$r@j$akN$O!$%@!<%&%#%K%:%`$r8;N.$H$9$k%M%*%@!<%&%#%K%:%`G"$j!$%i%^%k%-%:%`$
GDLC$F$$$k@b (%i%^%k%/@b) $O0[C<$H5l$F$$$k!%

3.1.1 %i%^%k%-%:%`

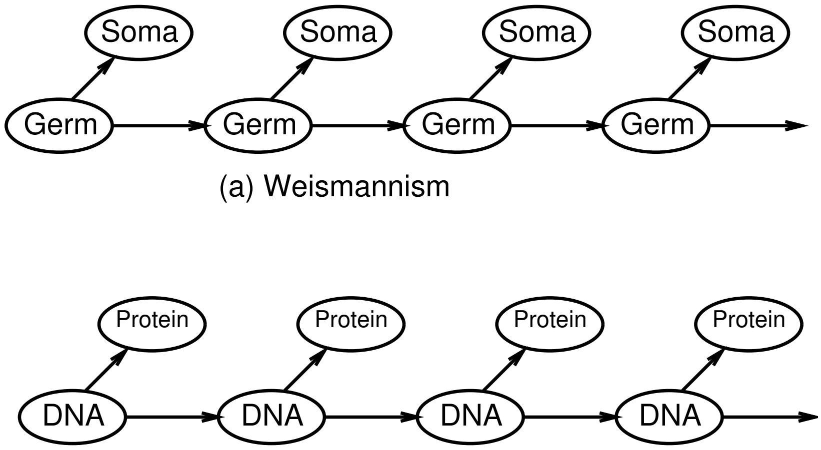
%U%i%s%9$N@8J*3X<T Lamarck (1744 - 1829) $KM3Mh$9$k%i%^%k%/@b$NCf?4E*$J35G0$O!V3MF@7A
<A$N0dEA!W$K$"$j!$85!9$N9M$(J}$O0J2<Nh$&$JbNG"$k!%@8J*$O$=$N0l@8$N4V$K<~0O$N4
$KE,1~$9$k!%$h$/MQ$$$ilkNcH7FO!$CC<#20$,$=$N;E;v$KE,$7$?OS$N6ZFy$rH/C#$5$;$?
I89b$N9b$$>l=j$K@83h$9$k?M4V$,@V7l5e$rA};:$9k3Hd!$<+$i$,;/$5lF$$$k1VIBKBP9$
1V$r3MF@$9k3$H!$99KOF;O)$N@5$7$$B&$r1?E>$9kh$&$K3X=,9k3HJI$,5s$2il$k!
li$NJQ2=$NA4FO!$@8J*8DBN$,hj@8B8$7$d$9$$$h$&$K0l@8$N4V$K9T$&4D6-$KBP9k1~Ez$
$j!$$3$&$7$?8DBN$K5/$-$?E,1~E*$JJQ2=$,;RB9$K2?$i$+$N7AGEA(ilk3HKhC$F?J2=$
$7?J$ail$k!%

Darwin O3$N@b$N2DG=@-OG'a!$!VMQ!&ITMQ$N8z2L!W(*the effects of use and disuse*) $H$$$&8@
MU$G8F$s$@$,!$<+A3EqBA$NJ}$,?J2=$N860xH7Fh$j=EMW$GBg$-$JLr3d$r2L$?9H9M$($F$$
$^$? Darwin $O!$@8J*KOK\Mh!$$h$j9bEY$GhjJ#;($J7ABV$K?J2=9k798~$,$"kH$$$&%i%^
%/@b$N:,Dl$K$"$k?.G0KO;?@.G-J+C?!%$`$7$m!$JQ0[$KJ}8~@-$OJ/!$$?$^$?$^4D6-$
1~E*$JJQ0[$r9TC?8DBN$,<+A3EqBA$N2aDx$G@8$-1dSFHK1I9k$H$$$&N, Darwin $N<gD%$
$"$k!%

3.1.2 %M%*%@!<%&%#%K%:%`$HJ,;R@8J*3X$K$*$1$k%;%s%H%i%k%I%0%^

Weismann (1834-1914) $O!$3MF@7A<A$N0dEA$N2DG=@-$r40A4$KH]Dj$7!$:#F|$N%M%*%@!<%&%#%K
%:%`$N8;N.$rD/C?!%Weismann $O!$?^ 3.1 (a) $K<($9h&$K<u@:Mq$+$i:YK&J,Nv$KhCF?
Ik:YK&7ONsKOFsDNFHN)$JF;6Z$,$"$k$H<gD%$7$? (%t%!%$%9%^%s<g5A)!%0lJ}$O!$@8J*8DB
BN$N<gMW9=@.MWAG$HJk!VBN:YK&!W(*Soma*) XNF;G"$j!$$b$&0lJ}$O<!@BeN=PH/E@HJ$k
6v;RNbHHJk!V@8?#7ONs!W(*Germ*) XNF;G"$k!%$3liFsDN:YK&7ONsN&$ABN:YK&$O
L?Kh$j;`$K@d$($k$,!$@8?#7ONs$O1J5W$KB8B3$9$k2DG=@-$r;}$D!%Weismann $N<gD%$NCf?4E@$
BN:YK&$K5/$3$kJQ2=$O@8?#7ONs$K1F6A$rM?$($k3HOJ$$$N$G!$3MF@7A<A$O0dEA$9k3H,$

$H$$$&3HG"$k!%$?7+$K@TDGF0J*$d:+CnGO!$8e$KG[6v;RHJ$k86@8?#:YK&$,H/@8$N=i4
CJ3,$+$iJ,$+$l$F$$$k!%87L)$K8@$&$H!$G[6v;RrD$/$kNKI,MW$J%(%M%k%.!<$dJ*<A$OG[6v;
30$NItJ,$+$i6!5k$5lkNGBN:YK&$,@8?#7ONs$K1F6A$rM?$(k3HO$"$jF@k7!$$=b=$b9
?"J*KOFHN)$J@8?#7ONs<+BN$,B8:_7J$$$H$$$&;XE&b"$k!%$7$+$7!$Weismann $O!$$3$N5DO
$KK\<AE*$J0UL#$r;}$DNO!$J*<A$d%(%M%k%.!<$N<u$1EO7GOJ$/>pJs$N<u$1EO$7G"k3$
8+H4$$$F$$$?!%D^$j!$CC<#20$NH/C#$7$?6ZFy$,CC<#20ND$/$k@:;R$K1F6A$7$F!$$=NCfKE
$N6ZFy$,H/C#9kh&$J>pJs$r:~$j9~$`3HOJ$$!%



(a) Weismannism

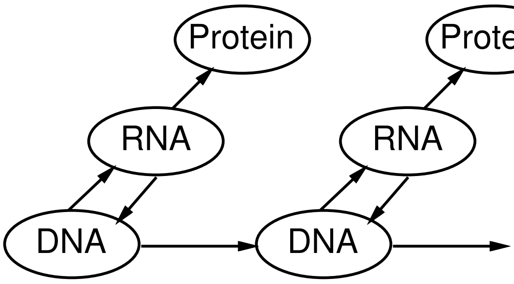
(b) Central Dogma

?^ 3.1: %t%!%$%9%^%s<g5A$H%;%s%H%i%k%I%0%^

Weismann $N5DO@$OJ,;R@8J*3XK*1k!V%;%s%H%i%k%I%0%^!W(*Central Dogma*) $H8F$Plk65
5AKCV-49$($k3H$,$G$-$k!%?^ 3.1 (b) $K<($9h&$K!$>pJs$O DNA $+$i DNA $X!$$=7F
DNA $+$i%?%s%Q%/<A (Protein) XHEAok$,!$%?%s%Q%/<A$+$i DNA XOEAoi$J$$!%D^$j!
b7:YK&Fb$K?7$7$$%"%_%N;@G[Ns$r;}$D%?%s%Q%/<A$,B8:_$7Fb!$$=$N%?%s%Q%/<A<+?H$,$=$
AjEv9k1v4pG[Ns$r;}$D DNA J,;RrD$/$k3H$O=PMh$J$$$NG"$k!%87L)$K$O!$DNA $N>pJs$
m-RNA (%a%C%;%s%8%c RNA) $rCg2p$7$F%?%s%Q%/<A$KEAok!%5i$K!$5UE><L9ZAG$H$$$& RNA
$N1v4pG[Ns$r DNA $KJ#@=$G$-$k9ZAG$rMQ$$$k3H$G@w?'BN>e$rJ|O2$9$k$+$Nh&$K0\F0$9$k
%i%s%9%]%>%s$H8F$Plk0dEA;R72 (DNA $NItJ,1v4pG[Ns) $,B8:_$9$k [Smi89] 3H$d!$$"$k<o$N
RNA %&%#%k%9$,5UE><L9ZAG$rMQ$$$F<+J,$N0dEA>pJs$r4s@8<g$N DNA $KJ#<L$9kH$$$&8=>]$
$"$k$H$$$&3H$r9MN8$9kH!$%;%s%H%i%k%I%0%^$K$*$1$k>pJs$NN.lO?^ 3.2 Nh$&$K=$@5$5
kY$-$G$"$k$,!$5DO@$NK\<A$rJQ$($ko1GO$J$$!%

b7!$DNA $,>pJs$r@Ber1[$($FEA$($k$?$a$NM#0l$N<jCJG"kH9l$P!$$3N3HO?J
KBP7$F7hDjE*$J0UL#$r;}$D!%$=$l$O!$?J2=KO DNA $NJQ2=$,I,MWG"$j!$$=$NJQ2=!$$D$^

FMA3JQ0[$OK\<AE*$K6vA3$K5/$3$kHsE,1~E*$JbNG"k3Hr0UL#7F$$$k!%8DBN$,01@8$rD
$F4D6-$K1~Ez9k7A$G!$<+J,$N@-<A$rJQ$($k3H$,=PMh$F$b!$$=$NJQ2=$, DNA $K5/$3iJ$$
$j!$D94|KEOk?J2=E*$J1F6A$r;}D3HO$J$$!%



?^ 3.2: 0dEA%7%9%F%`FbK*1k>pJs$NN.$l

3.2 3X=,$H?J2=$NAj8_:nMQ

3.2.1 %\!<%k%I%&%#%s8z2L

3MF@7A<A$N0dEA$rH]Dj9k%M%*%@!<%&%#%K%:%`$N9M$($r!V3X=,!W$H!V?J2=!W$H$$$&8@MU$rM
$F7+$jJV9H!$@8J*8DBN$,01@8$N4V$K9T$&3X=,$,0dEA7ONs$K1F6A$rM?$($k3HOJ$/!$$7$?$
$F8DBN$,3X=,7?7k2L$,D>@\E*$K;RB9KEAok3HO$"$jF@$J$$$H$$$&3HKJ$k!%$=lK$
oi$:!$3X=,$,?J2=$K1F6A$rM?$(F@k3H,2??M$+$N@8J*3X<TKhCF<(:6$5$l$F$$$k [Smi8
$=$N4pK\E*$J9M$(J}$O!$1890 G/BeK^GALj!$0lHL$K!V%\!<%k%I%&%#%s8z2L!W(*Baldwin effect*) $N
L>GCNilF$$$k!%%\!<%k%I%&%#%s8z2LHO!$8DBN$Khk3X=,$,4V@\E*$K=8CD$N?J2=$N2aDx$
6A$r5Z$\$7$F!$$"$?$+$b?J2=$KJ}8~@-$rM?$($F?JJb$rB%?J9k$+$Nh&$J8=>]$r@8$`$3Hr;

b7!$$"$k3X=,$,@8J*8DBN$N@8B8$KHC$FM-Mx$JE,1~E*$J7A<A$r3MF@5;kbNG$"$kJi
$=$N3X=,$r!V9T$&!WG=NO$,9b$/Jkh&$J0dEA>pJs$r;}$D8DBN$[$IB?$/$N;RB9$r;D$9$3HK$J
H3m,!$$3Nh$&$JEqBA$N2aDx$,7Pi/B3$/$H!$3X=,$N!V7k2L!W<+BN$,@8$^lD$-$N>pJ
7F0dEA;RFb$K:~$j9~$^$l$?E,1~:Q$_$N8DBN$,?J2=KhCF@8$8$F$/$k!%%bAm$s!$3X=,$rA
9ToJ$/$H$b0dEA;R$N8r:5$dFMA3JQ0\$JIGE,1~E*$J7A<A$O?J2=$7F@$k!%%\!<%k%I%&%#%s8z2
hk=EMW$JE@$O!$$3$NE,1~7A<A$N?J2=$NB.EY$,3X=,KhCF9bailk3HG"$k!%$D$^$j!
=,KhCF3MF@5l$?E,1~E*$J7A<A$,;RB9$KEA$($ilk$+$Nh&$J5?;w%i%^%k%/E*$J2aDx$,8
lkNG$"$k!%

3.2.2 %K%e!<%i%k%M%C%H%o!<%/$H **GA** $rMQ$$$??J2=$H3X=,$K4X9k8&5fNc

%\!<%k%I%&%#%s8z2L$O!$A4FN@8J*3X<T$KD>$A$K<u$1F~lil?o1GO$J$$!%$=$NM}M3$
FO%i%^%k%-%:%`$N1F$,@xsG$$$k3H$b5s$2ilk,!$<B:]$K$=$Nh&$J8z2L$,:nMQ9k$
I&$+$,L@i+GJ$+$C$?$3H,:GBg$NM}M3$G$"$k!%0lJ}!$6aG/!$7W;;5!$NEP>l$KhC$F%b%
>eGN%7%_%e%l!<%7%g%srDL8$F%\!<%k%I%&%#%s8z2L$r3NG'9k3H$,$G$-$kh&KJC?

3X=,$O?J2=$KJ}8~@-$rM?$(k+!)

Hinton $H Nowlan $O!$6KaFC1=c$J%b%G%k>e$G3X=,$,?J2=$KM?$($k1F6AKD$$$FI>2A$r9T$C
$? [HN87]!%H`$i$O!$7k9g$N?t$, 20 G"$k%K%e!<%i%k%M%C%H%o!<%/$r8DBNH7!$$3li$N@\B3A
F,@5$7$$CM(“off” $+ “on”)$K@_Dj5l$F$$$k8DBNKN$_9b$$E,1~EY$,M?$(ilkh$&$J>u67$
9M$($?!%3N>u67K*1kE,1~EY6JLL$O!$%@!<%&%#%sE*?J2=r9$k8DBN=8CD$KHCFO6Ka
9g$,0-$$$bNG$"$k!%2?8NJi$P!$@52rHJ$k8DBN$O $2^{20} \simeq 10^6$ 2LjNAH$_9g$;$NI=8=7?$NCf$N
$?$@0lDG$"$j!$ $=$l0J30KOE,1~EY$,M?$(il$J$$$N$GE,1~EY6JLL$N<PLLrEPkh&$J?J2
$JC5:w$,9T$($J$$$NG"$k!%$$$o$P!V43$7Ap$N;3$NCf$N?K!W(*a needle in a haystack*)$rC5$9h&
JbNG$"$k!%

8DBN$N@w?'BN$O 20 8D$N0dEA;R:B$+$i@.$CF*$j!$$=l>$l $\{0,1,?\}$ $N$$$:l+NCMrHk
3F0dEA;R:B$O%K%e!<%i%k%M%C%H%o!<%/$N7k9gNCMKBP1~7F$*$j!$“0”!$“1” O=l>$l “off” $
“on” $r0UL#$7!$“?” $O7k9g$NCM$,2DJQ$G$"$k3H$rI=$9!%8DBN$O!$0l@8$N4V$KA4FN “?” $K “off”
$+ “on” $N$$$:l+$r%i%s%@%`$K%;%C%H9k3H$r7+$jJV$7!$@5$7$$7k9g$NAH9g$;$r3MF@$7h
9k!%3NC1=c$J3X=,%9%F%C%W$O:GBg 1000 %9%F%C%W7+jJV5$l!$@5$7$$7k9g$NAH9g$;$r3MF@
k^GKMW7?%9%F%C%W?t$N5U?t$N4X?tH7$F8DBN$NE,1~EY$,7hDj$5lk!%J*!$$bHb$H0
E*$K8GDj$5l?CM$,@5$7$/$J$$$h$&$J7k9g$r;}$D8DBN$O!$$3$N%9%F%C%W$r2?EY7+jJV7Fb@
KO;jiJ$$!%$=$7$F!$E,1~EYHfNc@oN,KhCF8rG[$KMQ$$$k?F$rA*$S!$$=li$N@w?'BN$r8
5;$F<!$N@BeK;D$9;R$r:n$k!%Hinton $H Nowlan $O!$“?” $r 50%!$“0”!$“1” r=l>$l 25%
$:$D4^$`@w?'BN$r 1000 8DMQ0U$7!$$3lr=i4|=8CDH7$F GA $G?J2=$5$;$F=8CDA4BN$NJ?6Q$N
1~EY$N?d0\$r4QB,7?!%3F@BeK$*$$$F$O!$8DBN@w?'BNCf$NJ?6Q 10 8D$N0dEA;R:B$,8GDj$5$l
$$$k3HKJ$k!%$7$?$,CF!$$"i+8a7hDj5l$F$$$k7k9g$NA4$F$,@5$7$$CM$K@_Dj$5l
$F3X=,$KhC$F@52r$KC)jCe1$k2DG=@-$N$"$k8DBN$,$2^{10}$ 1000 8D$K 1 8D$N3d9g$GB8:_$9$k!%
$^$?!$$3Nh$&$J8DBN$N7k9g$N$&$AJ?6Q 10 8D$,2DJQIt$G$"$kNG 1000 2s$N3X=,%9%F%C%W$N4
$K@52r$K;j$k5!2q$O$"$k!%

<B837P2a$r4QB,$9kH!$=8CD$NJ?6QE,1~EY$O=i4|$NCJ3,GOfC$/$jH7$+>e>:$7$J$$$,!
@Ber1[$($?JUjG5^7c$J>e>:$r;Oak!%3X=,$r8zN(E*$K9T$&$3HN=PMh$k8DBN$O9b3NN($GA
5lkN$G!$@Ber7PkKDl$F3F8DBN@w?'BNCf$N@5$7$$CM$K8GDj$5l?0dEA;R:B$N?t$,A}2

$F$$$/!%7?$,$C$F!$3X=,KMW9$k;~4V$,C;$/$JCF$$$/NG$""$k!%5i$KH`$i$N<B83$K$*$
:G=*E*$KA4$F$N0dEA;R:B$,@5$7$/@_Dj5l$?8DBN$,@8$8$?!%0lJ}!$GA N_$rMQ$$$?>l9gKC
2r$,5a$^k3HOJ+C?!%3X=,$N8z2L$KhC$F!$85!9@mCF$$$?E,1~EY6JLL$N7A>u$OJQ7A$
$F@52r$N<~0O$K<PLL$r7A@.9kh&KJ$k!%$3$N<PLL$r?J2=$N2aDx$,EPCF$$$/3H$,=PMh$
$&$KJkNG$""$k!%J,$+$jd9$/8@$$49$($k$H!$6a$$>l=jKMh?i=N3Hr65$($Fbi$$$
$i?K$rC5$9$h$&$JLdBjXHJQokNG$""$k!%

H3mG!$Hinton $H Nowlan $NMQ$$$?3X=,$NJ}K!$O!$BP K!$JIN%K%e!<%i%k%M%C%H%o!<%/
$N$$$ofk0lHLE*$J3X=,K!$GOJ$$!%$^$?!$@m$C$?E,1~EY6JLL (@52r$+IT@52r$+$NIAi+N
C<7+$J$$) $rA[Dj$7$?!$$+Jj6KC<$JLdBj@_Dj$Gb""$k!%$7$+$7!$$=$N5DO@$,hj0lHLE*$
=,K!$rMQ$$$?>l9gKb@.$jN)$D2DG=@-$r<(:6$9k?aK!$H`$i$O4:$($F!V%K%e!<%i%k%M%C%H%
%/$N3X=,!W$H$$$&I=8=$rO@J8Cf$GMQ$$$F$$$k!%0lJ}!$Parisi iO!$<B:]$KE,1~EY6JLL$,;3G""
h&$J>u67$K$*$$$F!$BP K!$Khk3X=,$r9T$&%K%e!<%i%k%M%C%H%o!<%/$r GA $G?J2=$5$;$k<B
$NI>2A$r9TCF$$$k [PNC91]!%H`iO!$Fs<!853J;RJ?LL>e$K%K%e!<%i%k%M%C%H%o!<%/$N=PNO$K
8F9TF0$r7hDj$9$k%(!<%8%'%s%H$H?)NH$rG[CV$7!$7h$ail$?0lDj$N%9%F%C%W (8DBN$N0l@8) F
3MF@7??)NH$K1~$8$F%(!<%8%'%s%H$KE,1~EY$rM?$(kh$&$J<B83$r9T$C$?!%$J$*!$3F%(!<%8%
%H$N;}$D%K%e!<%i%k%M%C%H%o!<%/$N=i4|7k9g6/EY$O@w?'BN>e$N>pJs$Khj7hDj5l!$0l@8$N4
3X=,KhCF<u1?7k9g6/EY$NJQ99$O;RKOEA$($ilJ$$$bNH9k!%3Nh&$JLdBj@_Dj$
$$$F!$0l@8$N4V$K3X=,$r9ToJ$$%(!<%8%'%s%H=8CD$H3X=,$r9T$&%(!<%8%'%s%H=8CD$N?J2=$NM
$rHf3S$7$?$H3m!$8e<T$N=8CD$NJ}$,A0<T$N=8CD$KHfYF?J2=$NB.EY$,B.$$$H$$$&7k2L$rF@$

0J>e$K=R$Y$?<B83$N7k2L$,<($9$3$H$O!$3X=,7?7k2L$r?F$+$i;R$KD>@\EA$($k5!9=$,$J$$$
4Xoi$:!$3X=,$,?J2=$KJ}8~@-$rM?$($k8z2L$r;}DH$$$&3HG""$k!%

3X=,G=NO$H@hE7E*9TF0$N0dEAE*$J=EMW@-

Ackley $H Littman $b!$Parisi i,9TC?NHF1MM$K%K%e!<%i%k%M%C%H%o!<%/$N=PNO$K1~$8$F
9TF0$r7hDj$9$k%(!<%8%'%s%H$rFs<!853J;RJ?LL>e$N4D6-$KG[CV7F<B83$r9T$C$? [AL92]!%4D6-
$O!$?)NHHJ$kJ*;q$N$[$+$K%(!<%8%'%s%H$NE7E(HJ$kFy?)=C$d$=$NB>$NJ*<A$,B8:_9k!%%
%8%'%s%H$O4D6-Fb$r0\F0$9$k3HKhCF!$?)NH$K$""$jD1$?$jFy?)=C$KAx6x$7$F4m81$JL\$K
$?$j9k!%%(!<%8%'%s%H$O!$!V9TF0 (7hDj) %M%C%H%o!<%/!W(*action-network*) $H!VI>2A%M%C%H%o!<
%/!W(*evaluation-network*) $H8F$PlkFsDN%K%e!<%i%k%M%C%H%o!<%/$r;}$A!$$$$:lb<+J,$N;k
Ln$KF~$C$F$$$kJ*BN$N0LCV$r8=:_>uBV$NF~NO$H9k!%%(!<%8%'%s%H$O9TF0%M%C%H%o!<%/$N=PN
hC$F9TF0$r7hDj$74D6-Fb$r0\F0$9$k!%I>2A%M%C%H%o!<%/$O!$8=:_$N>uBV$,Il$@$1K>$^$7$
BVG""k+$rH=Dj$9$k%9%+%i!<CM$r=PNO9k!%$$$:lN%K%e!<%i%k%M%C%H%o!<%/$N=i4|7k9gC
@w?'BN>e$N0dEA;R$KhC$F7hDj$5lk!%I>2A%M%C%H%o!<%/$N7k9gCM$O@8$^$l$?$H$-$N>uBVN

0l@88GDj5l$?$^$^$G$"$j!$AD@h$+iEAo$k@hE7E*$JL\E*$dM_K> — Nc$($P!$!V?)NH$N6a$/$K
CV9k3H$OK>$^$7$$!WJI — $rI=$9!%0lJ}!$9TF0%M%C%H%o!<%/$N7k9gCM$O!$6/2=3X=,K
$F BP K!$rMQ$$$F=$@5$5lk!%D^$j!$G$0U$N;~E@ t K*$$$F!$%(!<%8%'%s%H$OI>2A%M%C%H%o
%/$rMQ$$$F8=:_$N>uBV$rI>2A$7!$$3NCMr0l$DA0$N;~E@ $t-1$ $N>uBV$NI>2ACM$HHf3S$9$k!%$=
:9$r!$D>A0KHC?9TF0KBP7$F9TF0%M%C%H%o!<%/$N7k9gCM$r=$@5$9$k:]$N3X=,N($r7hDj9
2=?.9fH7$FMQ$$$k!%7?$,$C$F!$!VFy?)=C$N6a$/$K$$$k3H$OK>$^$7$$!WJINh$&$J@hE
$KK>$^7/$J$$M_K>$r;}$C$?%(!<%8%'%s%H$O!$@8B8$KITMx$J9TF0$r3X=,7F7^$&$N$G4D6-$
1~G-$J$$!%$^$?!$0l@8$N4V$N3X=,$KhC$F=$@5$5$l$?9TF0%M%C%H%o!<%/$N7k9g6/EY$O?F$+$
KEAoiJ$$$bNH9k!%

Ackley $H Littman $O!$%\!<%k%I%&%#%s8z2L$K4XO"$7$F!$?J2=$NCJ3,$,?J$`$KDl$F!V3X=,$N
G=NO!W$H!V@hE7E*9TF0!W$N0dEAE*$J=EMW@-$,5UE>9k$H$$$&6=L#?<$$8=>]$r3NG'$7$?!%<+A33
@8J*K*$$$F!$@8B8$K$"$^$j=EMW$J1F6A$r5Z$\$5$J$$7A<A$K4X$9$k0dEA;R$[$I!$@BerDL$8
4QB,5l$kJQ2=$NEY9g$,Bg$-$$$H$$$&;v<B$,$"$k [Gou89]!%Nc$($P!$LUL\$N%b%0%i$N0l<o$G$"
spalax ehrenbergi $N4c$N?e>=BN$K4X$9$k0dEA;R$N@BerDL8?JQ2=$NEY9g$r4QB,9k$H!$;kNO$r
;}$D%M%:%_$N$=$lhjbBg-$$!%FMA3JQ0[N($d8r:5N($,N><T$GF1$8G"kH9k$H!$3F@$Be8
K*$$$F0dEA>pJs$,3IMp$5lkDxEY$OF1Ey$KJkO:G"$k!%$7$+$7!$;kNO$r;}$D%M%:%_$K$
FOFMA3JQ0[JI$G0dEA;R%9%-!<%^$,GK2u5l$F?e>=BN$,5!G=7J$$$h$&$J8DBN$,@8$8kH@
$K=EBg$J;Y>cr-$?$9NKBP7F!$85!9LUL\$G$"$k%b%0%i$N>l9g$K$O?e>=BN$K4X9k0dEA;R>
$,$$$/i+3IMp5lh&Hb@8B8$NM-Mx$5KBP7F5$7$F1F6A$O5Z$\$5$J$$!%3Nh&$JM}M
hj!$7k6I@$BerDL7$F@8$-;DCF$$$/8DBN$N@w?'BN>e$N0dEA>pJs$r4QB,$9kH!$@8B8$K1F6
$k7A<A$K4X9k0dEA;R$OCfN)$J0dEA;RKHfY$F0dEA;R$NJQ2=$NEY9g$O>.$5$$/JkNG$"$k!%

Ackley $H Littman $O!$$3$N5DO@$rH`iN9TC?<B83KbE,MQ7?!%3F%(!<%8%'%s%H$N9TF0
%M%C%H%o!<%/$HI>2A%M%C%H%o!<%/$K4X9k$=$l$>$l$N0dEA;R$NJQ2=$NEY9g$rB,Dj7?NG$"
$=$N7k2L$O0J2<$NDLjG$"$k!%?J2=$N=i4|$NCJ3,K*$$$F$O!$0dEA;R$NJQ2=$NEY9g$O!$I>2A%
%H%o!<%/$K4X$9kbNK$D$$$F$O>.$5$/!$9TF0%M%C%H%o!<%/$K4X$9kbNK$D$$$FOBg-$$!
J}!$@$Be$r7P$F?J2=$,?J$`KDlF!$:#EY$O5U$KI>2A%M%C%H%o!<%/$K4X9k0dEA;R$NJQ2=EY9
Bg$-$/!$9TF0%M%C%H%o!<%/$K4X9kbN$,>.$5$/$J$k!%Ackley $H Littman $O!$$3lb%\!<%k%I
%&%#%s8z2L$K4XO"$9kbNG$"$k$HO@$8$F$$$k!%D^$j!$=i4|$NCJ3,$K$*$$$F$O!$(@5$7$/) 3
9kG=NO$"$k$$$O3X=,$NJ}8~$r<($9M_K> — !V?)NH$N6a$/$K$$$k3H$OK>$^$7$$!W — $H$$$&
$,%(!<%8%'%s%H$N@8B8KHCF=EMWG"k,!$@$Be$r7P$kKDlF!V?)NH$N6a$/$K$$$k3H
$^$7$$!W$H$$$&CN<1$O!$!V?)NH$K6a$E$/!W$H$$$&9TF0%Q%?!<%s$N7A$G9TF0%M%C%H%o!<%/$N0
;RFb$K<h$j9~$^$l$F$$$/!%$=$7$F!$@hE7E*$K?)NH$K6aE/h&$J9TF0$rHkh&$J8DBN$K$*$
$O!$$bOdI>2A%M%C%H%o!<%/O5$[$I=EMWGJ$/$JkNG"$k!%

Bh **4** >O

?J2=KBP9$k?7$7$$;kE@: F0E*$J4D6-2<$K$*$1$kE,1~

Bh 2 >OGO!$:#8e$N%7%9%F%`K*$$$FM-K>JbNKJk$H;W$olk!$@8J*$N?J2=$*$h$S3X=,
$=$l$>$l$N;EAH$_$KCeA[$rF@$?>pJs=hM}$N7ABV$r=R$Y!$$^$?!$Bh 3 >OGO!$$d$d@8J*3XE*$JN
$+$i!$3X=,$H0dEA$*$hS=$N7k2L$H7F$N?J2=$NAj8_:nMQ$K4X$7$F!$$3l^GK9TolF-$
MW$J8&5f$N$$$/D+$r=R$Y$?!%K\>O$G$O!$$3l^GK9TolF-$?$3li$N8&5f$NIT==J,$JE
;XE&9kHHbK!$$3l^GK=RYF$-$?GX7JrbHK!$3+J|7?J,;64D6-2<$G$N?J2=E*%(!<%
%s%H$NE,1~2aDx$NB&LL$K>GE@$rEvFD$D!$K\8&5f$NL\E*$K$D$$$F5DO@9k!%

4.1 =>Mh$^$G$N8&5f$NIT==J,$JE@

4.1.1 %@!<%&%#%s7?$N0dEA5!9=$H%i%^%k%/7?$N5!9=$H$NHf3SI>2A

3X=,$H?J2=$K4X9k8&5fNc$NB?$/$O!$3.2 @a$G>R2p$7$?$h$&$J%@!<%&%#%s7?$N0dEA$N%b%G%k
4pE/bNG"$j!$%i%^%k%/7?$N0dEA$N%b%G%k$OHf3SE*7Z;k$5lF$-$?!%%i%^%k%/7?$N0dEA$
%G%k$,7Z;k$5lkM}M3H7FO!$3.2 @a$G=RY?h&$K!$<+A33&K*1k?J2=$N<gMW$J?d?JN
<+A3EqBAG"kH9k%M%*%@!<%&%#%K%:%`$K4p$E$$$F$$$k3H$,5s$2il$k!%$7$+$7!$$3N
$rM}M3$K%i%^%k%/7?$N0dEA5!9=$r7Z;k9k3HKO!$9)3XE*$J4QE@$+$iObAm$s!$2J3X (F
@8J*3X) E*$J8+CO$+ib5?Ld$,$"$k!%

$^$:!$9)3XE*$J4QE@$+$i8+kH!$0l@8$N4V$K3MF@$7$?E,1~7A<A$r<!@BeN%7%9%F%`KEA($
$$$C$?%i%^%k%/E*$J?J2=7ABVKO6KaF8zN($NNI$$E,1~2aDx$r<B8=$9$k2DG=@-$,$"$k!%7?$
$F!$?J2=!&E,1~%7%9%F%`$N9=C[5;K!$H7F$N4QE@$+$iD/$a$?>l9g$K$O!$%i%^%k%/E*$J?J2=7AB
9k%7%9%F%`KD$$$F$b9MN8$7$F!$%@!<%&%#%s7?$N?J2=7ABV$H$NHf3S$rDL8F$=$NFC@-$rL@$
K9kI,MW,$"$k!%

0lJ}!$@8J*3XE*$K$b!$%M%*%@!<%&%#%K%:%`$N<gD%$KH?9k8=>]$b$$$/D+Js9p5l$F$$$k [Smi
Nc$($P!$%_%8%s%3$OJa?)<T$,B?$$4D6-K*$$$F;I$rH/C#$5$;$k3H$,$"$j!$$3$NE,1~E*$JJQ2
0lEY5/3kHMqrDL8F;R$K<u$17Q$,$l$k!%$3$NJQ2=$O!$DNA $N1v4pG[Ns$NJQ2=GOJ/!$
EA;RH/8=5!9=$NJQ2=$,860x$G@8$8$F$$$k3H$,J,$+CF$$$k!%$$$:lN0dEA5!9=KhkbN
$l!$$3lOL@i+$KE,1~E*$JJQ2=G"$j!$$=$N%i%^%k%/E*$J?J2=$N2aDx$rL5;k9ko1KO$
$J$$!%

$^$?!$2?$hjb?J2=KHCF=EMWG"kN$O!$J82=E*7Q>5KhkbNG$"$k!%Nc$($P!$$"$
J*$,$I3K?e>l$,$"kN$+!$$I$N?"J*$r?)Yk3H$,$G$-$F!$2?$,FGG"kN$+$r3XYP!$$
>pJs$O;RB9$KEA$($ilk$+$b7l$J$$!%FC$K2f!9?MN`$K$*$$$F$O!$J82=$N7Q>5$ONr;KE*JQ2=$
ACHJCF$$$k!%bAms!$Nr;K$H?J2=$N%a%+%K%:%`$OA4$/$0[JkNG!$$3liFsDOOC$-
6hJL9Y$-$G$"$kHN8+J}b"$k!%$7$+$7!$@8J*$N?J2=K*$$$FK\<AE*$K=EMW$JNOM-Mx$J!
EA;R!W — >pJs$NC10L — $NHK1I$G$"$kHNN)>l$+$i!$J82=$H$$$&NbB??t$N?M4V$NG>NCfG

@=!&HK?#$7<+A3EqBAE*$J2aDx$r7P$F7A@.$5$1$k>pJs$N0l72$HB*$(kH!$$=$N:9$O>pJs$rEAC#$
J*<AE*<BBN$,2?$G$"$k$+$H$$$&3H$K2a$.$J$$!%J*!$<R2q@8J*3X<T$G$"$k Dawkins $O!$$3$
J82=rEA(k?aN0dEAE*C10LH7$F%_!<%‘ (*meme*) $H$$$&2>A[E*$JN3;R$N9M$(J}$rDs0F7F
$k [Daw89]!%$3$3$G!$J82=$d2J3X5;=QJI$N<R2qE*$J?J2=$r8+$F$_$k$H!$40A4KGOJ$$$K$7
b"$k<o$N%i%^%k%/E*$J?J2=2aDx$G?JsG$$$kh&$K;W$olk!%

H3mG!$9)3XE*$J8+CO$+$i%i%^%k%/7?$N0dEA$N%b%G%k$rDs0F$7!$$3lKhC$F%7%9%F%‘$
G=8~>e$,<B8=$5l?3H$rJs9p$7$F$$$k8&5fNcb"kKO"k,!$%@!<%&%#%s7?$N0dEA$N%b%
HNE0Dl7?Hf3SI>2A$r9T$C$?8&5fNc$O>/$J$$!%$=$NM}M3H7FO!$9)3XE*$J4QE@$+$i$O%i%
%/7?$N0dEA5!9=$,%@!<%&%#%s7?NbNKHfYFM%lF$$$k3H$,<+L@$G$"$k$+$Nh&$K;W$o$
$$$k3H$,5s$2ilk+b7lJ$$!%Montana $H Davis $O!$%=%J!<Kh$k3$LL2<$N2;6A2r@O$r
9T$&%K%e!<%i%k%M%C%H%o!<%/$N7k9g6/EY$r GA $G5a$a$k<B83$r9TCF$*$j!$$=3G$OA*Br!&8r
FMA3JQ0[$H$$$C$?DL>o$N GA $GMQ$$$$kbN$NB>$K “HILLCLIMB” $H$$$C$?E,1~E*$J0dEA;R$NJQ
0[$r;\$90dEAE*A‘:n$rF3F~$7$F$$$k [MD89]!%$^$?!$OBED$i$b%J%C%W%6%C%/LdBj$rNcBjH7$F G
$H;3EP$jC5:wK!$rC1=c$KAH$_9g$o$;$?J}K!KD$$$F$NI>2A$r9TCF$$$k [OBED 92]!%3liN8
$OL@$i$+$K%i%^%k%/E*$J?J2=2aDx$r:N$jF~$l$?$bNG$"$kKb4Xoi$:!$H‘iO$$$:lbO@J
Cf$G!V%i%^%k%/!W$H$$$&8@MU$r0lEY$bMQ$$$F$$$J$$!%$^$7Fd%@!<%&%#%s7?$N?J2=2aDx$H$NH
I>2A$O0l@Z9T$C$F$$$J$$!%0lJ}!$Grefenstette $O SAMUEL $H8F$Plk%W%m%@%/%7%g%s%7%9%F%‘
K*$$$F!$“GENERALIZE”!$“SPECIALIZE” JI$N3X=,A‘:n$rF3F~7F!$$3li$N3X=,$KhC
$F=$@5$5$l$?5,B’72$r%i%^%k%/E*$K?J2=$5$;$k3H$G!$85$N SAMUEL $N<jK!$rMQ$$$?H-h
$b8z2LE*$JLdBj2r7h%7%9%F%‘$,F@$ilk3H$r<($7$F$$$k [Gre91]!%Ackley $H Littman $O!$%0
%i%UJ,3dLdBj$rNcBj$H7F%i%^%k%/7?$H%@!<%&%#%s7?$K4X9kHf3S<B83$r9T$C$F$$$k [AL93]!%
iO%i%^%k%/7?$N?J2=$r9$k=8CD$NJ}$,%@!<%&%#%s7?$N=8CDhj$b05E]E*$K8zN(G"kH$
2L$rF@$F$*$j!$$=$l0J>e?<$/$OHf3SI>2A$r9TCF$$$J$$!%$3$3$G!$A0=R$N9)3XE*$J8+CO$+$i$
%^%k%/7?$N?J2=5!9=$NM-8z@-$N<(:6$H$O5U@bE*$K!$2L$?7FG!2?Jk>u67K*$$$F$b%i%^%k%
$N?J2=5!9=$O%@!<%&%#%s7?$N5!9=$hjbM%lF$$$k$H8@$(k+I&$+$H$$$&5?Ldb"$k!%

$$$:lK$;$h!$<+A33&$N?J2=$N2aDx$,%@!<%&%#%s7?G"k+iH$$$C$?M}M3$G%i%^%k%/7?$
Nr7Z;k7?$j!$5U$K9)3XE*$K$O%i%^%k%/7?$NJ}$,M-K>$K8+$($k$+$i$H$$$C$?M}M3$G%@!<%&%
7?$N?J2=7ABV$H$NHf3SI>2A$N0UL#$r7Z;k$9$k;Q@*$O@5$7$/$J$$!%

4.1.2 F0E*$J4D6-$X$NE,1~$K4X9k5DO@

=>Mh$N8&5f$K$*$1$k99$K=EMW$JLdBjE@$O!$$=N[HsI,@EE*$J<B834D6-$N>eGN$_$NI
$*$h$S9M;!$K4pE/bNG"$j!$F0E*@-<A$r;}$D4D6-$K4X$9$k5DO@$,FCKJ5lF3J+C
G"$k!%A0$N 4.1.1 @aGb4JC1$K>R2p$7$?!$Montana $H Davis $N%7%9%F%‘ [MD89] K7Fb!$

Grefenstette $N SAMUEL $N2~NIHG%7%9%F%` [Gre91] $K$7$F$b!$07$C$F$$$kLdBjNN0h$O@EE*$J$b $N$G$"$j!$H`$i$N%7%9%F%`$O@EE*$J4D6-$KBP7FE,1~9k$@$1Gh$$!%$^$?!$Ackley $H Littma i,9M$($?h&$JFs<!853J;R>e$K!$<+J, (%(!<%8%'%s%H) 0J30Kb0\F0G=NO$r;}$DFy?)=CJI G[CV$5lkh&$J<B834D6- [AL92] K*$$$F$b!$<+J,$,3X=,$;MPJi$J$$5,B' — !VFy?)=C$ $iN%$l$h!%?)NH$K$O6a$E$1!%W — $OIaJWE*$G$"$j!$$7$?$,CF@EE*G"$k!%$3l^GO3N$ $JHf3SE* "*well-defined*" $G@EE*$JLdBjNN0h$NHO0O$G1?MQ5l$k%7%9%F%`$,<g$K3+H/$5$l!$MxMQ$ $l$F$-$?!%$3$N$h$&$J4D6-$N2<$G$O!$Grefenstette[Gre91] $d Ackley $i [AL93] $,<($7$?$h$&$K!$ 3N$+$K%i%^%k%/7?$N$h$&$J8zN(E*$J0dEA5!9=$r;}$D%7%9%F%`$,M-8zG"$k!%

7+$7!$2.4 @a$G=R$Y$?$h$&$K!$$RH?$S<B@$3&$KB8:_$9$kLdBj$X1~MQHO0O$N;kLn$r9-2k $$$J$d!$$=3K$O3+J|7?J,;64D6-$NFC<AG"$kJ#;($GM=B,IT2DG=$J4D6-$N5sF0$,BT$A<u1F$ 3Nh&$J4D6-$N2<GO!$LdBj2r7h%7%9%F%`$,3X=,$;$M$P$J$i$J$$5,B'$,ITJQ$G$"$k$H$O8B$ $$!%F0E*$J4D6-2<$K$*$1$kLdBj2r7h%7%9%F%`$N?J2=$N2aDx$K$*$$$F$O‼$VIl$@$14D6-$NJQ2=$ =>9k3H$,$G$-$k$+!W$H$$$&3H$b=EMW$KJCF/$k!%

4.2 K\8&5f$NL\;X$9bN

0J>e=RYF$-$?h&$K!$%@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=$NHf3SI>2A!$$=lb4D6-$NF FC@-$r9MN8$7$?>eGN5DO@O3l^GK$b0Y$5lF3J$+$C$?!%$3li$NLdBjE@$rF'$^$($F! 2=E*%7%9%F%`$"$k$$$O?J2=E*%(!<%8%'%s%H$NE,1~E*$JB&LL$N:G>.8B$rCj=P7?%b%G%k$rMQ$$ %@!<%&%#%s7?$*$h$S%i%^%k%/7?$N0dEA5!9=$K4p$E$/=8CD$N?J2=$N2aDx$r:F8=$7!$$=$N%@%$%J% %9$r4Q;!$9k3HGN><T$rHf3S$9$k!%6qBNE*$K$O!$E,1~@-!$E,1~?J2=$NB.EY!$4h7r@-$KM?$($ 6AJIKD$$$FI>2A$*$h$S5DO@$7!$$=l>lN0dEA5!9=$NFC@-$rL@i+K9$k!%

Bh **5** >O

%@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=$NI>2A!&9M;!

K\8&5fGO!$4D6-$NF0E*FC@-$r9MN8$N>e$G!$?J2=E*%7%9%F%`$"$k$$$O?J2=E*%(!<%8%'%s%H$

1k%i%^%k%/7?$H%@!<%&%#%s7?$N0dEA5!9=$NFC@-$rL@i+K9$k!%?J2=E*%(!<%8%'%s%H=8CD$

1~E*$JB&LL$rCj=P7F$=$N%@%$%J%_%/%9$r4Q;!9k$?$a$K!$3F%(!<%8%'%s%H$r%K%e!<%i%k%M%

%o!<%/H7$FCj>]2=$7!$$3li$N%(!<%8%'%s%H=8CD$K0dEAE*%"%k%4%j%:%`$r;\$9!%3Nh&$

=c2=7?%b%G%k>eGN%7%_%e%l!<%7%g%srDL8$F!$FsDN0dEA5!9=$NFC@-$rI>2A9k!%

5.1 <B83$N@_Dj

%K%e!<%i%k%M%C%H%o!<%/$N3X=,$r!$?J2=E*%(!<%8%'%s%H$N=@Fp$J3X=,2aDx$N%b%G%kH7$FM

$k!%%K%e!<%i%k%M%C%H%o!<%/$N3X=,$N?J$_J}$OA2?JE*G"$j!$;~H7$F6I=j2r$KJaol$F<sH

$/3X=,$,$,?J$^$J$$$$3Hb$"$k$H$$$&@-<A$b;}$C$F$$$k!%3liN@-<A$O!$3+J|7?J,;64D6-N

$JJ#;($J4D6-2<GN3X=,$N2aDx$rh/%b%G%k2=G-kbNH;Wol$k!%$^$?!$0dEA$*$h$S?J2

2aDx$r<B8=$9k?aK0dEAE*%"%k%4%j%:%`$rMQ$$$k!%@8J*3XE*$J>\:Y$JItJ,O+Jj>JN,5

$$$kbN$N!$0dEAE*%"%k%4%j%:%`O3$&$7$?=8CD$N?J2=$N2aDx$r%b%G%k2=9k3H$,=PMh$k!

3G$O!$2?i+$N:GE,2=LdBj$r2r7h9k3H$,L\E*$JNGOJ$/!$$"$/$^Gb=8CD$N?J2=$N%

%kH7$F0dEAE*%"%k%4%j%:%`$rF3F~9k!%

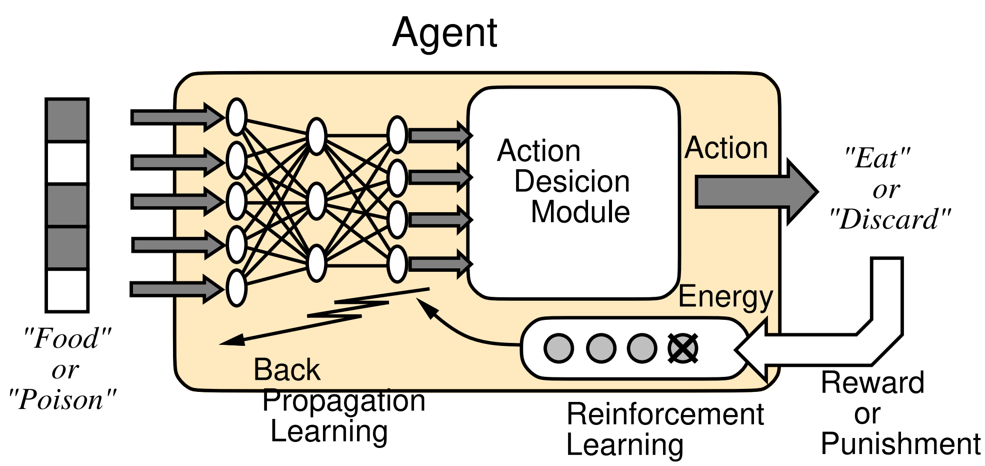
K\@aGO!$K\8&5f$K$*$1$k<B83$N@_DjKD$$$F>\:Y$K=R$Y$k!%$^$:!$%(!<%8%'%s%H8DBN$N9

$r>\:Y$K=RY?8e!$<B83$GA[Dj7?4D6-(D^$j%(!<%8%'%s%H$N@3$`@$3&)KD$$$F6qBNE*$

Yk!%

5.1.1 %(!<%8%'%s%H$N9=B$

%(!<%8%'%s%H$N9TF07hDj$H3X=,



?^ 5.1: %(!<%8%'%s%H$N9=B$

?^ 5.1 $K<($9h&$K!$3F%(!<%8%'%s%H$O4D6-$+$i<u$1<hC?F~NO$r85$K=PNOCM$r7W;;$9$k%U%
%I%U%)%o!<%I7?$N%K%e!<%i%k%M%C%H%o!<%/$r;}$A!$%(!<%8%'%s%HO=$N=PNOCM$K1~8F9TF0$
Dj9kh&$J8DBN$G$"$kH9$k!%

%(!<%8%'%s%H$O!$<B9T7?9TF0$N7k2L$KhC$F3X=,$r9T$&!%9TF07hDj$NCf?uG"$k%K%e!<%
%M%C%H%o!<%/$N3X=,$NItJ,KO!$2.3.3 @a$G@bL@7?8m:95UEAGEK! (BP K!) $rMQ$$$k$,!$BP K
N_$@$H>o$KM}A[=PNO$r<(7F$/$l$k65;U$NB8:_$,I,MW$HJk!%7+7J$,$i!$%+%*%9E*$G$
$=$N5sF0$NM=B,$,:FqG$"$k3+J|7O$N@-<A$r9MN8$9$k$H!$;vA0$KAx6x$7F@$kF~NO$H$=$lKBP
@5$7$$9TF0NAHrA4$FDj5A$7MQ0U9k3HOG$-$J$$!%0lJ}!$@8J*$JIOM}A[E*$J65;U$,B8:
J/Hb!$2w3Z$dMx1Wrb$?$i$99TF0$G$"$kJiP=lr7+jJV9$3$H$r3X=,$7!$4m81$d61D
HbJ&9TF0G"kJiP$=$lrHr1k3Hr3X=,9k!%$^$?!$$ICAD+$:$N9TF0$OK:$l$
G"$k!%$=3G3+J|7?$N4D6-2<$K$*$1$k%b%G%k$H7F$NBEEv@-$r;}$?$;k?aK!$>e5-$Nh
6/2=3X=, **(Reinforcement Learning)** $NOHAH$rF3F~9k!%6/2=3X=,HO!$65;UL5$7$N3X=,$G$"
$j!$<B:]$N9TF0$N7k2LH7$F4D6-$+$iM?$(il$kJs=7?.9f$rbH$K!$$=$N>u67$KBP7F!VE,@
9TF0!WG"C?$+$I$&$+$NH=CG$,J5l$k!%!V6/2=3X=,!W$O85!9$O@8J*3X$NMQ8lG"k,!$6
$O5!3#3X=,$K$*$1$k0l$D$NJ}K!$H7F<h$jF~$lil!$**Q-Learning** $rBeI=Nc$H9kMM!9$J<jK!$
Ds0F5l$F$$$k [Sut88, Sut90, WD92]!%

%(!<%8%'%s%H$O%K%e!<%i%k%M%C%H%o!<%/$N=PNOCM$rD>@\E*$KG$0U$N9TF0$K<LA|$9kNGO$J
$=$N=PNOCM$K1~$8$?3NN($G3NDj=PNO$r;;=P$9$k9TF07hDj%b%8%e!<%k$N=PNOKhCF9TF0$N:G=
$J7hDj$r9T$&!%$3Nh$&$J3NN(E*$J5!9=$rF3F~9kNO!$6/2=3X=,$r8z2LE*$K?J$ak?aG$
Nc$($P!$%(!<%8%'%s%H$,$"$k>u67 s K*$$$FJs=7$N860x$HJkh&J"$k9TF0 a $r3X=,$7$?$
$k!%$3NH$-$K!$$b$73NN(E*$K9TF0$r7hDj$9$k5!9=$,$J$$$H7?$i!$%(!<%8%'%s%H$O!$0J8e>
s $KAx6x$7$?:]$K$O>o$K0lEY3X=,7F7^C?9TF0 a $r<h$jB3$1!$$hjBg-$JJs=7$rb?i
b7lJ$$B>$N9TF0$r3X=,9k2DG=@-$O<:$olF7^$&!%$7$?$,CF!$$h$jM-1W$J9TF0%Q%?!
$r3X=,$9$k2DG=@-$r$$$/i+GbJ];}9k$?$a$K!$9TF07hDj%b%8%e!<%kNh$&$J3NN(E*$J5!9
I,MWHJkNG"$k!%9TF07hDj%b%8%e!<%k$G$O!$%K%e!<%i%k%M%C%H%o!<%/$N3F=PNO%K%e!<%m%
<h$jF@$k9TF0N=l>lKBP1~E1$F!$3F=PNO%K%e!<%m%s$N=PNOCM$N6/5K1~8F0J2<$N<0$
;;5l$k%\%k%D%^%s3NN(J,I[$K7?$,$C$F9TF0$N:G=*E*$J7hDj$r9T$&!%

$$p(a_i|s) = \frac{\exp(o_i/T)}{\sum_{j\in possible\_actions} exp(o_j/T)} \tag{5.1}$$

$3$3$G!$ $p(a_i|s)$ $O>u67 s K*$$$F9TF0 a_i $r<h$k3NN($rI=$7F*$j!$$3$3$G9TF0 a_i $KBP1~$E$1$5$l
$?=PNO%K%e!<%m%s (0l$DHO8BiJ$$) $N=PNOCM$N9g7WG"$k!%$^$?!$ T $O29EYDj?t$H8FPl
bNG"$j!$%(!<%8%'%s%H$NKA81EY$rI=9bNG$"$k!% T $,>.$5$$$H%(!<%8%'%s%H$O2a5n$N7
$K4p$E$$$FJ]<iE*$J9TF0$r<h$k798~$KJj!$5U$K T $,Bg$-$$$H%(!<%8%'%s%H$O2a5n$N7P83$E

ol$:$KMM!9$J9TF0$r;n7F$_$k$H$$$&KA81E*$J798~$r6/$/<($9h&KJ$k!%9TF07hDj%b%8%

%k$N3NDj=PNO$KhC$F<B9T$5l?9TF0$,!$Js=7$rA}Bg$5$;$?JiP=NH$-$NF~NOKBP7$FF

=PNO$,F@$ilk3NN($,9b$/Jkh&$K!$5U$KD(H3$r<u1?JiP=Nh$&$J=PNO$r=P$5$J$$$

$K%K%e!<%i%k%M%C%H%o!<%/$N3X=,$,9T$olk!%

%(!<%8%'%s%H$N0dEA;RI=8=

8DBN$N;}$D%K%e!<%i%k%M%C%H%o!<%/$N9=B$$O8GDjG"kH$7!$8DBNCB@8;~$N3F7k9g$N=i4|6

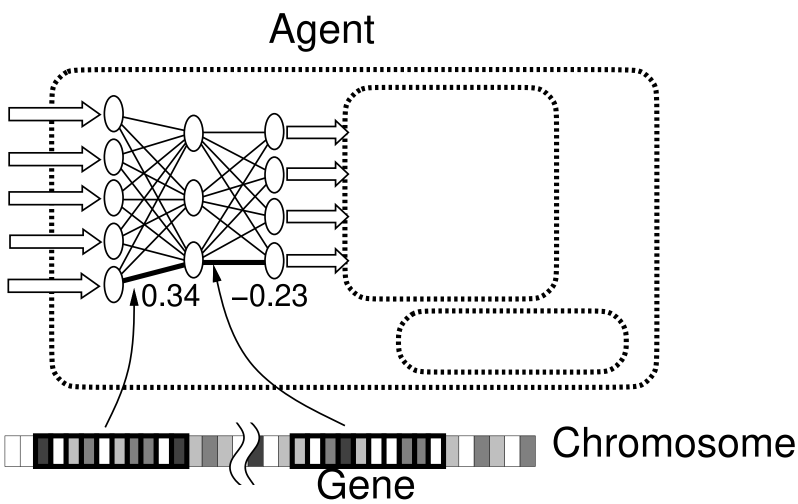
$O@w?'BN>e$K0dEA;RH7$FId9g2=$5lF$$$kbNH9$k (?^ 5.1)!%@w?'BN$NI=8=H7FO!$Ib

>.?tE@$NG[Ns$KhC$FI=8=$5lkD>@\%(%s%3!<%I K! [MD89, WH89] $rMQ$$$k!%$^$?!$@w?'BN$N

D9$5$r$"$kDxEYD9$/$7$F GA $,8z2LE*$KF/$/$h$&$K!$10 8D$N0dEA;R$,0l$D$N7k9g$N6/EY$r7h

9kh&$J9=B$$rMQ$$$k!%J*!$3F%K%e!<%m%s4V$N7k9g$N6/EY$r w_{ij} J/!$3F%K%e!<%m%s$Nog

CM θ_i $b@w?'BN>e$KId9f2=9k!%



?^ 5.2: @w?'BN$+$i@8@.5l$k%(!<%8%'%s%H

5.1.2 %(!<%8%'%s%H$N@$3&

<!$K!$K\<B83K*1k%(!<%8%'%s%H$N@$3&$N@_Dj$r!$D>4QE*$KM}2r7d$9$$$h$&$K6qBNE*$

H7$F=R$Y$k!%8DBN$G$"$k%(!<%8%'%s%H$,B??t!$$=l>l"$k0lDj$NCM$r=i4|CM$H9k@8L?%

%k%.!<$r;}$C$F@$3&$KCB@8$9$k!%@$3&KO!$@8L?%(%M%k%.!<$r0lDjNLA}2C5;$kM-1W$J?)NH$

$N5U$K@8L?%(%M%k%.!<$r0lDjNL8:>/$5$;$kM-32$JFGJ*$H$$$&Fs<oN`$NJ*<A$,;6:_$7!$$=l>$

FCD'E*$J7A>u (%S%C%H%Q%?!<%s) $r;}$D!%8DBN$O!$$"$kJ*<A$r8+k3HG%K%e!<%i%k%M%C%H%o!

K=$N%Q%?!<%s$rF~NO$7!$$=$N=PNOCM$K1~8F!V?)Yk!W$+!V<N$F$k!W$N$$$:l+$N9TF0$r3

E*$K7hDj$9$k (?^ 5.1)!%!V?)$Y$?!WJ*<A$,?)NHG"C?>l9gKO@8L?%(%M%k%.!<$,A}2C$9kN$
$=$N%Q%?!<%sKBP7$F!V?)$Y$k!W9TF0$rHk3NN($,9b$/Jkh&JCMr%K%e!<%i%k%M%C%H%o!
$,=PNO$9kh$&$K3X=,$r9T$&!%5UK=l,FGJ*G"C?>l9gKO@8L?%(%M%k%.!<$,8:>/$9kN
$=$N%Q%?!<%sKBP7FO!V<NFk!W9TF0rH$k3NN($,9b$/$Jkh$&$JCM$r=PNO$9kh$&$K3X=
9T$&!%$3$3$G!$$b7"$kJ*<A$r?)$Y$$:$K!V<N$F$?!W>l9g$K$O!$$=l,?)NHG"kN$+FGJ*$G$
N+$OJ,$+iJ$$$N$G3X=,$O9Tol$J$$$3H,DL>o$N BP K!$N$_$rMQ$$$?3X=,$NJ}K!$H0[J
G"$k!%?)NH$HFGJ*$r<1JL$9k?aKI,MW$JCN<1$r!V5,B'!W$H8F$V3HK9kH!$%(!<%8%'%
$O<+$i$,9TF0$r5/$3$9$3$HKhCF!$$3$N5,B'$r3X=,7F$$$/3HKJkNG"$k!%

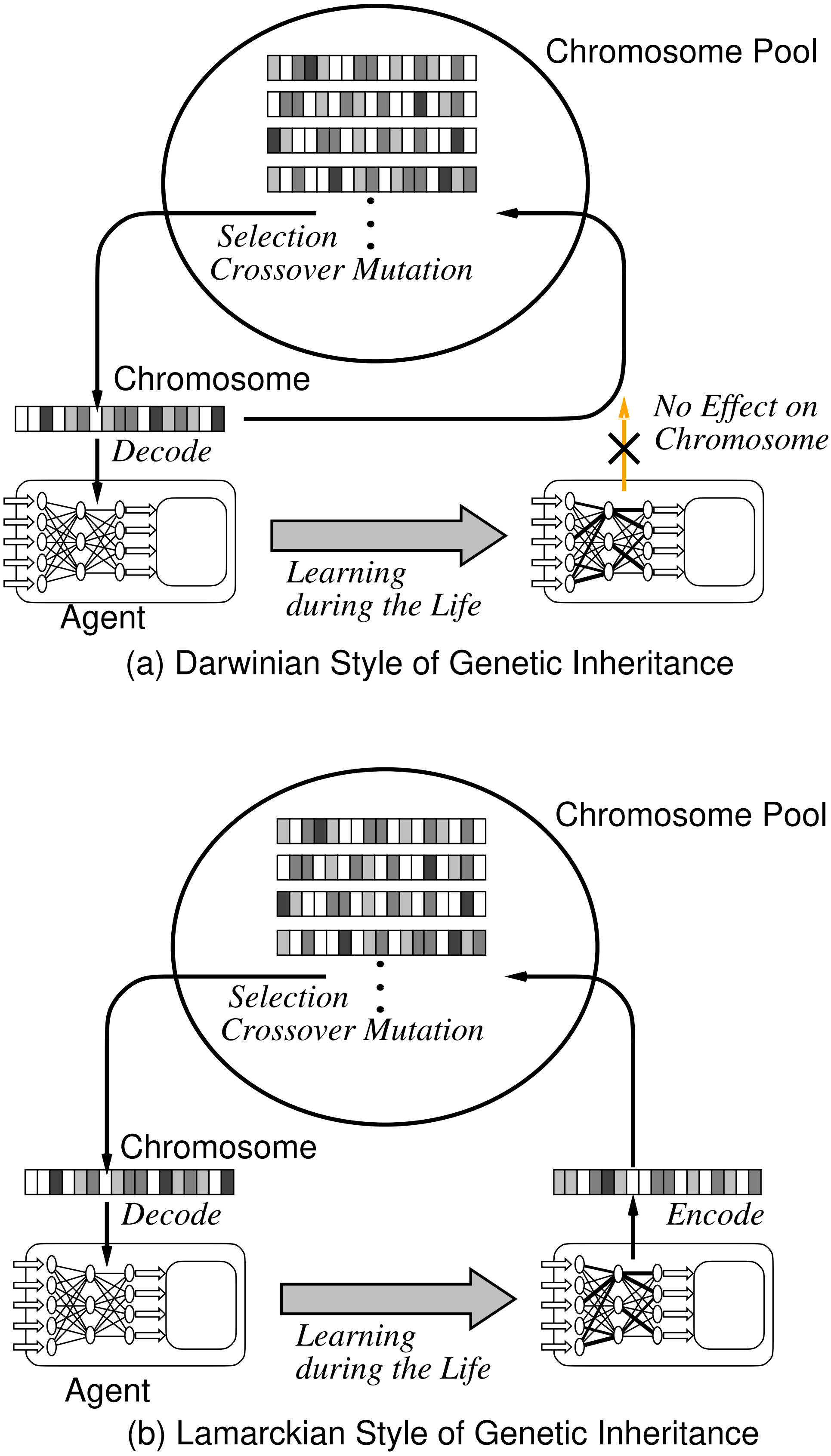
3F%(!<%8%'%s%H8DBN$O!$$3Nh$&$J?)NH$"$k$$$OFGJ*$rI=$9%S%C%H%Q%?!<%s$r!$$"$k7h$a$
$?2s?t$@$1Ds<($5lF6/2=3X=,$r9T$&!%%(!<%8%'%s%H$,%Q%?!<%s$r8+$k2s?t$r!$%(!<%8%'%s%
!V0l@8!W(*LifeSteps*) $N3X=,%9%F%C%W?t$H9k!%0l@8$r=*$($?%(!<%8%'%s%H$O!$@8L?%(%M%k%.!<$
;DNL$K1~$8$?3NN($GA*Br5l$F<!@$Be$K;RB9$r;D$9!%$3$N:]$K!$@w?'BN$N8r:5!&FMA3JQ0\J
GA $N0dEAE*A`:n$,;\$5lk!%

:#2s$N<B83$G$O!$@$3&$K$O==J,$JNL$NJ*;q$,$"$kbNH7!$?)NH$r=d$kD>@\E*$J%(!<%8%'%
4V$N6%Ah$O2>Dj7F$$$J$$!%$=$NBeoj$K!$8Bj"$k@8B8?t$H$$$&0X;R$r=d$CFN%(!<%8%'%
4V$N6%Ah$,9TolkbNH9k!%

5.1.3 %@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=

%@!<%&%#%s7?$*$h$S%i%^%k%/7?$N0dEA5!9=$r;}$D%(!<%8%'%s%H$N$$$:lb!$0l@8$N4V$N3X=
hC$F<+J,$N;}$D%K%e!<%i%k%M%C%H%o!<%/$N7k9g6/EY$r=$@5$7$F$$$/!%%@!<%&%#%s7?$N0dEA5
$r;}$D%(!<%8%'%s%H$O!$?^ 5.3 (a) $K<($9h&$K!$0l@8$N4V$K=$@5$5l?7k9g6/EY$rD>@\<!@$
KEA(k3HOJ/!$<+J,$N?F$+$i<u$17Q$$$@0dEA;Rr=N^$^<!@$Be$N;R$r:n$k:]$N0dEA;
7F GA $N%W%m%;%9$KEO$9!%0lJ}!$%i%^%k%/7?$N0dEA5!9=$r;}$D%(!<%8%'%s%H$O!$?^ 5.3 (b) $
<(9h$&$K!$0l@8$N4V$K=$@5$5$l$?7k9g6/EY$r:FId9f2=7F0dEA;R$r:n$jD>$9!%

J*<B83GO!$>e=R$N!V%@!<%&%#%s7?!W$H!V%i%^%k%/7?!W$N%(!<%8%'%s%H=8CD$NB>$K!$Hf3S
H7$F!$!V**GA-Only**!W$H!V**Learning-Only**!W$H$$$&%(!<%8%'%s%H=8CD$b9M$($k!%GA-Only $N
%(!<%8%'%s%H$O!$0l@8$N4V$K3X=,$r9T$o$:($9Jo$A%K%e!<%i%k%M%C%H%o!<%/$N7k9g6/EY$rA4$
@5$;$:) $K!$@8$^$lD-$N%K%e!<%i%k%M%C%H%o!<%/$N7k9g6/EYN^$^0l@8$r2a$4$9!%7?$,$C
GA-Only $N%(!<%8%'%s%H$N>l9g$O!$@8F@E*$K;}$D%K%e!<%i%k%M%C%H%o!<%/$NA1$70-7,E,1~EY
D>7k9k!%5U$K Learning-Only $N%(!<%8%'%s%H$O!$A*Br!&8r:5!&FMA3JQ0[$JIN0dEAE*A`:n$rA
$/<u$1k3HJ$/1J5WE*$K3X=,$7B3$1kh$&$J%(!<%8%'%s%HG"$k!%$7$?$,CF!$Learning-On
$N%(!<%8%'%s%H=8CD$K$O@$Be$H$$$&35G0$,$=b=$bB8:_$7$J$$$,!$Hf3S$N$?$a$KB>$N%(!<%8
%HK*1k0l@8$N%9%F%C%W?t$H$$$&C10L$r6h@Z$jH7$FJX59E*$K@Ber?t$($k!%



(a) Darwinian Style of Genetic Inheritance

(b) Lamarckian Style of Genetic Inheritance

?^ 5.3: %@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=

5.1.4 A4BN$NN.$lH=$NB>$N>\:Y$J@_Dj

%7%_%e%l!<%7%g%s$NA4BN$NN.lr$^$Hak$H0J2<$Nh&KJ$k!%

1. =i4|@BeN8DBN$r@8@. ($g = 1$)
2. Bh g @BeN8DBN3F!9$,!$$"$k0lDj4|4V9TF0$r7J$,$i3X=, (8DBNH7FN!V0l@8!W)
3. ;DB8@8L?%(%M%k%.!<$r85$KE,1~EY$NI>2A
4. E,1~EY$r85$K!$A*Br!$8r:5!$FMA3JQ0[$JIN0dEAE*A`:nKhCF $g+1$ @BeN?7$7$$ 8DBN72$r@8@.
5. $g = g + 1$ H7$F!$2. KLak

0J2<$K!$0J8eK\O@J8$G=R$Y$k<B83$K$D$$$F$N6&DL$N@_Dj$*$h$S%Q%i%a!<%?CM$r<($9!%

- =8CD$N8DBN?t$O8GDj$G 100 H9$k!%
- =i4|=8CD$N3F8DBN$,;}$D%K%e!<%i%k%M%C%H%o!<%/$N3F7k9g%f%K%C%H$O!$$-0.30 \sim 0.30$ $N4V
  $N%i%s%@%`$JCM$G=i4|2=$9$k!%
- =PNO%K%e!<%m%s$O 8 8D$"$j!$$=l>$l 4 8D$:D,!V?)Yk!W9TF0$H!V<N$F$k!W9TF0$K4sM
  9kbNH9$k!%
- (5.1) <0K*1k8DBN%(!<%8%'%s%H$NKA81EY$r<($9 T NCMr 0.3 $K@_Dj$9$k!%
- (2.7) <0$GI=$5lk BP K!K*$$$F!$3X=,N(η!$47@-78?t α r=l>$l 0.75!$0.8 $K@_Dj
  9k!%
- 3F8DBN%(!<%8%'%s%H$O=i4|CM 500 $N@8L?%(%M%k%.!<$r;}CF@8@.5l!$?)NH$r?)YkKh$
  +10 $NJs=7!$FGJ*$r?)$YkKhK -10 $ND(H3$,M?$($ilkbNH9$k!%
- %(!<%8%'%s%HKO!$?)NH$HFGJ*$NAPJ}$,$=$l$>$lF1$82s?tDs<($5lk!%
- %(!<%8%'%s%H$K?)NH$"$k$$$OFGJ*$,Ds<($5lk2s?t *LifeSteps* $r!$%(!<%8%'%s%H$N!V0l@8
  H9$k!%
- 0l@8$r=*$($?8e$N;DB8@8L?%(%M%k%.!<$r!$$=$N8DBN$NE,1~EYH9$k!%
- 8DBN$NE,1~EY$,<h$jF@$k:GBgCM$O0J2<$N<0$G7W;;$5lk!%

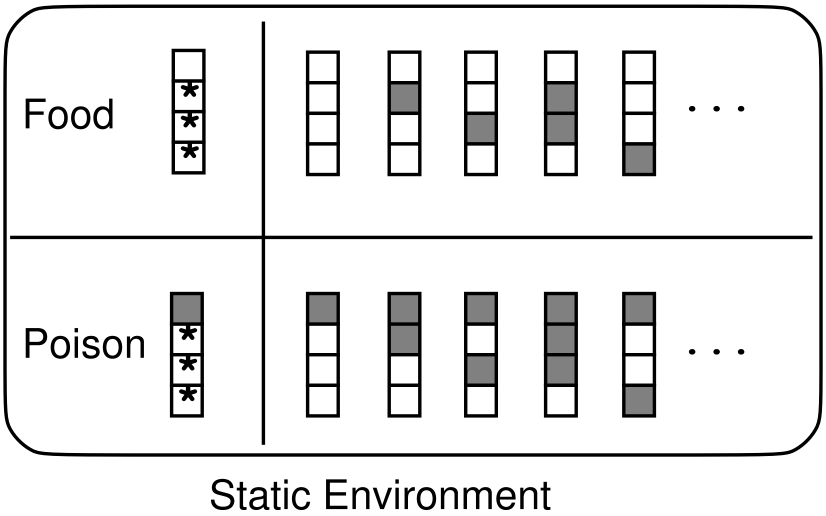
$$MaximumFitness = InitialEnergy + \frac{LifeSteps}{2} \tag{5.2}$$

- 0dEAE*A`:nK*$$$F!$8r:5E@$N?t$O $0 \sim 4$ 2s!$FMA3JQ0[N($O 5%!$JQ0[$NI}$O ± 0.5 H9$k!

5.2 @EE*$J4D6-

K\@aGO!$$^$:@EE*$J4D6-2<K*1k3X=,$H?J2=$NAj8_:nMQ$N4X78$rI>2A9k!%$3$3GO!$%
%8%'%s%H$N3X=,$9Y-5,B'$,@~7AJ,N%2DG=$J4JC1$J>l9g$H@~7AJ,N%IT2DG=JFq7$$>l9g$NFsD
$r9M$($k!%FC$K!$$=l>lN>l9gK*1k%\!<%k%I%&%#%s8z2LKD$$$FI>2A9k!%

5.2.1 <B83 **1:** @~7AJ,N%2DG=$J4JC1$J4D6-K*1k?J2=



?^ 5.4: 4D6- 1

$^$:!$?)NH$HFGJ*$,?^ 5.4 $K<($9%S%C%H%Q%?!<%sG=l>$lFCD'$E1ilkh&$J!V4D6-
$r9M$($k!%?^ 5.4 K*$$$F!$Gr$$%^%9$*$h$S9u$/Kdail?%^%9O=l>$l "0"!$"1" $rI=$7
"*" $N5-9f$O "0" $H "1" $N$$$:lNCMGb$h$$$3HrI=9bNH9k!%7?$,$C$F4D6- 1 GO
0lHV>e$N%S%C%H$, 0 G"kbN,?)NHG"$j!$1 G"kbN,FGJ*G"$k!%;D$j$N 3 %S%C%H$
$=$NJ*<A$,?)NH$G$"$k$+FGJ*$G$"$k$+$K$O4X$oiJ$$;(2;%S%C%HG"kH9k!%3Nh&$K?
G"kN$+FGJ*$G$"$kN+$r<1JL$9kNKI,MWJCN<1N3Hr!V5,B'!W$H8F$V3HK9$k!%$
ms3F%(!<%8%'%s%H$O!$$Il,;(2;%S%C%HG"kN$+$H$$$C$?$3Hr4^aF!$$3$N5,B'$rO
$+$iCNCF$$$ko1GO$J$$!%

?)NHG"k+FGJ*G"k+$r7hDj$9kNO?$@0l$D$N%S%C%H$@1G$"$kNG!$4D6- 1 K*
$k5,B'$O@~7AJ,N%$,2DG=[1]$JHf3SE*4JC1JbNG$"$k$H8@$($k!%?^ 5.5 $K!$3X=,$N7P2a$KBP9k
%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$NJQ2=$NMM;R$r<($9!%<B@~$G<(7?bN$,K\<B83$GMQ$$$

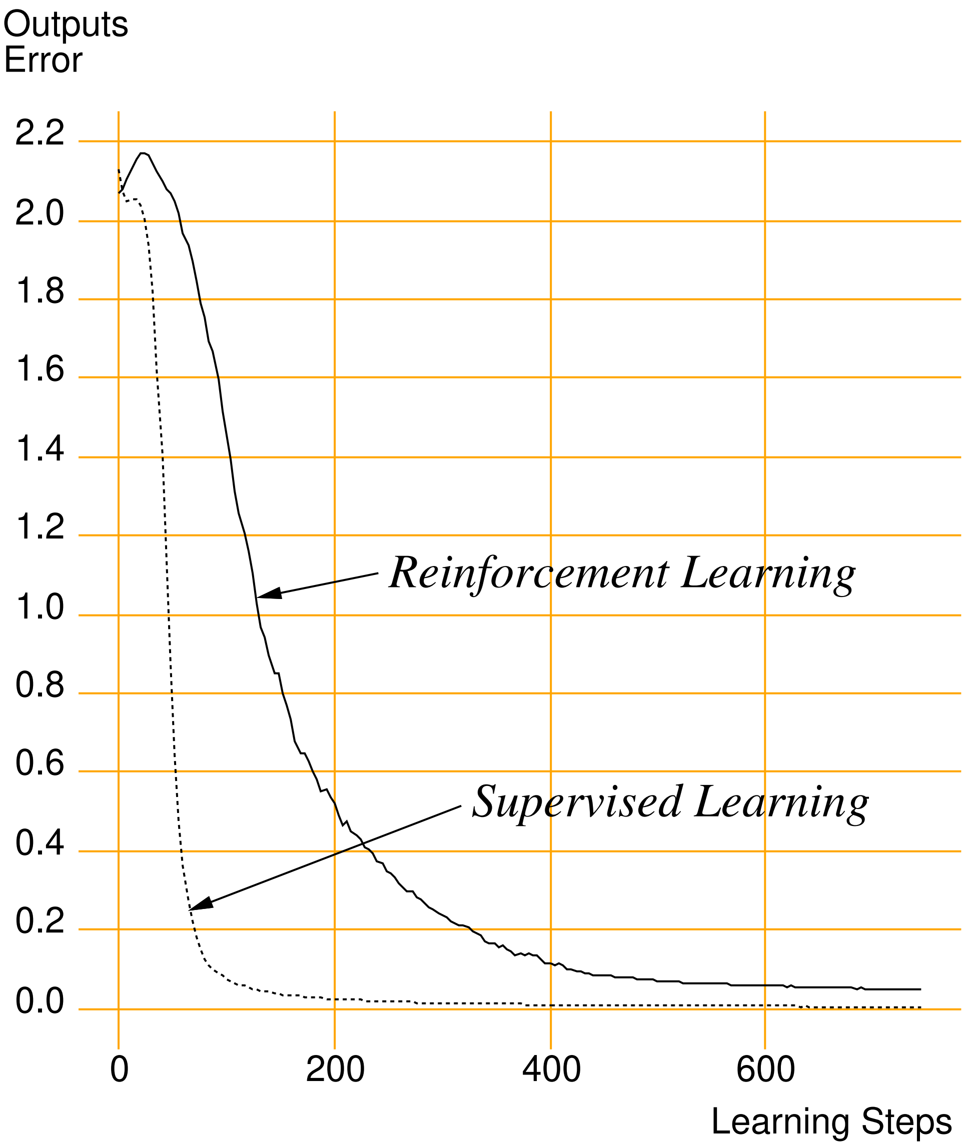
[1]D9$5 d $N%S%C%HNs$GI=8=5l$k?)NH$HFGJ*$r!$$=l>lN%Q%?!<%s$K4p$E$$$F d <!856u4V>e$KG[CV$5lk:BI
$H9M$($k!%Nc$($P!$?^ 5.4 Nh$&$J5,B'$N>l9g$K$O!$?)NH$rI=$9E@$O!$$(0,0,0,0)$!$$(0,1,0,0)$!$$(0,0,1,0)$...!$FGJ*$r
I=$9E@$O!$$(1,0,0,0)$!$$(1,1,0,0)$!$$(1,0,1,0)$... HJ$k!%$3NH$-$K!$?)NH$HFGJ*$NE@$N=89g$rFsJ,$9k3HNG-
$k ($d-1$ <!85) D6J?LL$,B8:_$9kh$&$JLdBj$r@~7AJ,N%2DG=$JLdBj$H$$$&!%

$k6/2=3X=,$NOHAH$rF3F~$7$?%(!<%8%'%s%H$N3X=,FC@-6J@~$rI=$7$F$$$k$,!$Hf3SBP>]N?$a
E@@~KFDL>o$N65;U$"$j3X=,(BP K!)$rMQ$$$?>l9g$N6J@~$bF1;~$K<($7$F$$$k!%J*!$$3li
3X=,FC@-6J@~$O!$100 $N%(!<%8%'%s%H$K$D$$$F$NJ?6Q$r<hC?bNG"$k!%$3$N3X=,FC@-6J@
$j!$=PNO8m:9$,3X=,%9%F%C%W$,?J$`$KDl$F35$MC1D4$K8:>/$7$F$$$k3H$+$i!$5,B'$r3X=,$
3H$,%(!<%8%'%s%H$KHC$FMF0W$G$"$k3H$,3NG'$G$-$k!%

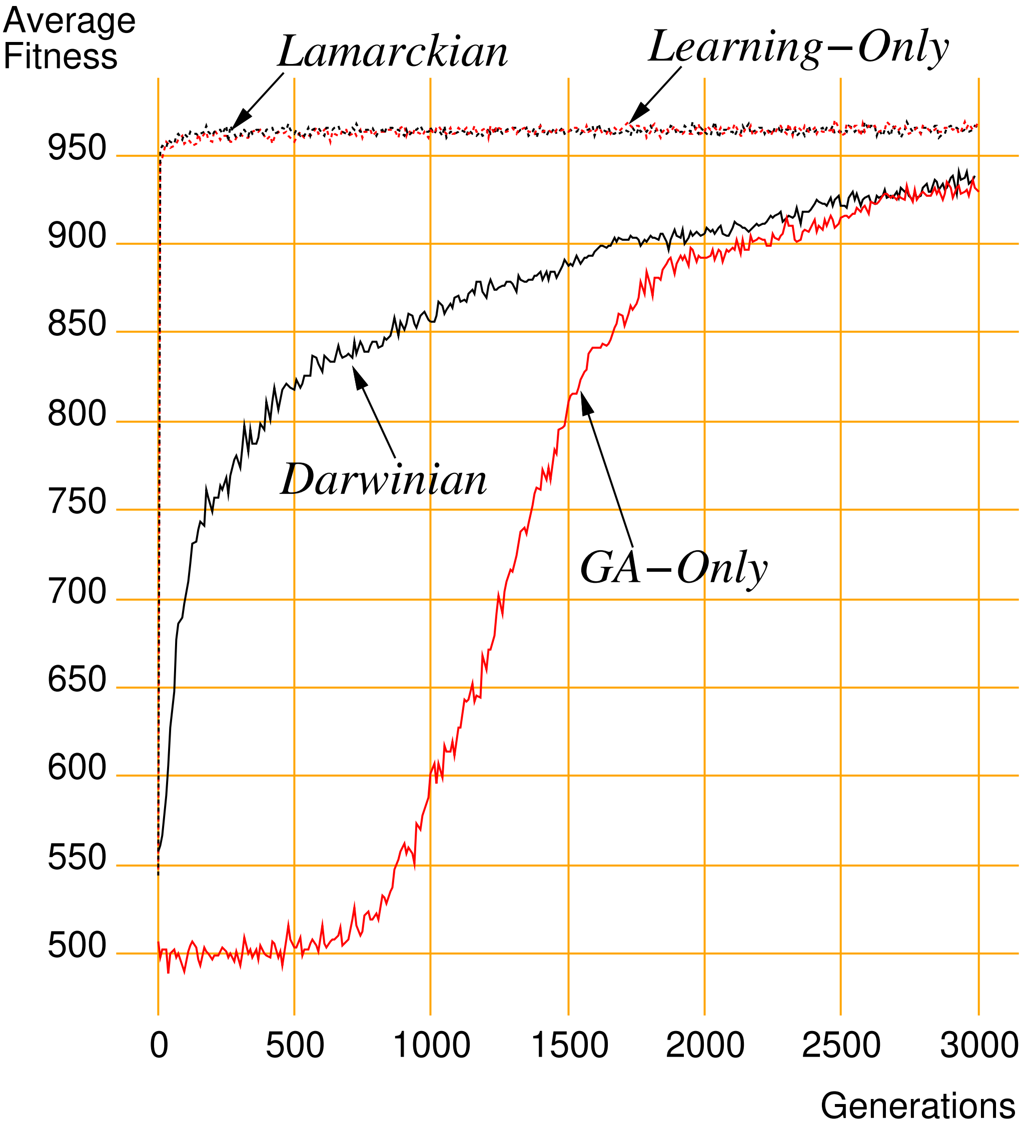
4D6- 1 K*$$$F!$3F8DBN$N0l@8$r 100 %9%F%C%W (?^ 5.4 $K<($7$?%Q%?!<%s$r=gHV$K7W 100 2s
Ds<(9k) H7$?$H$-$N 3000 @Be^GNJ?6QE,1~EY$N?d0\$r?^ 5.6 $K<($9!%J*!$3X=,%9%F%
%W$, 100 G"k3Hh$j!$%(!<%8%'%s%H$N<h$jF@$kE,1~EY$N:GBgCM$O 1000 G"$k!%?^ 5.6 $h
$j!$%i%^%k%/7?$H Learning-Only $N%(!<%8%'%s%H=8CD$,4D6-KBP9$kE,1~B.EY$NLL$G:G$bM%l
$$$k3H$,J,$+$k!%$=7F!$%@!<%&%#%s7?$,$=$l$KB3$-!$:G8e$K GA-Only $H$$$&7k2LKJC
$$$k!%GA-Only $N=8CD$O!$Hf3S$7$?;M<oN`$NCf$G:G$b0-$$7k2LHJCF$O$$$kbN$N:G=*E*$
$O%@!<%&%#%s7?$N=8CD$HF1DxEY$NE,1~EY$r3MF@$7$F$$$k!%3l$O!$3X=,9k3HJ/!$8r:5$
A3JQ0[JI$N0dEAE*A`:n$rH<C?<+A3EqBA$N2aDx$N$_$,F/$/$h$&$J=8CDGb@8B8$KM-Mx$JCN<
3MF@7F$$$/3H$,2DG=$G$"$j!$=8CD$,E,1~@-$r;}$C$F$$$k3H$r<($7$F$$$k!%?^ 5.6 K*$
:G$bFCI.$9Y-JN$O!$GA-Only $N=8CD$KBP9k%@!<%&%#%s7?=8CD$NJ?6QE,1~EY$N>e>:$NEY
G"$k!%%@!<%&%#%s7?$N%(!<%8%'%s%HGO!$3F8DBN$,0l@8$N4V$K3X=,7?7k2L$OD>@\;RB9$KE
ilk3HO$J$$$N$G!$0dEA5!9=$=$NbN$O GA-Only $HA4$/F1EyG"$k!%$7$?$,CFD>4QE*$
$O%@!<%&%#%s7?$H GA-Only $N=8CD$K$*$$$FE,1~EY$N>e>:$NEY9g$OF1DxEY$KJk$+$Nh&$KA[A
5lkNG"k,!$<B:]$K$O%@!<%&%#%s7?=8CD$NJ}$,?J2=$NB.EY$,B.$$$H$$$&7k2L$rF@$k!%$
ms!$GA-Only $N=8CD$,3X=,$r9T$o$J$$$NKBP7$F%@!<%&%#%s7?$O0l@8$N4V$K3X=,$r9T$&N
%@!<%&%#%s7?$NJ}$,E,1~EY$,>e2s$k3H$OEvA3$G$"$k!%$3$3$G!$CmL\$7$F$$$kNOE,1~EY$N>
$NEY9g$G$"$k!%$3$3$G8+$ilk3X=,$N8z2L$,?J2=$r2CB.$9$k8=>]$O!$$^5K 3.2.1 @a$G@bL@$7
%\!<%k%I%&%#%s8z2LG"$j!$Hinton!$Ackley!$Parisi i,4Q;!7?NHF1Ey$N8=>]$G$"$k!%

%\!<%k%I%&%#%s8z2Lrh$j0lAX3NG'$9k?aK!$?^ 5.7 $K!$3F@BeK$*$$$F8DBN$,@8@.$5$l
D>8e$N%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$N=8CDJ?6Q$r<($9!%$3$N8m:9$O!$8DBN$,@8F@E*K
DxEY4D6-$KE,1~$7$F$$$k$+$rI=$9;XI8$HJj!$8m:9$,>.$5$$$[$I@8$^lD$-M%=($J8DBNG"$
8@$($k!%GA-Only $N=8CD$N=i4|8m:9$,@$Be$r7P$kK7$?$,CF=y!9$K2<$,CF$/$kNO!$<+A3
BA$K4p$E$/E,1~2aDx$KhkbNG"$k!%$3$3$G!$7+$jJV$76/D4$9k,!$%@!<%&%#%s7?$N%(!<%
%s%H$O3X=,$N7k2L$rD>@\?F$+$i;R$KEA$($k5!9=$O;}$?$J$$$?$a!$D>4QE*KO=i4|8m:9$N2<$,$
$O GA-Only $N=8CD$HF1DxEYKJkHA[A|5l$FA3$kY-JNG"$k!%$H3m$,<B:]$K$O!$?^ 5
$K<($7$?$h$&$K!$%@!<%&%#%s7?$Nh&$K3X=,$r9k%(!<%8%'%s%H=8CDGO!$$"$?$+$b?J2=$KJ
E1$,$J5l$F$$$k$+$N4H$/!$=i4|8m:9$N2<$,$jJ}$,, GA-Only $N=8CD$KHfYF5^KJkN$
$"$k!%

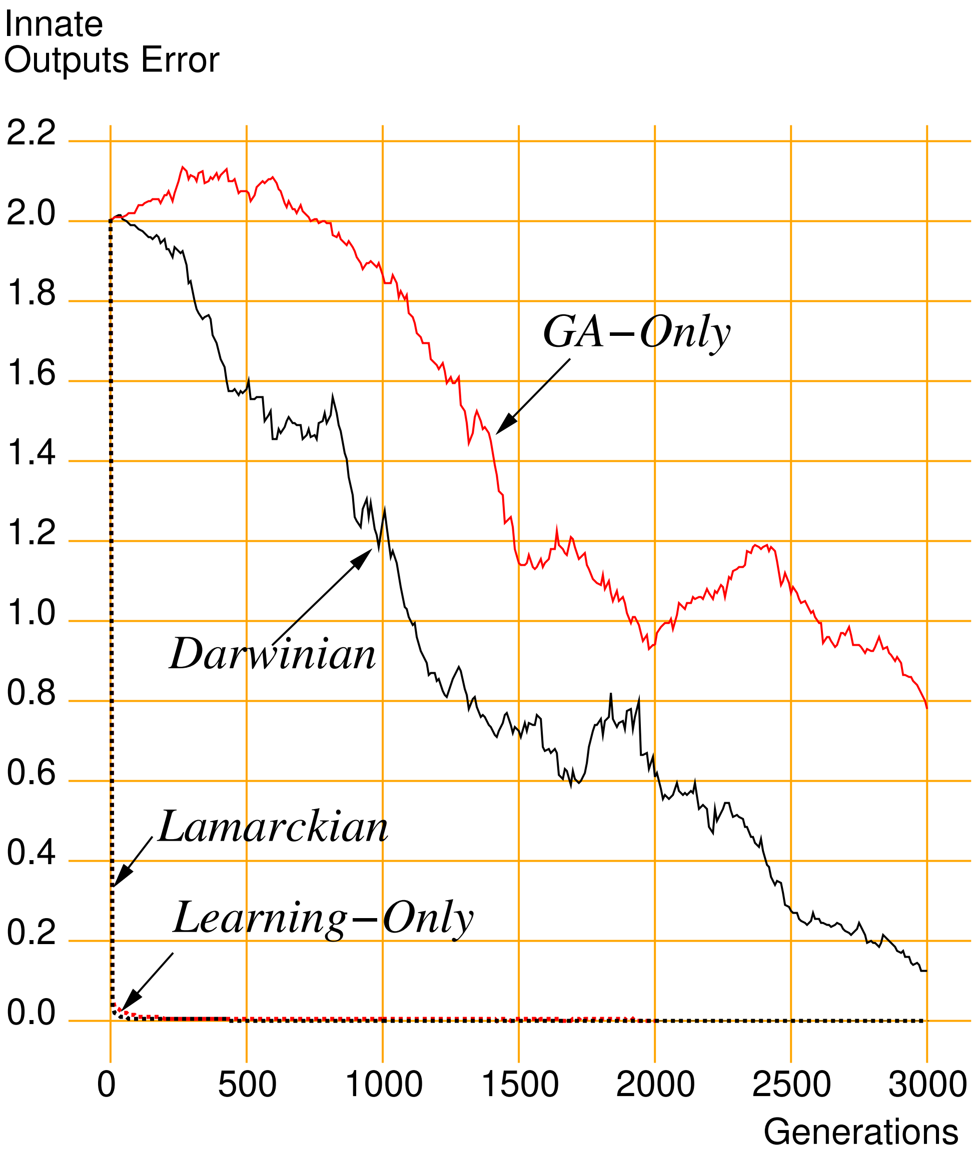
8DBN$N3X=,$,=8CD$N?J2=$KM?$($k1F6A$O!$K\O@J8$N0J8e$NItJ,GN=EMW$JO@E@$N0lDG$b
kN$G!$$3$3$Gdd>\:Y$K%\!<%k%I%&%#%s8z2L$,@8$8$k860xKD$$$F9M;!7F$*$/!%%@!<%&%
7?$N%(!<%8%'%s%H$G$O!$3F8DBN$,0l@8$N4V$K3X=,$7$?7k2L$OD>@\;RB9KEA(ilk3H,J
$G!$0dEA5!9=$=$NbN$O GA-Only $HA4$/F1EyG"$k!%$7$?$,CF!$D>4QE*$K$O%@!<%&%#%s7?$
GA-Only $N=8CD$K$*$$$FE,1~EY$N>e>:$,;O$^$k;~4|$d@$BerDL8FNCB@8;~$N=i4|8m:9$N?d(
$,!$$[$\0lCW$9kH0l8+A[A|5l$k!%$H3m$,!$$3l^GK$b=R$YF-$?$H$*$j!$<B:]$K$O!
F@7A<A$,D>@\;RB9$KEA$($ilk3HNJ$$%@!<%&%#%s7?$N=8CD$K$*$$$F$b!$8DBNKh$k3X=,$
CD$N?J2=$KJ}8~@-$rM?$($F?J2=$NB.EY$rB%?J$9k+Nh$&$J5?;w%i%^%k%/8z2L$,@8$8kN$r8
3Nh&$J8z2L$,@8$8$k860x$O0J2<$Nh&$K9M$(il$k!%%K%e!<%i%k%M%C%H$N7k9g6/EY%Y%/%
6u4VK*$$$F!$$[$\F1DxEY$N@-G=$r<($97k9g6/EY%Y%/%H%k$OJ#?t$"$jF@$k$,!$$=l>lN%Y%
%k$rI=$9E@$N<~0O$N>u67$OF10l$G$"$kHO8BiJ$$!%D^$j!$7k9gCM$N0lItJ,$ro:$+$KJQ2
$;$k$@$1$G@-G=$,HtLvE*$K8~>e$9kh$&$J8e@BeKBP7FM-K>$J7k9g6/EY%Y%/%H%k$b$"$l$P!
>/$NJQ99$r;\$7Fb@-G=$,$[Hs$I>e>:$7$J$$$h$&$JbNb"$k!%$H3m$,!$$=li$N7k9g6
%Y%/%H%k<+BN$O$$$:lbF1DxEY$N@-G=$r<(9?$a!$$3li$NE@$N$_$r8+$F$$$k GA-Only $N=8C
K*$$$F$O!$<+A3EqBA$N5!9=$OM-K>JbNrA*$S=P$9$3$H$,=PMh$J$$!%0lJ}!$@836$N3X=,K
$F7k9g6/EY$,JQ99$5$lkh$&$J%@!<%&%#%s7?$N=8CD$N>l9gKO!$@8F@E*$KM?$($il?7k9g6/E
%/%H%k$N<~JU$r6I=jE*$KC5:w$9k3HGM-K>JbNrA*JL9k3H$,$G$-$k!%$=$N$?$a!$0dE
$J5!9=<+BN$OF1$8$G$b?J2=$NB.EY$K:9$,=PkNG"$k!%



?^ 5.5: [4D6- 1] %(!<%8%'%s%H$N3X=,6J@~



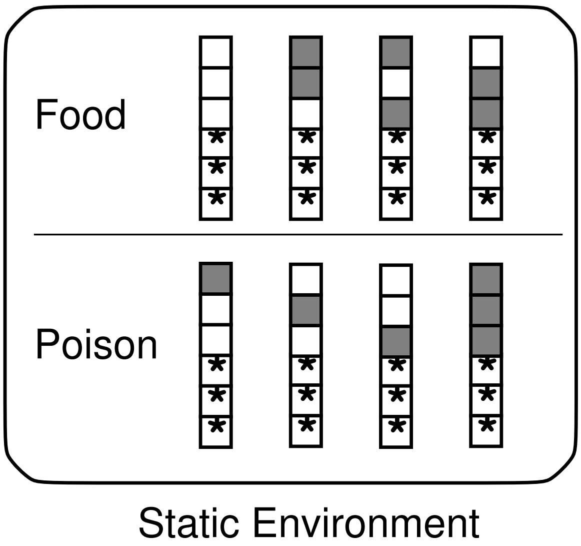
?^ 5.6: [4D6- 1] J?6QE,1~EY (01@8 = 100 3X=,%9%F%C%W)



?^ 5.7: [4D6- 1] %K%e!<%i%k%M%C%H$N@8F@E*$J=PNO8m:9 (01@8 = 100 3X=,%9%F%C%W)

5.2.2 <B83 **2:** Hs@~7A@-$r;}$DFq$7$$4D6-K*1k?J2=

@h$N<B83 1 GO!$%@!<%&%#%s7?$N?J2=$N2aDxK*$$$F!$<+A3EqBA$K2C$($F8DBN$N3X=,$,?J2=
BP7FBg$-$J1F6ANO$r;}$D$H$$$&%\!<%k%I%&%#%s8z2L$,$OC-jH3NG'G-$?!%$7$+$7$3$3
!V>o$K!$8DBN$N3X=,$,?J2=$rB%?J$9kh$&$K1F6A9kNG$"$m$&$+!)!W$H$$$&5?Ld$,@8$8$k!



?^ 5.8: 4D6- 2

$3$3GO!$?^ 5.8 $K<($9h&$J%S%C%H%Q%?!<%s$r;}$D?)NH$HFGJ*$,B8:_$9$k!V4D6- 2!W$r9M
$k!%4D6- 2 GO!$?)NHG"k+FGJ*G"k+$N5,B'$O>e$+$i;0DN%S%C%H$N4X78KhCF7h$
1F$*$j!$@h$N4D6- 1 NH$-$Nh&$K01$D$N%S%C%H$@1KhC$F<1JL$G$-$kh&$JC1=c$J4D6
OJ$$!%;(2;%S%C%H$NItJ,$r=|1P!$?)NH$HFGJ*$r<1JL$9kN$O 3 %S%C%H$N%Q%j%F%#LdBj$r2
3HG"$k!%01HL$K!$$3Nh$&$J n %S%C%H!&%Q%j%F%#LdBj$O@~7AJ,N%IT2DG=%i%k
%M%C%H%o!<%/KHCF2r$/$3H,:FqJNcH7FCNi1F$$$k [0B@> 89]!%?^ 5.9 $K4D6- 2 K
1k%(!<%8%'%s%H$N3X=,FC@-6J@~ (100 %(!<%8%'%s%H$NJ?6Q) $r<($9!%2#<4$O3X=,$N7P2aG"$
=D<4$O%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$r<($7$F$$$k!%<B@~$G<($7$?$bN,!$K\<B83$GMQ$
$$$k6/2=3X=,7?$N%(!<%8%'%s%H%"!<%-%F%/%A%c$NFC@-6J@~$G$"$j!$Hf3SBP>]$N$?$aE@@~$G<($
bN$,DL>o$N BP K!KhkbNN3X=,FC@-6J@~G"$k!%?^ 5.5 $N3X=,6J@~$HHf3S9k$H!$4D6-
K*$$$FM?$($il?LdBj$O4D6- 1 NbN[$I4JC1$GOJ$$$3H,3NG'G-$k!%$J$*<B@$3&K
$kLdBj$K$O!$$3$&$7$?Hs@~7A@-$rH<C?bN$,B?$$!%

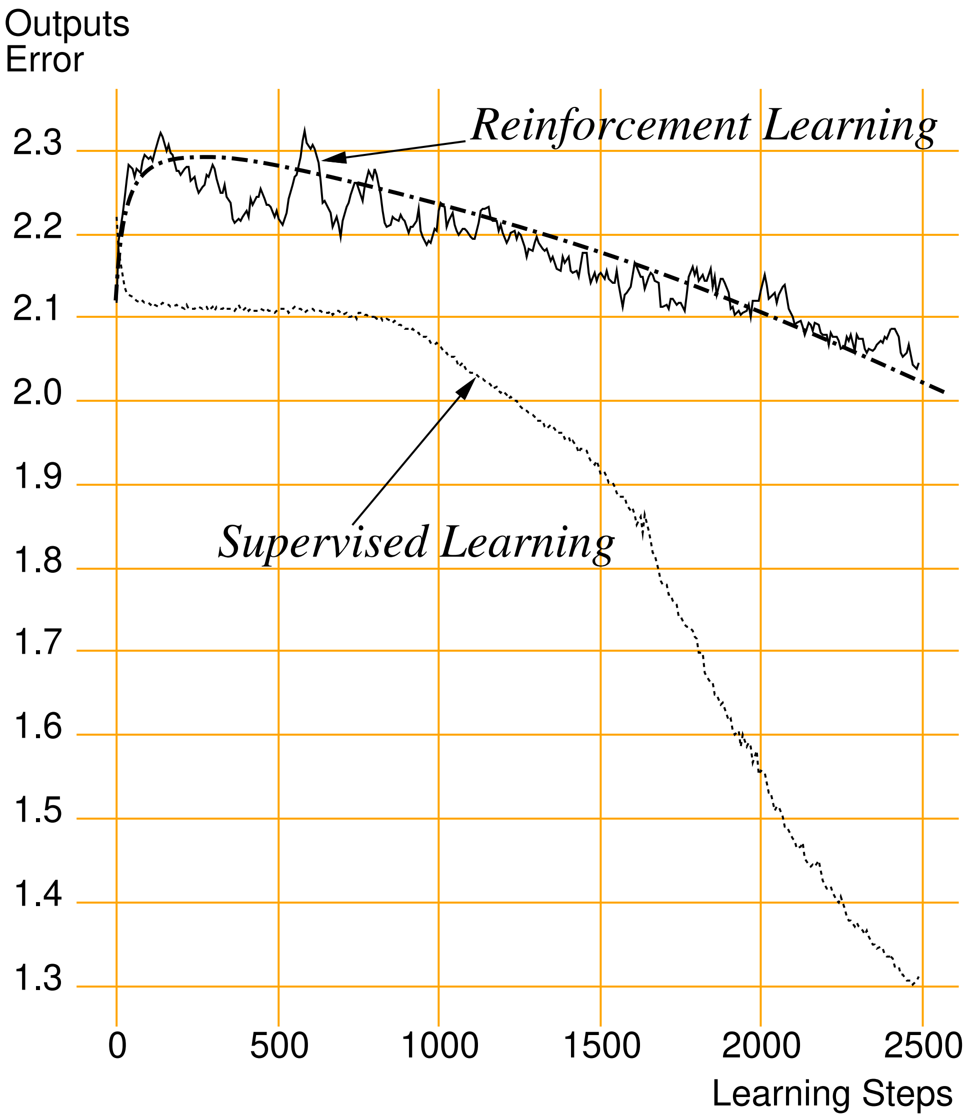
4D6- 2 K*$$$F!$3F8DBN$N0l@8$r 200 %9%F%C%W$H7?H-$N 6000 @$Be$^$G$NJ?6QE,1~EY$N?

[2] 4D6- 2 $N5,B'$K4p$E$$$F?)NH$HFGJ*$r$=$l$>$l$BP1~$9$k 6 <!856u4V>e$NE@$KG[CV$7$?$H$-$K!$E@=89g$r?)NH$H
J*$KFsJ,$9kh$&$J (5 <!85) D6J?LL$OB8:_$7$J$$!%7?$,$C$F!$4D6- 2 $N5,B'$O@~7AJ,N%IT2DG=$JLdBj$G$"$k!%

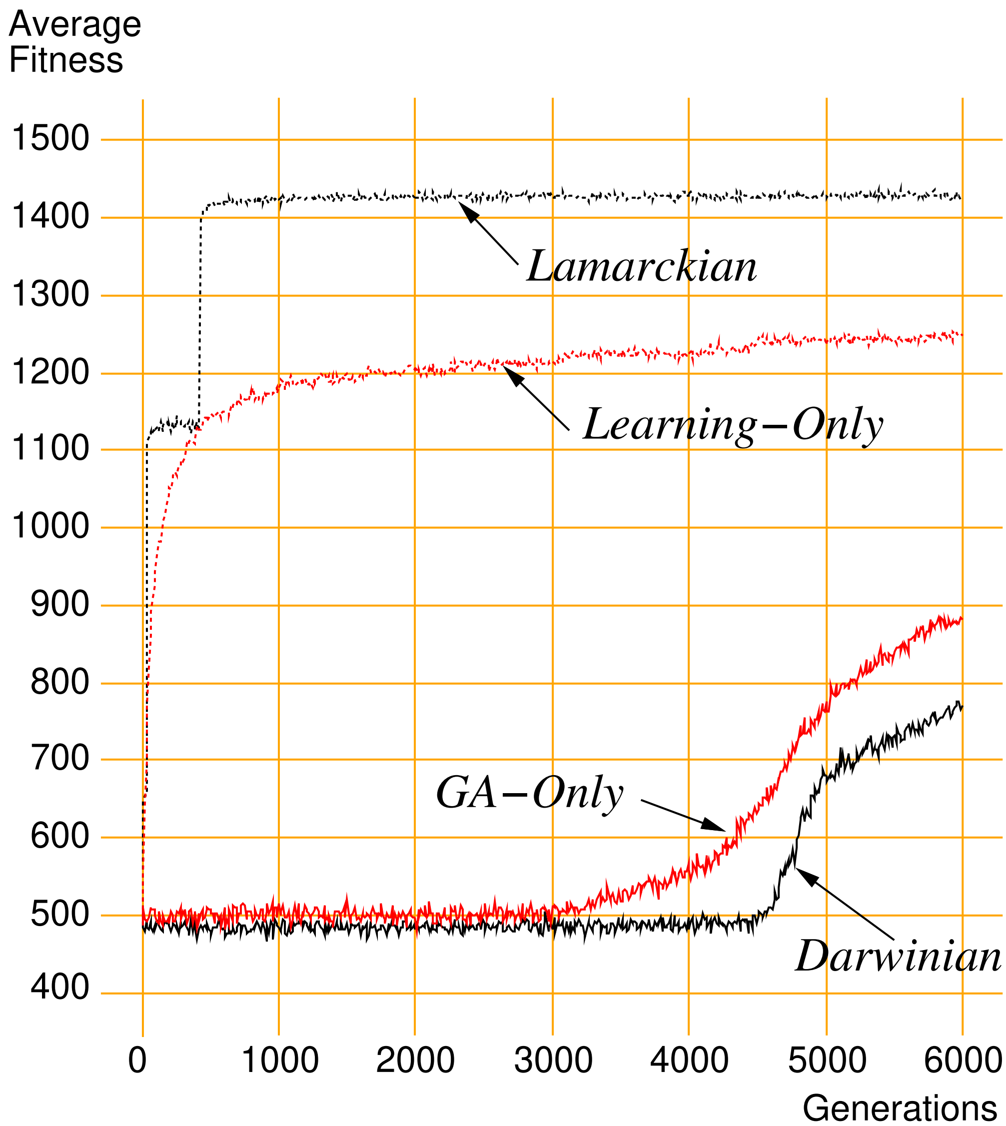
0\$NE57?E*JNcr?^ 5.10 $K<($9!%J*!$3X=,%9%F%C%W$, 200 G"k3Hh$j!$%(!<%8%'%s%H$
<h$jF@$kE,1~EY$N:GBgCM$O 1500 G"$k!%?^ 5.10 hj!$$dOj%i%^%k%/7?$*$h$S Learning-Only
$N=8CD$,M%=(G"$j!$$7$+$bFC$K%i%^%k%/7?$NM%0L@-$,L\N)$D!%$3$3$G9M$($F$$$kHs@~7A@-$
s@4D6-GO!$6I=j2r$,B??tB8:_9k!%0dEAE*A`:n$,A4$/9Tol$J$$ Learning-Only $N%(!<%8%
%s%HNCfK$O!$$3Nh$&$J6I=j2r$KN1$^C?$^$^$=$3$+$iH4$1=P$;$J$$$bNbB?$$!%0lJ}!$%
%k%/7?$, Learning-Only KHfY$FM-Mx$JE@$N0lDO!$@-G=8~>e$,$"$kDxEY0J>eK>a=$&KJ$
8DBN$,A*Br05$KhC$FEqBA$5lk$?$aG"kH9M$($ilk!%$^$?!$%i%^%k%/7?$N=8CD$rM-Mx$
8~$KF3$/b&0lDNE@$O!$FMA3JQ0[$d8r:9$H$$$C$?LdBj6u4V$rBg0hE*$KC5:w2DG=$H9k0dE
A`:n$N8z2L$,5s2ilk!%3lKhCF!$2>$K6I=j2rKHiolF7^C?>l9gGb$=$3$+$
$1=P$92DG=@-$,=P$F$/$k!%$"$k$$$O!$2.2.4 @a$G=RY? GA $N0EL[E*$JJBNs=hM}$N8z2L$b1F6A$
$F$$$k3H$b9M$(il$k!%%i%^%k%/7?$N%(!<%8%'%s%H$N=8CD$G$O!$JBNs$KC5:w$5l?J#?t$NM
$J%S%k%G%#%s%0%V%m%C%/$r8r:5KhCF9bB.$K=8@Q$7$F$$$/NKBP7F!$0dEAE*A`:n$r<u1
Learning-Only $N%(!<%8%'%s%H$OM-8z$J%9%-!<%^$rA4$F<+J,0l?M$G8+D1J/FOJi$J$$!%$
Am$s!$?^ 5.6 $N<B83$K$*$$$F$b!$%i%^%k%/7?$N=8CD$O3&7? GA Kh$k8z2L$N287C$r<u$1
NG$"$k$,!$4D6- 1 $OLdBj$,4JC1$9$.kN$G!$$=$N8z2L$,$"$^$j8=$l$J$$$NG"m&!%
5F!$?^ 5.10 $H?^ 5.6 rHfYkH99$K=EMW$JAj0c$,$"k3HK5IU/!%?^ 5.6 K*$$$F$O
%\!<%k%I%&%#%s8z2LKhCF%@!<%&%#%s7?$N%(!<%8%'%s%H=8CD$N?J2=$,B.$ail$k8=>]$,4Q;
l?$,!$4D6- 2 $N7k2L$N?^ 5.10 $r8+$k$H!$5U$K3X=,$r9T$&%@!<%&%#%s7?$N=8CD$O!$3X=,$r9T$c
$$ GA-Only $N=8CD$hjb?J2=$,CY$$$3H,3NG'5l$k!%<!$K?^ 5.11 $K!$3F@BeK$*$1$k8DBN$
%K%e!<%i%k%M%C%H%o!<%/$N@8F@E*$J=PNO8m:9$N=8CDJ?6Q$r<($9!%$3$N?^$+ib!$%@!<%&%#%s7
=8CD$N?J2=$, GA-Only $N=8CD$KCYlr<hCF$$$k3H$,L@$i$+$K3NG'G-$k!%$J$*!$$3Nh$
$J GA-Only $H%@!<%&%#%s7?$N?J2=$N6J@~$N5UE>$,>o$K5/3ko1GO$J$$!%7+$7!$$3$N5U
8=>]O+Jj$NIQEY$G5/3j!$:#2s9T$C$? 6 2s$N;n9TN&$A 3 2s$O!$%@!<%&%#%s7?$, GA-Onl
hjbNtk$H$$$&7k2L$rF@$?!%$^$?!$$?H(5UE>8=>]$,@8$8$J$$>l9gG"CF$b!$?^ 5.12 $K
9h$&$K=8CD$,E,1~EY$r3MF@9k$^$GKI,MWJ@$Be?t$,B?$$(?^ 5.6HrHf3S;2>HN3$H)!%$^
?^ 5.13 $K<($9h&$J6KC<$JNcH7$F 6000 @$Be$r7P$?8eG5$($b%@!<%&%#%s7?$,A4$/E,1~@-$
<(5J$+$C$?Nc$b$"$C$?!%$3liN3HO!$3X=,$N8z2L$,?J2=$rB%?J9k$H$$$&%\!<%k%I%&%
8z2L$KH?$7$?8=>]$G$"$k!%
3Nh&$J5UE>$,@8$8$kM}M3$O!$4D6- 2 K*1kLdBj$,Fq$7$$$?aK!$>/$J$$3X=,%9%F%C%W
GO?J2=$K1F6A$rM?$(F@$k$[$I$NM-8z$J3X=,$,$J5l$J$$$?aG$"$k$H9M$(il$k!%$h$j>\:
2r@O9k$H0J2<$NDLjG$"$k!%?^ 5.9 $K<($7$?%(!<%8%'%s%H$N3X=,FC@-6J@~KO5/Iz$,B8:_$
$,!$$3lKBP7F3ji+$K6J@~Jd40$r;\$9 (?^ 5.9 GOGK@~$G<($9) $H!$3X=,%9%F%C%W?t$,$*$h
500 %9%F%C%W$NIU6a$r6KCMH7$F%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$,0l;~E*$K>e>:9kh

798~rHk3H,J,$+$k!%D^$j!$%(!<%8%'%s%H$,@5$7$/3X=,$r9T$&$?aK$O!$%K%e!<%i%k%
%H%o!<%/$N7k9g6/EY$rD4@0$7$F$$$/2aDxK*$$$F!$=PNO8m:9$N4QE@$+$i0lEY1s2sjr$;$MP
$J$$!%$3$3$G!$%(!<%8%'%s%H$N0l@8$, 200 3X=,%9%F%C%WG"kH9k$H!$1s2sjr;Oah$&$E
$k@5$K$=$N=i4|$NCJ3,$GE,@Z$J8z2L$,F@il$J$$$^$^3X=,$,BG$A@Z$ilF7^$&!%

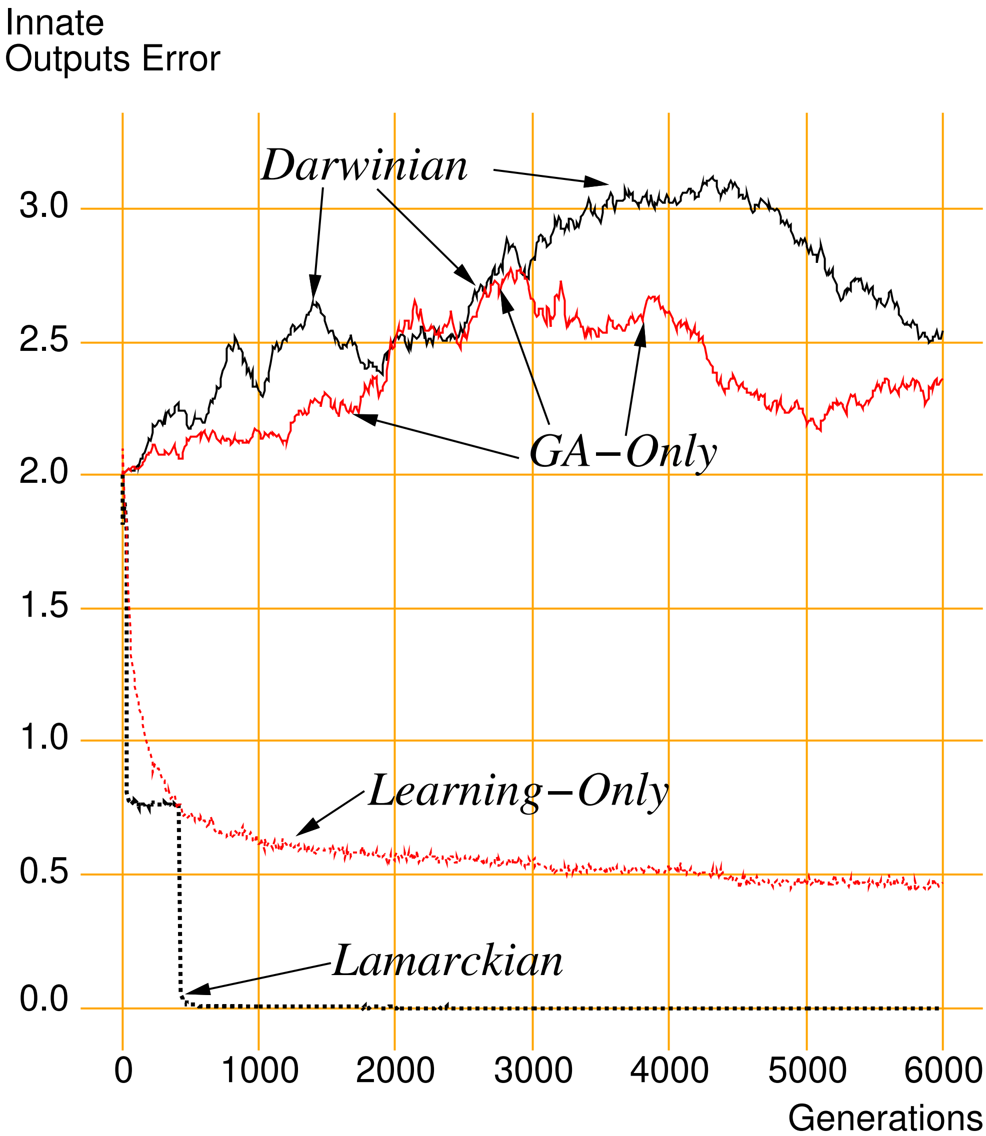
$=$3$G!$B>$N>r7o$OF1$8$G!$0l@8$r 400 3X=,%9%F%C%W$KA}$d7?H-KD$$$F<B83$r9T$C$
3X=,%9%F%C%W$, 400 G"k3Hh$j!$%(!<%8%'%s%H$N<h$jF@$kE,1~EY$N:GBgCM$O 2500 G"$E
?^ 5.14!$?^ 5.15 K=l>$l=8CD$NJ?6QE,1~EY$N?d0\$H3F@BeK$*$1$k%(!<%8%'%s%H$N%K%e!<%
%k%M%C%H%o!<%/$N=i4|=PNO8m:9$r<($9!%3X=,%9%F%C%W$r 400 H7$?$H$-$N7k2LG"$k?^ 5.14!$
5.15 r=l>$l3X=,%9%F%C%W$r 200 H7$?$H$-$N7k2LG"$k?^ 5.10!$?^ 5.11 HHfYF_kH!
==J,$J3X=,%9%F%C%W?t$,$"$kA0<T$N>l9g$K$O%\!<%k%I%&%#%s8z2L$,6/$/@8$8$F$$$k3H$,$O$
jH3NG'G-$k!%$J$*!$0l@8$r 400 3X=,%9%F%C%W$H7F9TC?:#2s$N 6 2s$N;n9T$NA4$F$N7k
$,!$?^ 5.14!$?^ 5.15 $HF1MM$J798~$r<($7!$%@!<%&%#%s7?$H GA-Only $N?J2=$N6J@~$K5UE>$,@8
8k3HOJ$+$C$?!%



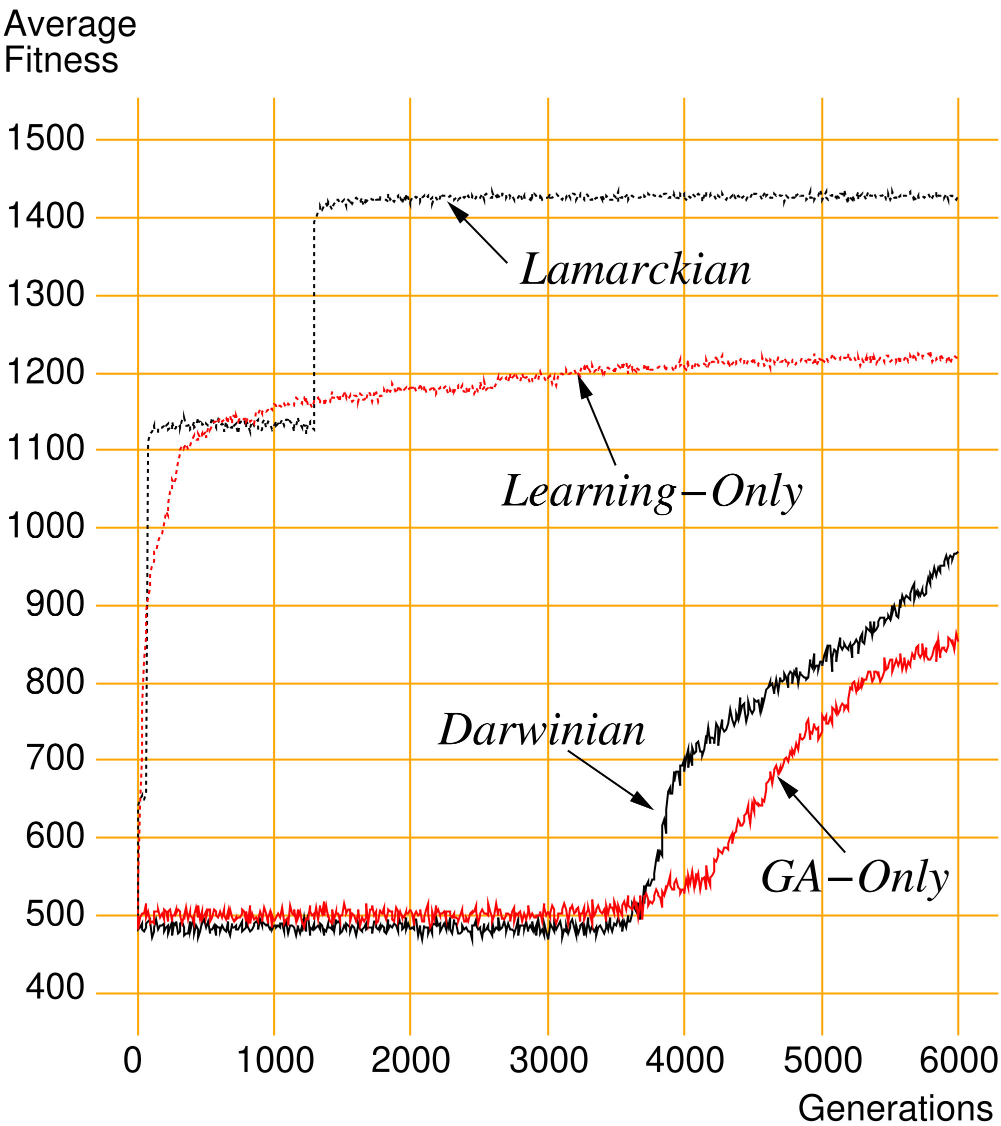
?^ 5.9: [4D6- 2] %(!<%8%'%s%H$N3X=,6J@~



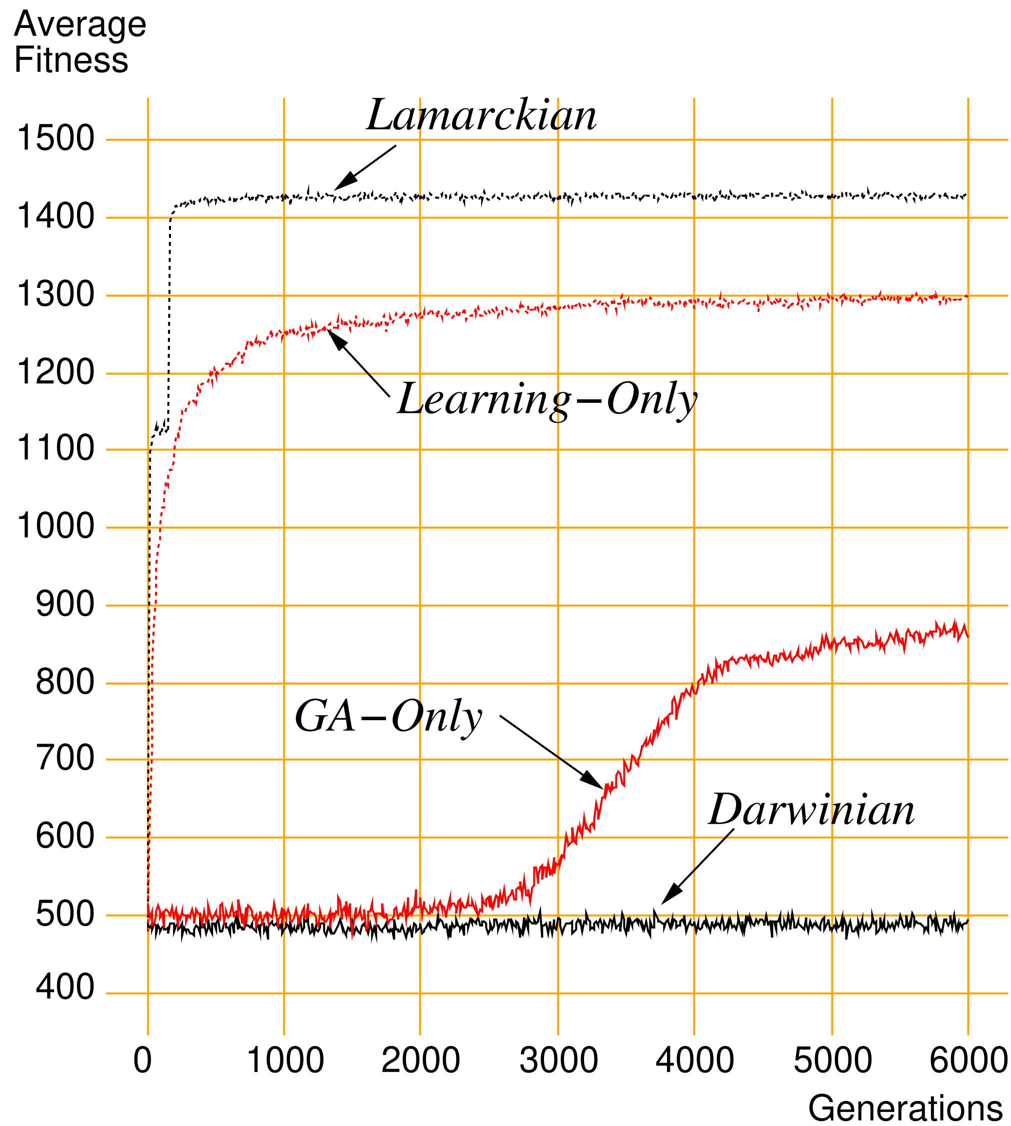
?^ 5.10: [4D6- 2] J?6QE,1~EY $=$N 1 (01@8 = 200 3X=,%9%F%C%W)



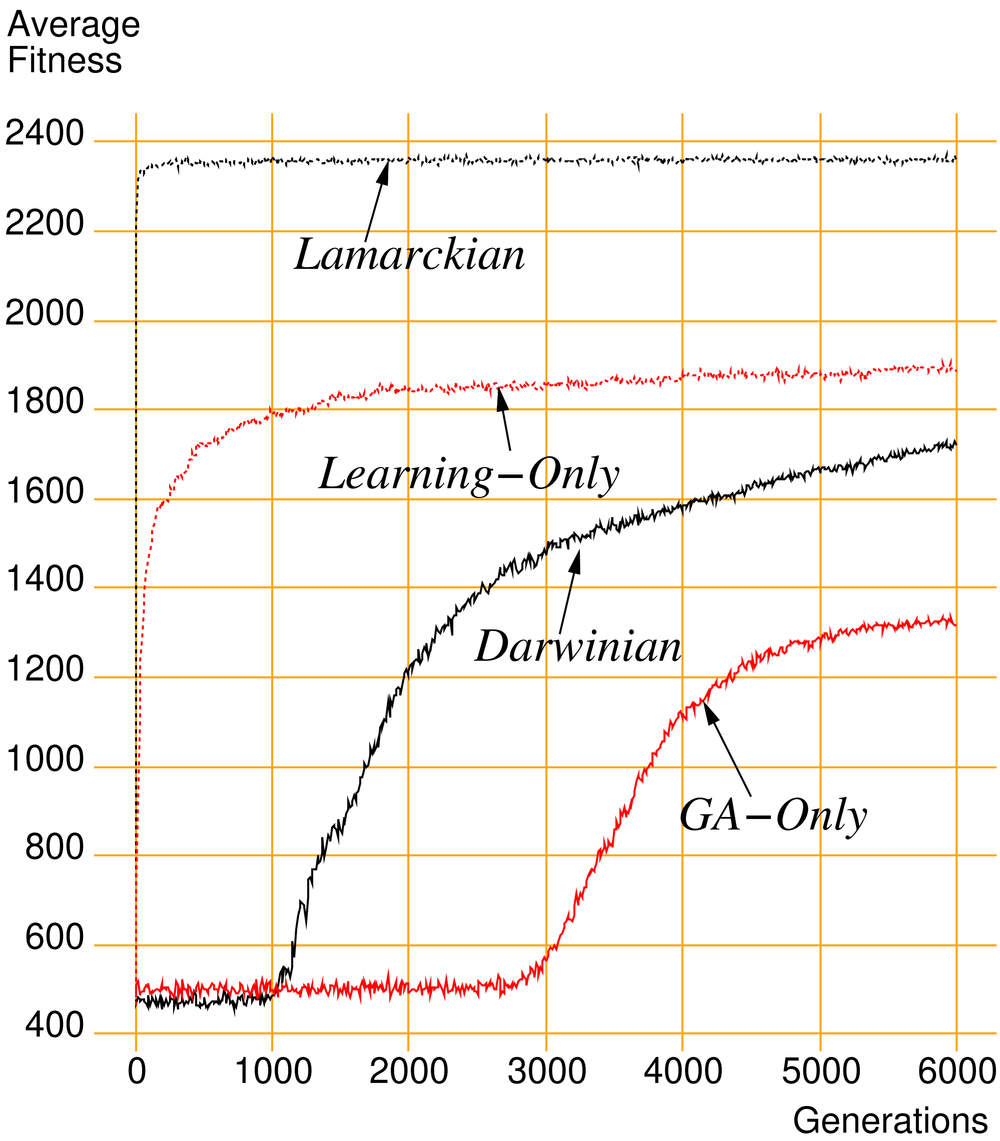
?^ 5.11: [4D6- 2] %K%e!<%i%k%M%C%H$N@8F@E*$J=PNO8m:9 (01@8 = 200 3X=,%9%F%C%W)



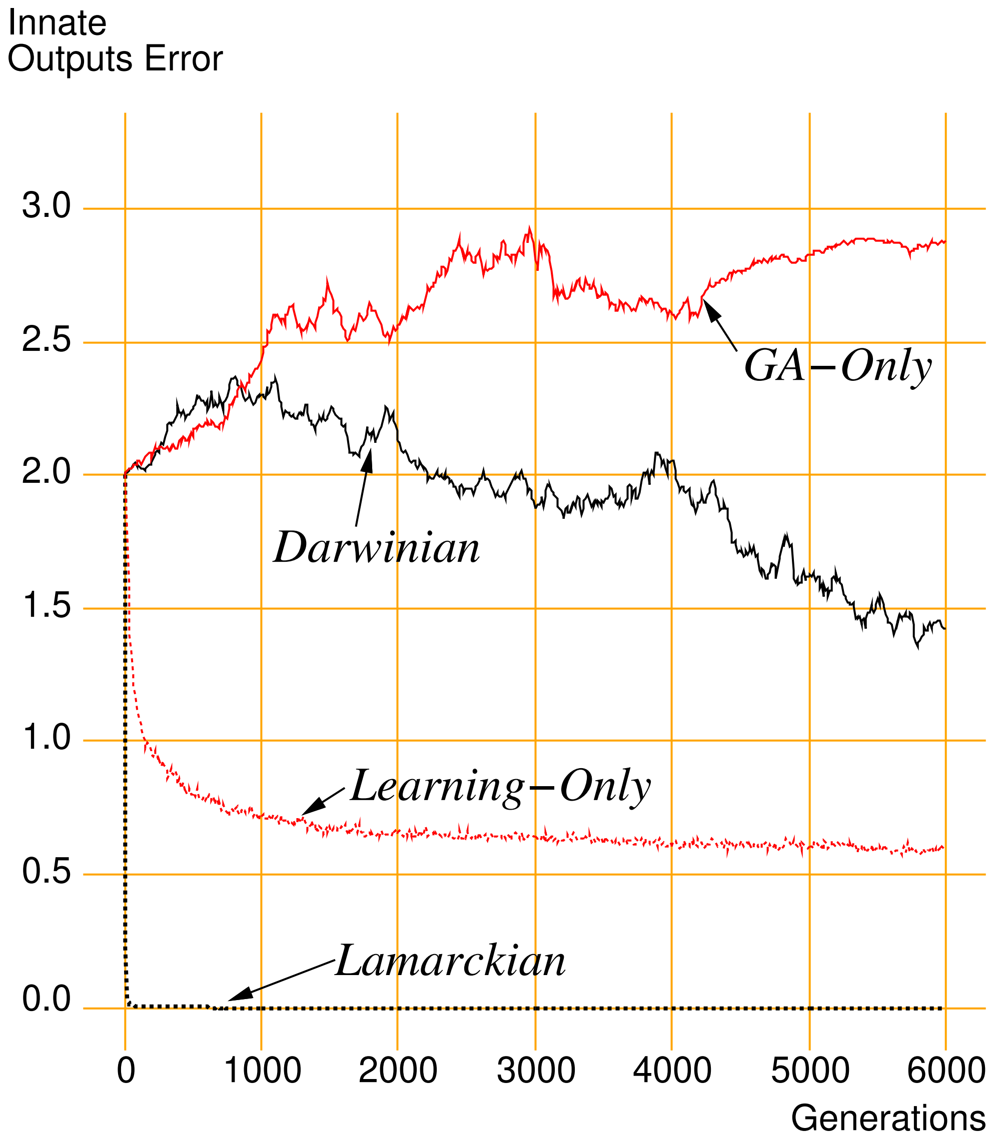
?^ 5.12: [4D6- 2] J?6QE,1~EY $=$N 2 (01@8 = 200 3X=,%9%F%C%W)



?^ 5.13: [4D6- 2] J?6QE,1~EY $=$N 3 (01@8 = 200 3X=,%9%F%C%W)



?^ 5.14: [4D6- 2] J?6QE,1~EY (01@8 = 400 3X=,%9%F%C%W)



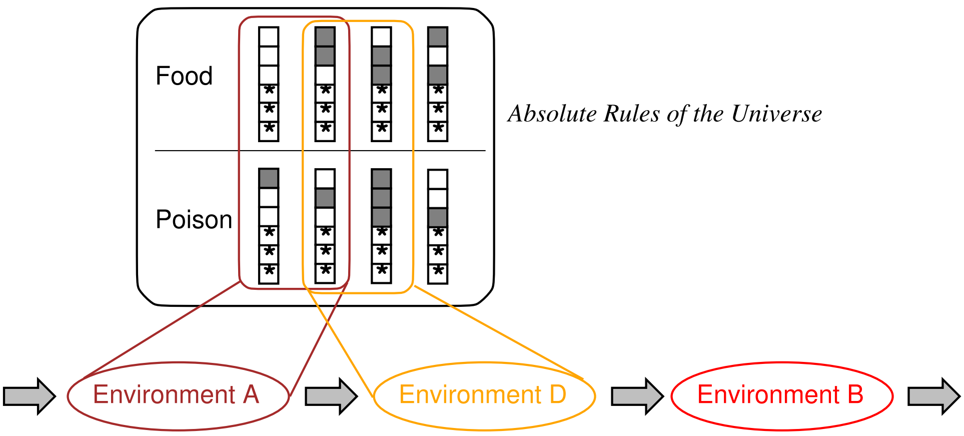
?^ 5.15: [4D6- 2] %K%e!<%i%k%M%C%H$N@8F@E*$J=PNO8m:9 (01@8 = 400 3X=,%9%F%C%W)

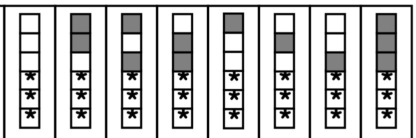
5.3 F0E*$J4D6-

5.2 @aKF9TC?<B83$N$$$:lN>19g$b!$%i%^%k%/7? ($*$h$S Learning-Only) $N%(!<%8%'%s%H =8CD$,%@!<%&%#%s7?$N=8CD$hjbE,1~B.EYNLLK$*$$$FM%lF$$$k$H$$$&7k2L$rF@$?!%7+ 3N3HhjD>AK%i%^%k%/7?Nh$&$K3X=,KhCF3MF@7?7k2L$rD>@\;RB9$KEA$($kh&$ EA5!9=$NJ}$,%@!<%&%#%s7?$N5!9=$hjbM%lF$$$k$H7kO@$E1kNOAa5^G"$k!%

5.2 @aGN<B83$O!$@EE*$J4D6-$rA[Dj7F$$$?!%0lJ}!$@8J*$,@3B)7F$$$k<+A33&$N4D6-$:#8e$N7W;;5!4D6-$Nh&$J3+J|7?J,;64D6-$G$O!$4D6-<+BN$,>o$KJQF0$7$F$$$k!%0J2<GO!$; $N0[$J$kF0E*FC@-$N%l%Y%k$r;}$D4D6-$rA[Dj$7$F!$$=3G$N%i%^%k%/7?$d%@!<%&%#%s7?$N0dE 9=$r;}$D=8CD$N?J2=E*$J2aDx$r4Q;!$7!$FC$K=8CD$N4h7r@-KD$$$FI>2A9k!%

5.3.1 <B83 3: >pJs$NItJ,@-$,$"$k4D6-K*1k?J2=





Environment A	○	○	×	×	○	○	×	×
Environment B	×	×	○	○	×	×	○	○
Environment C	○	×	○	×	○	×	○	×
Environment D	×	○	×	○	×	○	×	○
Environment E	○	×	×	○	×	○	○	×
Environment F	×	○	○	×	○	×	×	○

?^ 5.16: 4D6- 3

;~4VE*$"$k$$$O6u4VE*$J@)Ls$Khj!$%(!<%8%'%s%H$O@$3&$N>pJsA4FK%"%/%;%9=PMhkH$ iJ$$!%%(!<%8%'%s%H$,3MF@$9$k>pJs$K$O>o$KItJ,@-$dIT40A4@-$N2DG=@-$,4^$^lk3HK

$=$3$G!$$^$:$OF0E*FC@-$N%l%Y%k$H7F$O:G$bDc$$4D6-H7$F!$?^ 5.16 Nh$&$K%(!<%8%'%s
$N3MF@$G$-$k>pJs$,ItJ,E*$G$"$j!$IaJWE*$J5,B' — !V?)NHG"k+FGJ*G"k+!W — $r=,
9kNKI,MW$J40A4$J>pJsNAH,F1;~KOF@il$J$$$h$&$J>u67$r9M$($k!%$^$?!$3MF@G-$
Js$N<oN`$O;~Be$H6&$KJQ2=$9$k$b$N$H$9$k!%$D$^$j!$$"$k;~E@$GB8:_$7$J$+$C$?<oN`$NJ*<A$
G!8=l?$j>C$($?$j9k$H$$$&>u67$r9M$($F$$$k3H$KAjEv$9$k!%$3Nh$&$J4D6-$rF0E*$J$
$H8+$J$9$3HK$D$$$F$O5DO@$,J,$+$lk+b7lJ$$$,!$4D6-$KB8:_9kJ*<A$N<oN`$,JQ2=$
NG!$%(!<%8%'%s%H$KHCFOF0E*$J4D6-$H8@$($k[3] $N<+A33&$K$*$1$k@8J*$r8+Fb!$$=
$N;~E@$G%"%/%;%92DG=$J8B$il?>pJs$@$1$rMQ$$$F!$<sHxNI$/4D6-$KE,1~$7$F$$$k!%

?^ 5.16 $K<($9h&$K!$4D6-Cf$KB8:_$9$kJ*<A$N<oN`$,;~Be$HHb$KJQ2=$9kh$&$J!V4D6-
$r9M$($k!%$=l>lN;~BeK*$$$F4D6-CfKO 4 <oN`$NJ*<A$N$_$,B8:_$7!$$=N&ANFsD
NH$G;D$jNFsD$,FGJ*$G$"$kH9$k!%

?^ 5.17!$?^ 5.18 N=l>lO 20 @$BeKh$H 100 @$BeKh$K4D6-$KB8:_9kJ*<ANAHrJQ2=5;
$?$H$-$N!$6000 @$Be$^$G$NE,1~EY$N=8CDJ?6Q$N?d0\$r<(7F$$$k!%J*!$$3li$N?^$O3F%(
%8%'%s%H$N0l@8$r 200 3X=,%9%F%C%WH7$?$H$-$NbNG"$j!$$3$N>l9g%(!<%8%'%s%H$N<h$jF(
E,1~EY$N:GBgCM$O 1500 G"$k!%$J$* Learning-Only $N=8CD$NE,1~EY$O!$C1=c$K?6F0$rBg$-$/7+
jJV9$@$1GFCK6=L#?<$$5sF0$r<($5J+C?$?$a!$?^$N2DFI@-$r>e$2k?aK$b0J9_$N?^$
$O Learning-Only $N=8CD$N7k2L$r>J$-!$$^$?9M;!$NBP>]$+$i$b30$9!%?^ 5.17!$?^ 5.18 hj!$%i
%^%k%/7?$N=8CD$G$O!$4D6-$r9=@.$9$kJ*<A$N<oN`$,JQ2=$9kEYKE,1~EY$,Bg$-$/?6F0$7$F$$$
H,3NG'5l$k!%?^ 5.17 K*$$$F%i%^%k%/7?$N7k2L$,9-$$I}$r;}$C$FJ,I[$7$F$$$k$+$Nh&$
$($k$,!$$3lOE,1~EY$,:Y$+$/?6F0$7$F$$$k$?$aG"$k!%7k2L$N0lItJ,$r<h$j=P7F3HBgI=<
F_kH?6F0$NMM;R$r3NG'9k3H$,$G$-$k!%0lJ}!$%@!<%&%#%s7?$N=8CDGbE,1~EY$N?6F0
$,8+$ilk$,!$%i%^%k%/7?$N=8CD$N>l9gKHfY$F?6F0$NI}$,>.$5$$/0BDj7F$$$k!%9JoA4
$NJQF0$KBP9k4h7r@-NLLK$*$$$F%@!<%&%#%s7?$NJ}$,%i%^%k%/7?$N=8CD$hjbM%lF$$$k!
$+$b!$%@!<%&%#%s7?=8CD$GCmL\$KCM9kNO!$4D6-$,JQ2=9kEY$K?6$j=P7KLako1GO
E,1~EY$,?6F0$7DD$b@$Be$r=E$MkK7?$,$C$FA4BN$H7F>e>:7F$$$kE@G"$k!%GA-Only
%@!<%&%#%s7?=8CDKCYlO9kbNN!$CfHW$+$i=*HW$K$+$1$FE,1~EY$r>e>:5;DD$"$k!%$
$j!$%@!<%&%#%s7?$"$k$$$O GA-Only $N=8CD$O!$3F;~Be$G$OItJ,E*$J>pJs7+MxMQG-$J$$$K$
4Xoi$:!$@BerDL8F=y!9$KA4BN$N5,B'$r3MF@$7$F$$$k$+$Nh&$J5sF0$r<($9!%

%i%^%k%/7?$N=8CD$,!$%@!<%&%#%s7?$d GA-Only $N=8CD$Nh&K&$^$/A4BN$N5,B'$r3MF@9
3H$,=PMh$J$$$3HK$D$$$F9M;!9k!%?^ 5.16 K*$$$F!$Environment A GO!$$$$:lNJ*<A
$b>e$+$i;0HVL\$N%S%C%H$O “0” G"$k!%7?$,CF!$Environment A $N2<$G$O!$0lHVL\$N%S%C

[3] bAms!$IaJWE*$J5,B'<+BN$,JQ2=$7$J$$$3Hh$j!$4.1.2 @a$G=R$Y$?$h$&$J0UL#GO!$$3$3$G9M$($F$$$kbN
40A4$KF0E*$J4D6-HO8@$($J$$!%

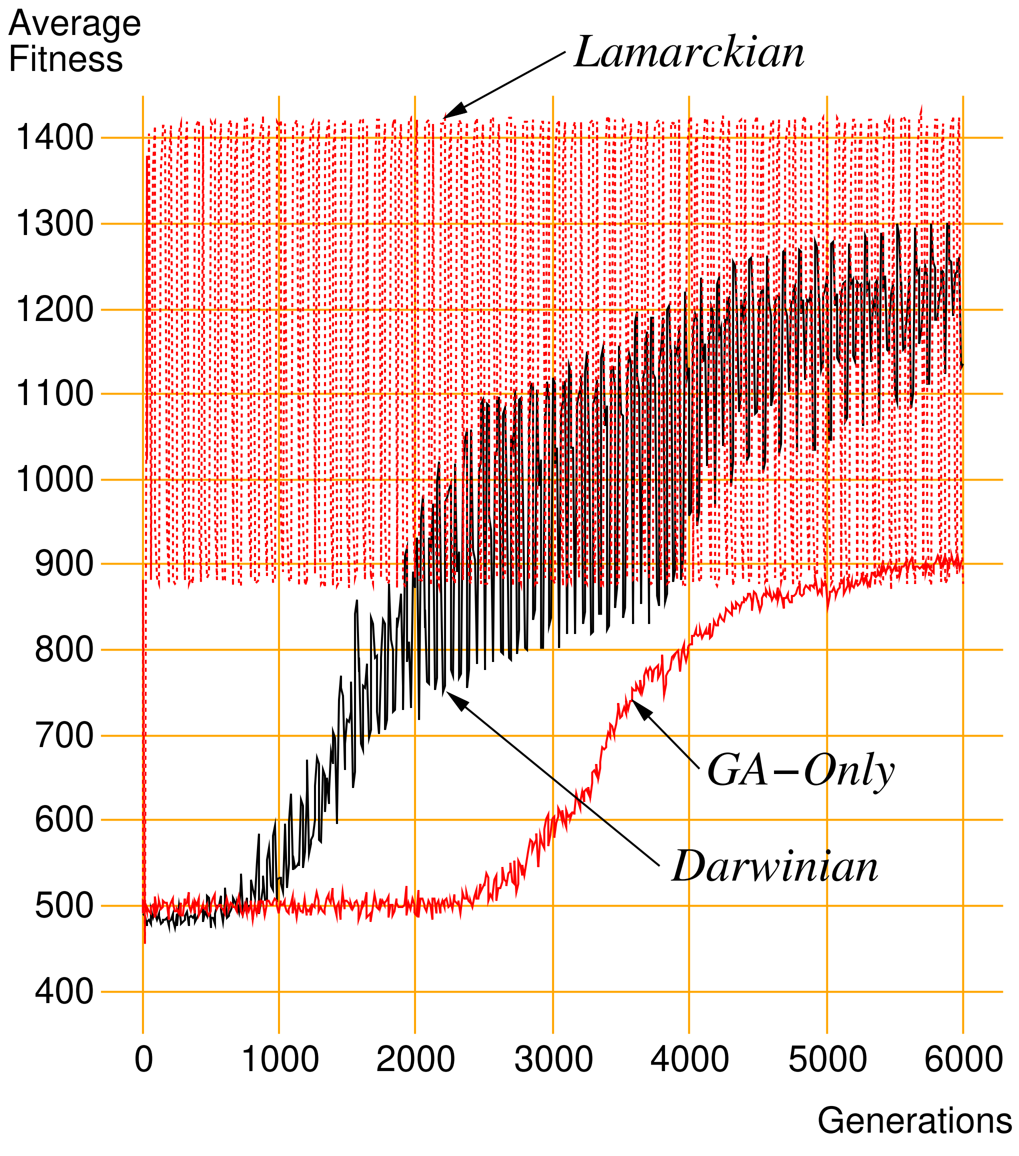
%H$HFsHVL\$N%S%C%H$N4X78$N$_$G?)NHG"k+FGJ*G"k+$,<1JL=PMh!$;0HVL\$N%S%C%H$rL
9k3H$,=PMh$k!%D^$j!$Environment A $N2<$G$O!$2 %S%C%H$N%Q%j%F%#LdBj!$$D$^$j XOR
LdBj$r2r7h$9$kCN<1$,3MF@=PMh1P==J,JNG"$k!%%(!<%8%'%s%H$O!$N><T$r<1JL9k$?$a$
B'$K;0HVL\$N%S%C%H$b4XM?$7$F$$$k3HrCNjF@$J$$$N$G!$2 %S%C%H$N%Q%j%F%#LdBj$r2r7h$
$?$a$NFC0[E*$J5,B'$r3X=,$7F7$^$&!%$3$3GNc($P!$$"$k;~Be$r6-$K4D6-$, Environment A
$+$i Environment B XH>uBV$,JQ$oC?H9$k!%$9kH!$Environment A $G4{$K3MF@:Q$_$N 2
%S%C%H$N%Q%j%F%#LdBj$K4X9kCN<1$OLrN)$?$J$$$I3m$+ Environment B GOA4$/@5H?BP$N0U
L#$r;}$D3HKJCF7^$&!%%i%^%k%/7?$N=8CDGO!$01@8$N4V$K3X=,$7$?7k2L$rD>@\?F$+$
XH0dEA5;F7$^$&$?$a!G0U$N5,B'$KBP7F?<$/E,1~$7$9$.F7$^$&!%$=$7$F!$01EY$=$
$&$J?<$$E,1~r7F7$^$&$H!$$=$N>uBV$+$iH4$1=P$9$3HOFMA3JQ0[JI$N0dEAE*A`:n$r0J$
$bHs>o$K:FqHJk!%FC$K!$$3$3$G$N<B83$Nh&$KFC0[E*$J5,B'KBP9$k?<$$E,1~$O?<9o$J>
$r>7$/!%01J}!$%@!<%&%#%s7?=8CD$G$O!$3X=,KhCFFC0[E*$J5,B'$K$b<h$j9g$($:E,1~7D$
D94|E*KO0dEAKhCFIaJWE*$J5,B'$r$b3MF@$7$F$$$/3H$,=PMh$k!%$3$1$O!$8DBN$N01@8$
$&C;$$;~4V%9%1!<%kK*1k3X=,$H!$@BeH$$$&D9$$;~4V%9%1!<%kK*1k0dEAHrL@3N$K6
7F$$$k$?$a$K2DG=$J3HJNG"$k!%

<!$K!$%@!<%&%#%s7?$N=8CD$,!$<B:]$KItJ,E*$J>pJs$N$_$+$iA4BNE*$J5,B'$r3MF@$7$F$$$k$
I&$+$rD4Yk$?$a$K!$$5iK0J2<Nh$&$J<B83$r9T$C$?!%$^$:!$4D6-$NJQF0$r 20 @$BeKh$
$?$H$-$N<B83(?^ 5.17 $K<($7$?<B83)$K$*$$$F!$=i4|=8CD!$Bh 2000 @$BeL\!$Bh 4000 @$BeL\!$Bh
6000 @$BeL\$N=8CDr=1>$1<h$j=P7F$/$k!%$=$7$F!$<h$j=P$7F-$?$3$1$i$N=8CD$KBP7
85$NA4BN$N5,B'$r3X=,$5$;$F$_$k!%D^$j!$$3$1$i$N=8CD$r?^ 5.8 $K<($7$?!V4D6- 2!W$NCf$G
=,5;$?$H$-$N3X=,FC@-$rI>2A$9$k!%$3$1$i$N<B83$KhC$FF@$i1?3F@BeN3X=,FC@-6J@~
?^ 5.19 $K<($5$1$F$$$k!%?^K*1k3F%0%i%U$O!$3X=,$N7P2a$KHbJ&%K%e!<%i%k%M%C%H%c
%/$N=PNO8m:9$NJQ2=$NMM;R$r<(7F$$$k!%$^$:=i4|@BeK$*$$$F$O!$%i%^%k%/7?$H%@!<%&%#%
$N%(!<%8%'%s%H=8CD$N$$$:1b3X=,r&$^$/9T$($:$K!$F1$8$h$&$J3X=,FC@-$r<($9(?^ 5.19 (a)
2000 @$BeL\$KJk$H!$%i%^%k%/7?$N=8CD$O@8F@E*K"$kDxEYE,$7$?=PNOCM$r=P$9%K%e!<%i%k%
%H%o!<%/$r;}$C$F@8$^1k$,!$$=$N8e$K3X=,$r9T$CFb%M%C%H%o!<%/$N=PNO8m:9$O$"$^$jDc8
$J$$!%01J}!$%@!<%&%#%s7?$N=8CD$O!$%i%^%k%/7?$N=8CD$hjb=PNO8m:9NBg-$$%K%e!<%i%k%
%H%o!<%/$r;}$C$F@8$^1F$/$k$,!$$=$N8e$N3X=,KhCF=PNO8m:9$O8:>/$9$k(?^ 5.19 (b))!%
5.19 $N (a)!$(b) $N%@!<%&%#%s7?$N3X=,6J@~$rHf3S$7F_kH!$$$$:1b3X=,$r;O$a$?CJ3,$G$
%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$OF1DxEYNCMG$"$k$,!$$=$N8e$N3X=,Kh$kFC@-$OBg$-$
Jk!%D^j3N3HO!$@8$^1?P+jNH-$O8+$+1O$[$HsI$+$oiJ$$$Kb+$+$oi:[4]G"k,!$F0$Be$r7P$kKD1F!$01

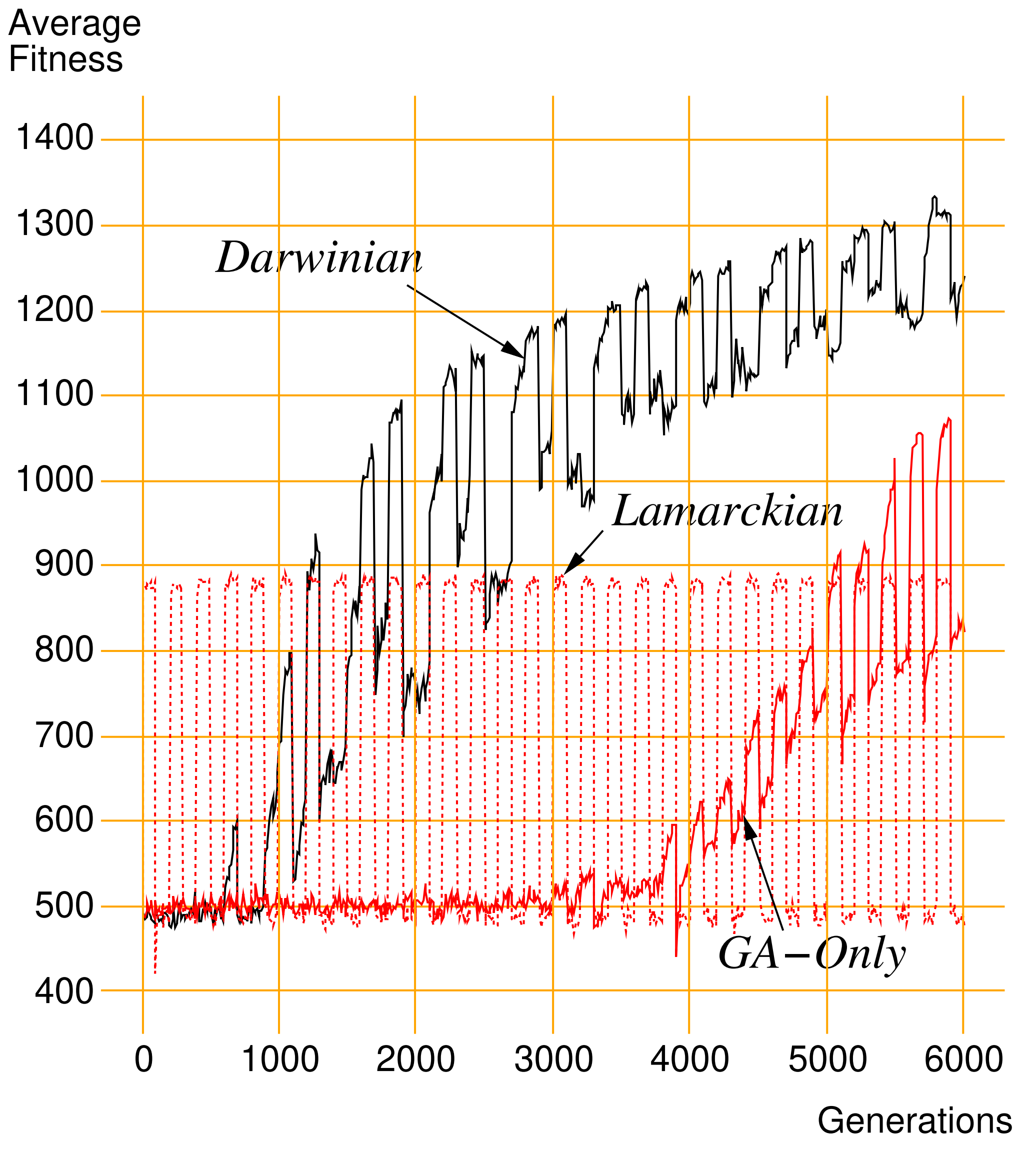
[4] bAms!$%M%C%H%o!<%/$N=i4|7k9g=E$_$O0[JC$?$bNHJk$,!$30$K8+$($k=PNO8m:9$,F1DxEY$H$$$&0UL#$G
3G$O!V8+$+1,F1$8!W$H$$$&8@MU$rMQ$$$F$$$k!%

@8$N4V$N3X=,KhCF=PNO8m:9$r>.$5$/$7d9$$$h$&$J%K%e!<%i%k%M%C%H%o!<%/$,3MF@$5l $/$3Hr0UL#7F$$$k!%$=$7$F!$4000 @$BeL\ (?^ 5.19 (c))!$6000 @$BeL\ (?^ 5.19 (d)) KJkH!$ %@!<%&%#%s7?$N0dEA5!9=$N2<GO!85NA4BN$N5,B'$KBP7F$b@5$7$/3X=,$r9T$&$3HNG-$ CD$,7A@.$5lF$$$k3H$,J,$+$k!%0lJ}!$%i%^%k%/7?$N0dEA5!9=$N2<GO!$3X=,%9%F%C%W$r@ Gb!$=PNO8m:9$,$"$kCMhj>.5/Ji$:$KE,@Z$K3X=,$r?Jak3H$,=PMh$J$$$h$&$J=8CD$ @.5l$F$$$k!%

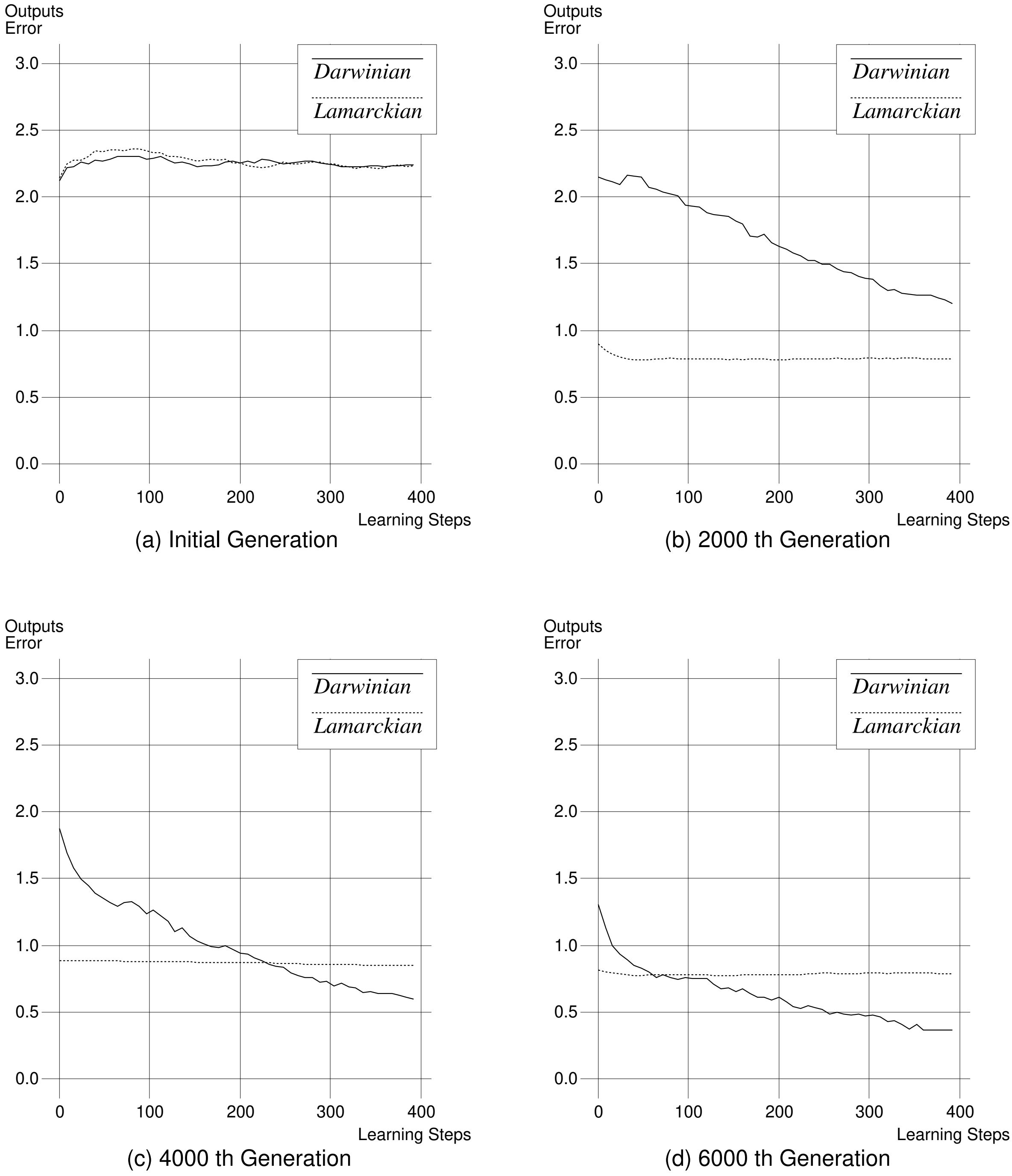
%@!<%&%#%s7?=8CD$N7k2L$K$*$$$F!$$5iK6=L#?<$$8=>]$,8+$ilk!%4D6- 2 K*1k<B83$ $$$F$N?^ 5.10!$?^ 5.12!$?^ 5.13!$$*hSK\@a$G=R$Y$F$$$k<B83KD$$$F$N?^ 5.18$N$$$:lb! 3F%(!<%8%'%s%H$N0l@8$r 200 %9%F%C%WH7$?>l9g$N7k2L$r<($7$F$$$k!%$^$?!$$$$:lN>l9g$ =*E*$KBh 6000 @$Be$KC#$9k^GK3F%Q%?!<%s$,%(!<%8%'%s%H=8CD$KDs<(5l$kDL;;2s?t$OEy $$!%3lirHf3S9k$H!$IaJWE*$J5,B'$N3X=,KI,MWJ>pJs$rA4$FF1;~$KM?$($?>l9g (?^ 5.1 ?^ 5.12!$?^ 5.13) hj$b!$>pJs$rItJ,$KJ,1F0lIt$:$D7+M?$($J$$>l9g (?^ 5.17!$?^ 5.18) $N J}$,!$%(!<%8%'%s%H=8CD$O$=$NIaJWE*$J5,B'$rAa$/3MF@$9kH$$$&3H$,3NG'$G$-$k!%D>4QE $O!$?M9)CNG=$N8&5f$K$*$1$k!V3,AXE*LdBj2r7h!W[Kno91] $N35G0$H?<$$4X78$,$"kh$&$K;W$($,!$87L)$J2r@O$r7?o1GO$J$$!%b7!$$3N3H,!$$3$3$G$N<B83$GMQ$$$?LdBj$@$1G hj0lHLE*$JLdBj$KBP7F$b@.$jN)DH9l$P!$Hs>o$K6=L#?<$$!%



?^ 5.17: [4D6- 3] J?6QE,1~EY (01@8 = 200 3X=,%9%F%C%W!$4D6-JQF0 = 20 @$BeKh)



?^ 5.18: [4D6- 3] J?6QE,1~EY (01@8 = 200 3X=,%9%F%C%W!$4D6-JQF0 = 100 @$BeKh)



?^ 5.19: [4D6- 3] @$Be7P2a$KHbJ&3X=,FC@-$NJQ2= (4D6-JQF0 = 20 @$BeKh)

5.3.2 <B83 4: 5,B′<+BN$,JQ2=$9$k4D6-$K$*$1$k?J2= (1)

Environment A	Food	Food	Poison	Poison
Environment B	Poison	Poison	Food	Food

Dynamic Change of the Rules of Universe

?^ 5.20: 4D6- 4

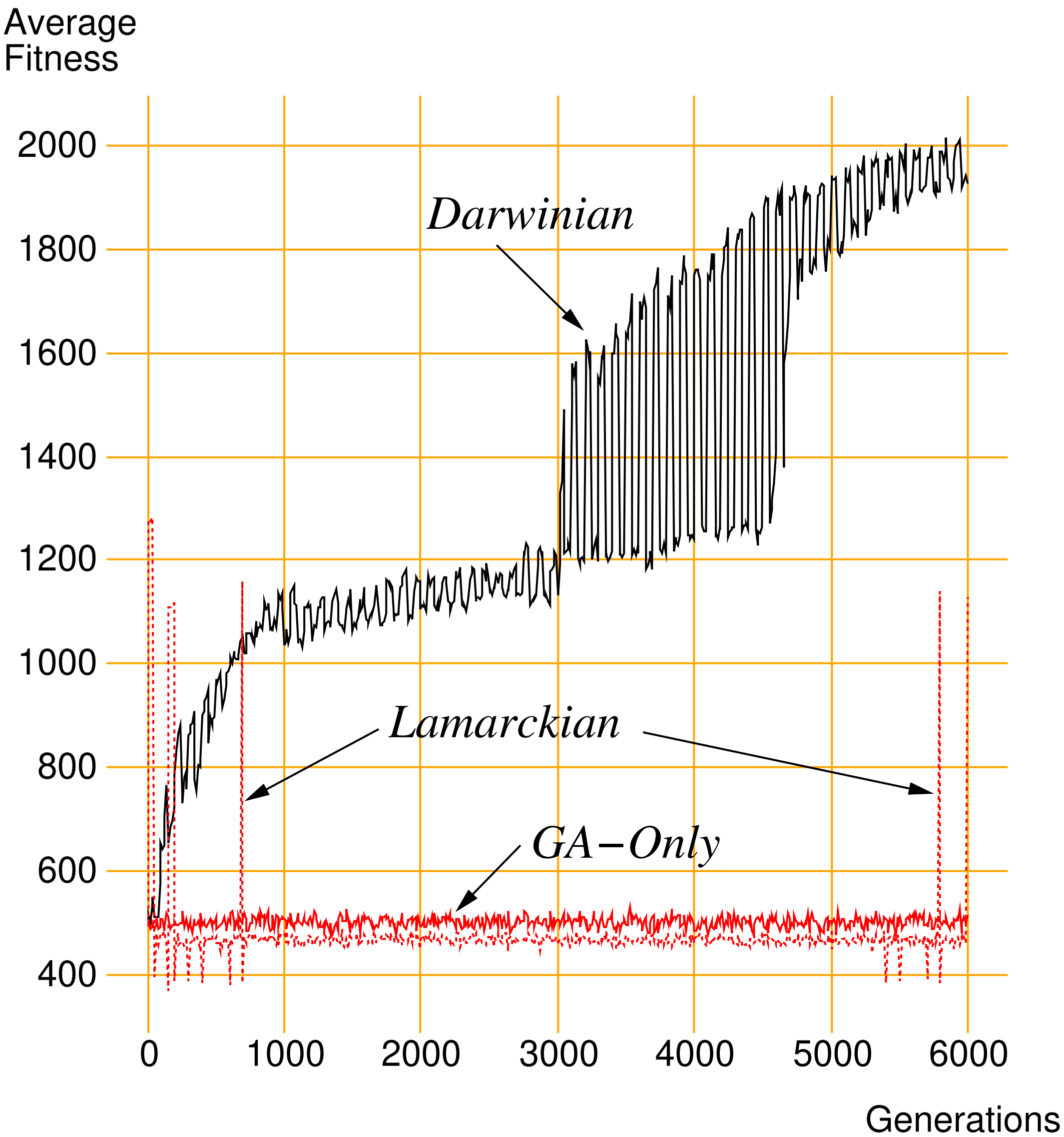
@h$N<B83 3 GO!$F0E*$J4D6-$N0l$DH7$F!$4D6-Fb$KB8:_9kJ*<ANAH_9go;$,JQ2=$9
h&$J>u67$r9M$($?!%7+$7!$$=3G$O?)NH$HFGJ*$r6hJL$9$k5,B′<+BN$OIaJWG"C?!%$=$3
$3$3GO!$$h$jF0E*$GFq$7$$4D6-H7$F!$?^ 5.20 $K<($9h&$K!$?)NH$HFGJ*$r<1JL9k5,B′
BN$,;~$HHb$KH?E>$9kh$&$J!V4D6- 4!W$r9M$($k!%$3Nh$&$K!$$"$k5,B′$,;~4VHHbKH
9kh&$J>u67$O!$7h$7$FFC<l$JbNGOJ/<B:]$K5/$3$jF@$kbNG"$k!%Nc$($P!$<+A33
$*$$$F@8$8$?8=>]H7FO!$%$%.%j%9$K@8B)$9$k%*%*%7%b%U%j%(%@%7%c%/ (*Biston betularia*) $H
$$$&2k$N9)6H9u2=$NNc$,M-L>$G$"$k [D9Ln 94]!%3N2k$OIaDL$O3%?′$N1):,$r;}CF$*$j!$<yL
44$K@8$8$kCO0aN‘$JIN>e$K;_$^kHJ]8n?′$G30E($K8+D+jK$/$/Jk!%H3m,!$19 @
KJCF%$%.%j%9CfFnIt$K$*$1$k9)6H2=$KhC$F@8$8$?@PC:$NGa$G<yLZ$NI=LL$,9u$/JQok
0JA0$+$i>/?t$$$k3H$,CN$ilF$$$?9u$$1):,$r;}$DJQ0[7A$NIQEY$,A}2C7?!%3%?′$N1):,$
$KL\N)$DNGJa?)5ld9$/$JCF7^$&$NG"$k!%$H3m$,6aG/!$%(%M%k%.!<$N;q8;$,@PC
$i@PL}Cf?4$K@ZjBXoC?3H$KH<$&4D6-$N>t2=$,?J$‘$KDl$F!$9u2=7?$NIQEY$,8:>/7F$
NG$"$k!%0J>eNNcO!$8DBN$N@8B8$KM-Mx$HJk5,B′$,8GDj$GOJ$/N.F0E*$G$"$k3H$r<($
$$$k!%

?^ 5.20 $K<($9h&$K4D6-$r 50 @$BeKh$K Environment A $H Environment B $N4V$GF~lBX(
k3Hr7+jJV7$?$H$-$N 6000 @Be^GN=8CD$NJ?6QE,1~EY$N?d0\$r4Q;!7?!%?)NH$HFGJ*
<1JL9k5,B′$O!$;(2;%S%C%H$NItJ,$r=|1P!$2 %S%C%H$N%Q%j%F%#LdBj (XOR LdBj) H7$FI=
lk$,!$$=$N5,B′$N0UL#$O;~$HHb$KH?E>$9$k!%?^ 5.21 $O!$8DBN$N0l@8$r 400 3X=,%9%F%C%W (
BgE,1~EY = 2500) H7$?$H$-$N7k2L$r<($7$F$$$k!%%i%^%k%/7?$d GA-Only $N=8CD$,$&$^$/4D6-
$KE,1~$G$-$J$$$H$$$&7k2L$O!$Hs>o$KD>4QE*$G$"$k!%7+$7!$%@!<%&%#%s7?$N=8CD$NE,1~EY$

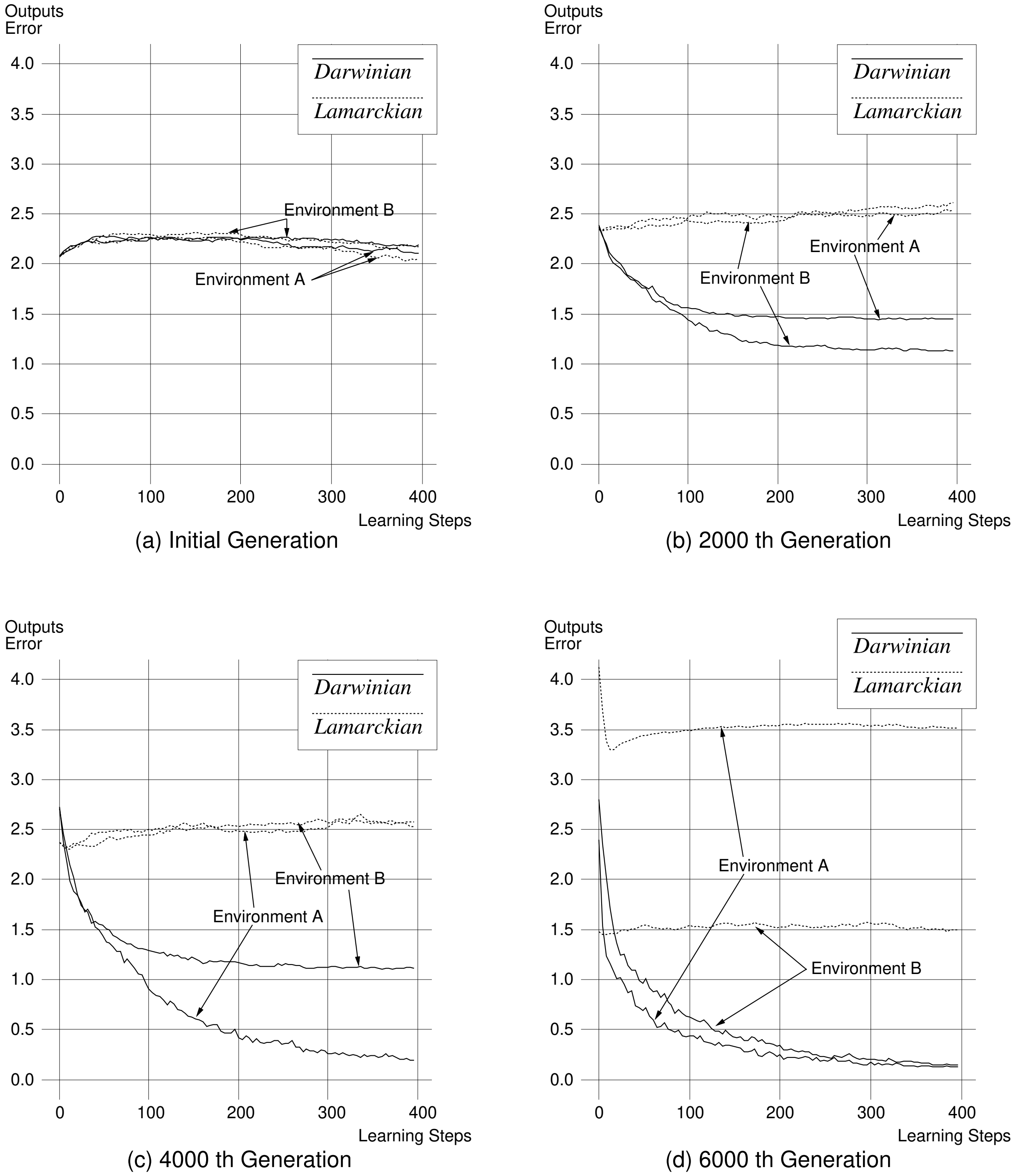
F0$7$J$,$i$b@$Be$r=E$MkKDl$F>e>:$7$F$$$kE@$O6K$a$FH?D>4QE*$G$"$k!%$H$$$&Nb!$5
@aK*1k<B83$N>l9g$H$O0[$J$j!$$3$3$G$OIaJWE*$J5,B'<+BN$,JQ2=$7$F$$$k$+$iG"$k!%

5F<!$K!$>e5-$N<B83$K$*$$$F!$=i4|=8CD!$Bh 2000 @$BeL\!$Bh 4000 @$BeL\!$Bh 6000 @$BeL\
$N=8CD$r$=$l$>$l<h$j=P$7$F!$$3li$N=8CD$KBP7F!$Environment A $H Environment B N=
l>lN5,B'$N2<$G3X=,$r9T$o$;$?H-$N3X=,FC@-$r4Q;!7?!%$=$N7k2L$r?^ 5.22 $K<($9!%
K*1k3F%0%i%U$O!$3X=,$N7P2a$KHbJ&%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$NJQ2=$NMM;
I=7F$$$k!%$^$:!$=i4|@$Be$N=8CD$K$D$$$F$O!$%@!<%&%#%s7?$H%i%^%i%/7?$$$:lN=8CD$b;
h&$K3X=,$r?Jak3H$,$G$-$:!$F1$8h&$J3X=,FC@-$r<($9(?^ 5.22 (a))!%$H3m$,!$Aa$/$
Bh 2000 @$BeL\$KJk$HN><T$NAj0c$OL@$i$+$KJCF/$k!%%@!<%&%#%s7?$N0dEA5!9=$N2<$G$
Environment A $H Environment B $N$$$:lN5,B'rb!$$"$kDxEY3X=,$9k3HN=PMh$k=8CD
$,7A@.$5lO8a$F$$$k (?^ 5.22 (b))!%5i$K!$@$Be?t$r=EMFBh 6000 @$Be (?^ 5.22 (d)) $K
;jkH!$%@!<%&%#%s7?$N0dEA5!9=$N2<$G$O!$$$$:lN5,B'rbE,@Z$K3X=,$9k3H,=PMhk
$J=8CD$,7A@.5l$F$$$k!%0lJ}!$Bh 6000 @$BeL\$N%i%^%k%/7?$N=8CD$G$O!$Environment A $H
Environment B N=l>lN5,B'$r3X=,$5$;$?H-$N3X=,FC@-$,Bg$-$/0[Jj!$F@0U$J5,B'$HI
F@0U$J5,B'$H$,L@3N$KJ,N%7F7^CF$$$k!%7+$b!$$=$NF@0U$JJ}$N5,B'$N3X=,FC@-G5
%@!<%&%#%s7?$N=8CD$N$$$:lN3X=,FC@-hjbNtC$F$$$k!%$^$?!FCK%@!<%&%#%s7?$N=8CD$
$9798~$H7F6=L#?<$$$N$O!$3F@BeNCB@8;~$N%K%e!<%i%k%M%C%H%o!<%/$N=i4|=PNO8m:9NBg
$,!$$?$@C1=c$K@Ber7PkKDl$F>.$5$/$JCF$$$/o1GO$J$$$H$$$&E@G"$k!%D>4QE*$
@Be,?J$`$4HK!$=8CD$O@8F@E*$KM%$l$?%K%e!<%i%k%M%C%H%o!<%/$r;}Dh$&$KJj!$$7$?$
$F=i4|=PNO8m:9$O>.5/JC$F$$$/h&$K4|BT$5lk!%7+$7!$%(!<%8%'%s%H$N=8CD$O!$@8F
$KM%$l$?%K%e!<%i%k%M%C%H%o!<%/$r5aak3Hhj$b!$$$$:lN5,B'rbE,@Z$K3X=,$9k3$
=PMh$k=@Fp$J%K%e!<%i%k%M%C%H%o!<%/$rM%@h$7$F5a$ak+Nh$&$J?J2=$N2aDx$rF'$`!%

IaJWE*$J5,B'<+BN$,JQ2=7F$$$kKb4Xoi$:!$%@!<%&%#%s7?$N=8CD$,$$$:lN5,B'KBP
$bE,@Z$J3X=,$r9T$&%K%e!<%i%k%M%C%H%o!<%/$r3MF@$9k3H,2DG=G"k3HNM}M3$N0l$D$
$F!$%@!<%&%#%s7?$N=8CD$,N><T$N5,B'$N4V$K1#$5l?2?i+$N6&DL$N9=B$$r3MF@7F$$$/2DG
$r5s$2k3H,=PMhh&!%Nc$($P!$$3$3$G9M$($F$$$k4D6-(?^ 5.20)GO!$5,B'<+BN$OJQ2=$9
bN$N!$$=$NJQ2=$O!VH?E>!W$H$$$&bNG"$k!%$D$^$j!$?)NH$G$"$k$+FGJ*$G$"$k$+$OJLLdE
7F!$0lHVL\$HFsHVL\$NFsDN%S%C%H$N4X78$KhC$F!$>/J/HbJ*<ArFsD$N%0%k!<%W$KJ
k3H,=PMh$k!%?)NH$HFGJ*$r<1JL$9$k5,B'$=NbNr0dEAKhCF3MF@9k3H$O=PMh$J$
!V%0%k!<%WJ,$1!W$H$$$&Cj>]EY$,0l$D>e$N%l%Y%k$N5,B'$@$1Gb%@!<%&%#%s7?$O?J2=E*$K3MF
$F$$$/N+b7lJ$$!%$=$N>e$G8DBN$N3X=,$N8z2L$KhC$F!$$IAi$N%0%k!<%W$,?)NHG"$
J*G"k+$r<1JL$9$k5,B'$r3MF@7F$$$/$H$$$&%7%J%j%*G"$k!%$7$+$7!$<!$N 5.3.3 @aGN
83$r9T$CF_kH!$>e=R$N%7%J%j%*N[$+$K$bM}M3$,$"$j$=$&J3H,J,$+$k!%



?^ 5.21: [4D6- 4] J?6QE,1~EY (01@8 = 400 3X=,%9%F%C%W!$4D6-JQF0 = 50 @$BeKh)



?^ 5.22: [4D6- 4] @$Be7P2a$KHbJ&3X=,FC@-$NJQ2= (4D6-JQF0 = 50 @$BeKh)

5.3.3 <B83 5: 5,B'<+BN$,JQ2=$9$k4D6-$K$*$1$k?J2= (2)

Environment A	Food	Food	Poison	Poison
Environment B	Poison	Poison	Food	Food
Environment C	Food	Poison	Food	Poison
Environment D	Poison	Food	Poison	Food
Environment E	Food	Poison	Poison	Food
Environment F	Poison	Food	Food	Poison

Dynamic Change of the Rules of Universe

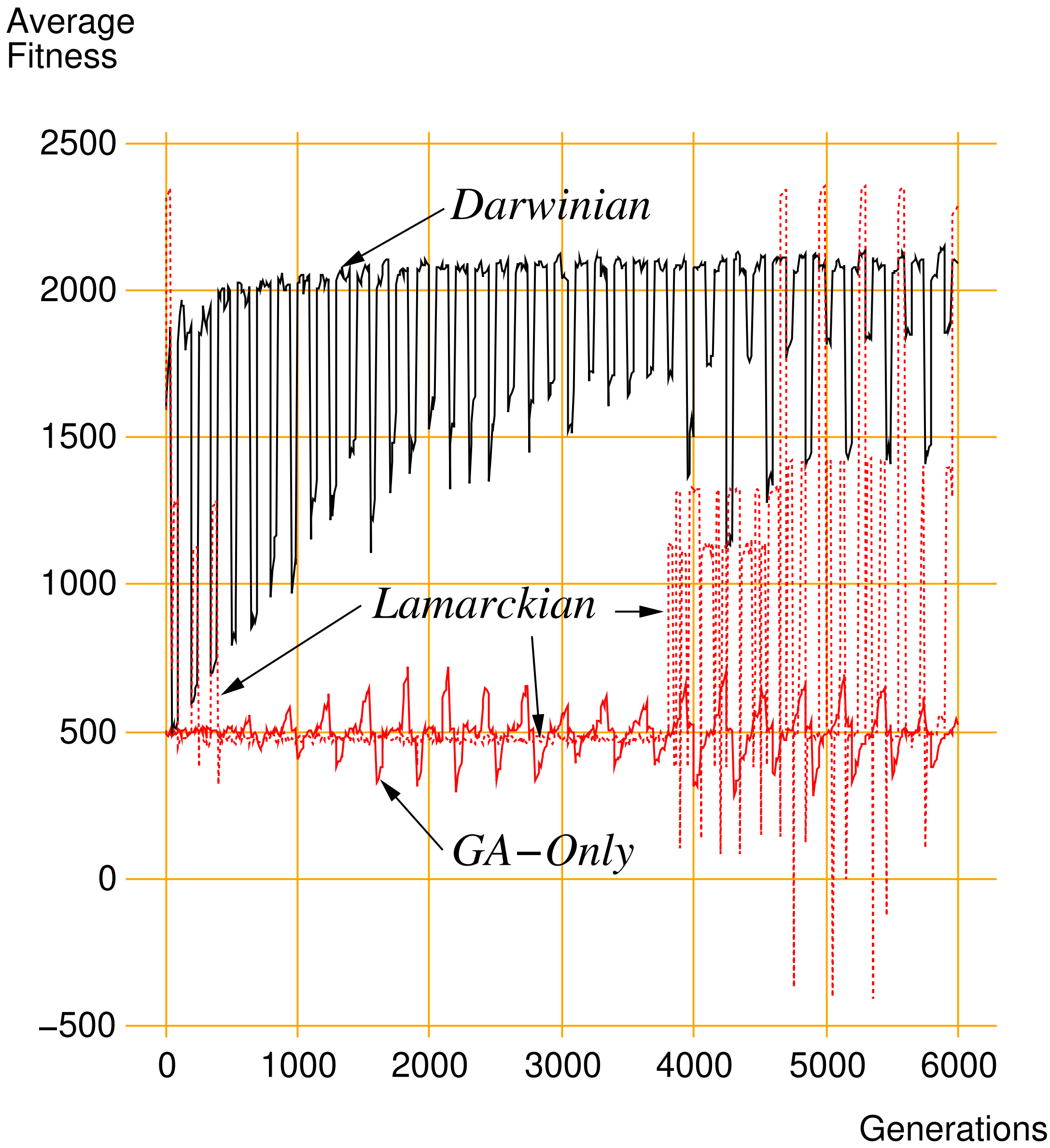
?^ 5.23: 4D6- 5

:G8e$K!$<B83 4 $G9M$($?$bNhjb99KFq7$$LdBjH7$F!$?^ 5.23 $K<($9h&$K?)NH$HF
J*$r6hJL$9$k5,B'$,40A4$KIT5,B'$KJQ2=9k!V4D6- 5!W$r9M$($k!%J*<A$rI=$9%S%C%H%Q%?!<%
5.3.2 @a$N?^ 5.20 $HF1MM$K 3 %S%C%H$N;(2;$r4^$` 5 %S%C%H$+$i@.$k!%?)NH$HFGJ*$r<1JL9k$N
$K!$01HVL\$HFsHVL\$N%S%C%H$,4XM?$9kNG"k,!$5.3.2 @a$G$N<B83$H$O0[$J$j!$$=$N5,B'$
%S%C%H$N%Q%j%F%#LdBj$G$"$kHO8Bi:!$$=$NAH9g$;$OA4$/IT5,B'E*$KJQ2=$9kbNH9k

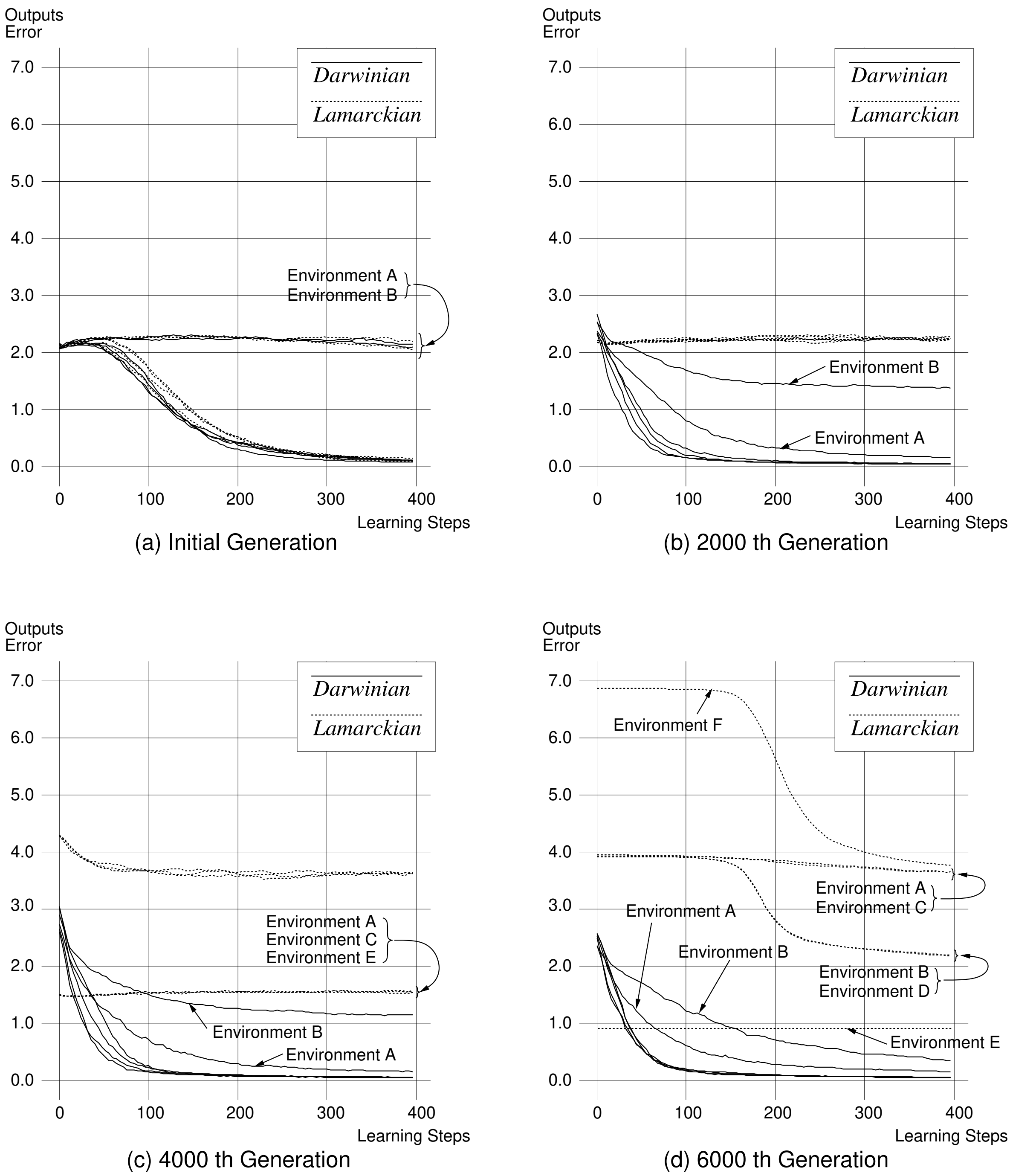
3Nh&$J>u67$N2<$G!$5,B'$r 50 @$BeKh$KJQ2=$5$;$?H-$N 6000 @$Be$^$G$N=8CD$NJ?6QE
1~EY$N?d0\$r4Q;!7?!%?^ 5.24 $O!$8DBN$N01@8$r 400 3X=,%9%F%C%W (:GBgE,1~EY = 2500) H7
$?$H$-$N7k2L$r<($7$F$$$k!%D>4QE*KO!$$I$N=8CD$b$&$^$/E,1~$G$-$J$$$bNHA[A|$5$1$k
<B:]$K?^ 5.24 $r8+$F$_$k$H!$%@!<%&%#%s7?$N=8CD$K$*$$$F$O!$@Ber=EMkKDlFE,1~EY
?6F0$NI}$,>.5/JC$F$$$-A4BNH7$F>e>:798~$r<(7F$$$k3H$,3NG'$G$-$k!%$3$3$G9M$
$$$k4D6- 5 KO!$5.3.2 @a$N8eHx$G=R$Y$?$h$&$J!V%0%k!<%WJ,$1!W$Nh&$J!$Cj>]EY$,01$D>e
%1%Y%kK*1k9=B$E*$J5,B'5(B8:_$;$:!$5,B'$OA4$/%i%s%@%`$KJQ2=9k!%3Nh&$J6K$
M=B,IT2DG=$J>u67$K$*$$$F5(!$%@!<%&%#%s7?$N%(!<%8%'%s%H=8CD$O2?$i$+$N;EAH$_$GM-1W$
JsrEA($F$$$k!%

5F!$>e5-$N<B83K*$$$F!$=i4|=8CD!$Bh 2000 @$BeL\!$Bh 4000 @$BeL\!$Bh 6000 @$BeL\$N
=8CDr=1>$1<h$j=P7F!$$3$1$i$N=8CD$KBP7F!$?^ 5.23 $G<($7$?$=1>1N5,B'$N2<$G
=,$r9T$o$;$?H-$N3X=,FC@-6J@~$r?^ 5.25 $K<($9!%?^K*1k3F%0%i%U$O!$3X=,$N7P2a$K$H

J&%K%e!<%i%k%M%C%H%o!<%/$N=PNO8m:9$NJQ2=$NMM;R$rI=7F$$$k!%$^$:!$=i4|@$Be$N=8CD$
$$$F$O!$%@!<%&%#%s7?$H%i%^%i%/7?$N=8CDHGF1$8$h$&$J3X=,FC@-$r<($9 (?^ 5.25 (a))!%$3$3$
Environment A $H Environment B K*$$$F$O!$5,B'$, 2 %S%C%H$N%Q%j%F%#LdBjHJ$k@~7AJ,N%
IT2DG=JFq7$$LdBjHJk?aK!$%(!<%8%'%s%H=8CD$O;W$&$h$&$K3X=,$r?J$ak3H,Fq$7
$=$N$[$+$N5,B'$O@~7AJ,N%2DG=$J0W$7$$LdBjJN$G!$3X=,7P2aKHbJCF%K%e!<%i%k%M%C%H%
%/$N=PNO8m:9$,B.d+$K8:>/$7$F$$$/!%$3$3$G!$=EMWJN$O!$5,B'$N0c$$$Khk3&7?3X=
@-$NAj0c$GOJ$/!$$=l>lN5,B'KBP7$F%@!<%&%#%s7?$H%i%^%k%/7?$NN><T$,F1Ey$J3X=,F
$r<($9$H$$$&3HG"$k!%$H3m$,!$Bh 2000 @$BeL\$KJk$HMM;R$,JQ2=7F$/$k (?^ 5.25 (b))
%@!<%&%#%s7?$N=8CD$N!$Environment A $H Environment B NFq7$$$bNr4^a?$=$l$>$l$N5,
B'KBP9$k3X=,FC@-$,$$$/i+8~>e5l$?$bNHJk!%0lJ}!$%i%^%k%/7?$N=8CD$O!$$$$:l
B'KBP7Fb3X=,$,;W$&h&$K?J$^J/JCF7$^$&!%@$Be?t$r=EMFBh 4000 @$Be (?^ 5.25 (c)
$K;j$k$H!$%@!<%&%#%s7?$N=8CD$K$*$$$F$O!$$$$:lN5,B'KBP7Fb3X=,FC@-$,$5iK8~>e$
$k!%0lJ}!$%i%^%k%/7?$N=8CD$G$O!$$=l>lN5,B'KBP9$k3X=,FC@-FC@-$,Bg$-$/0[Jj!$F
$J5,B'$HITF@0U$J5,B'$H$,L@3N$KJ,N%7F$/$k!%5i$K@$Be$,?J$s$GBh 6000 @$Be (?^ 5.25 (d)
KJkH!$0J>e$K=RYF$-$?798~$,99$KBg$-$/Jk!%$3$3Gb!$%(!<%8%'%s%H$N=8CD$,!$@8F
$KM%$l$?%K%e!<%i%k%M%C%H%o!<%/$r5aak3Hhj$b!$$$$:lN5,B'rbE,@Z$K3X=,$9k3$
=PMh$k=@Fp$J%K%e!<%i%k%M%C%H%o!<%/$rM%@h$7$F5a$ak+Nh$&$J?J2=$N2aDx$,:F8=5lF



?^ 5.24: [4D6- 5] J?6QE,1~EY (01@8 = 400 3X=,%9%F%C%W!$4D6-JQF0 = 50 @$BeKh)



?^ 5.25: [4D6- 5] @$Be7P2a$KHbJ&3X=,FC@-$NJQ2= (4D6-JQF0 = 50 @$BeKh)

5.4 <B837k2LN^Ha

K\@aGO!$0J>e$K=RYF$-$?<B83$N7k2L$K$D$$$F$^$Hak!%F@i1$?7k2L$OBg$-$/FsDG$"
0lDO!$3X=,$NNL$H%\!<%k%I%&%#%s8z2L$H$N4X78$K$D$$$FG"$j!$$b$&0l$D$O!$F0E*$J4D6-$
GN%@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=N=1>1NFC@-KD$$$FG"$k!%

5.4.1 %\!<%k%I%&%#%s8z2LK*1kLdBj$NFq0WEY$H3X=,2s?t$N1F6A

=>Mh$+$i9To1F-$?3X=,$H?J2=$K4X$9$k$$$/Db$N8&5f [HN87, PNC91, AL92] GO!$8DBN
$N3X=,$,=8CD$N?J2=$rB%?J9k%\!<%k%I%&%#%s8z2L$,@8$8k3H,Js9p$5$1$F$$$?!%7+$7!
2s9TC?<B83$GI,$:7b%\!<%k%I%&%#%s8z2L$,@8$8ko1GOJ$$$3H,L@i+KJC?!%F
Hs@~7A@-$r;}$DFq$7$$4D6-K*$$$F!$3X=,$NNL$,IT==J,$G$"$k>l9gKO%\!<%k%I%&%#%s8z2L$
8K$/$$$3H,J,$+$C$?!%$'7m!$8DBN$NCfESH>C<$J3X=,$O!$5U$K?J2=$rAK32$9k3Hb$"$
Hr3NG'7?!%0lJ}!$3X=,$r==J,$K9T$o$;$k$H!$Fq$7$$4D6-K*$$$F$b%\!<%k%I%&%#%s8z2L$,
$-$j$H@8$8k3H,J,$+$C$?!%

5.4.2 %@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=$NHf3S

		@~7AJ,N%2DG=$J5,B'	Hs@~7AE*$J5,B'
@EE*$J 4D6-		%i%^%k%/7? (<B83 1)	%i%^%k%/7? (<B83 2)
F0E*$J 4D6-	5,B'$OITJQ (>pJs$NItJ,@-)	%i%^%k%/7? (<B83 A-1)	%@!<%&%#%s7? (<B83 3)
	5,B'$,JQ2= (H?E>$N$_)	%@!<%&%#%s7? (<B83 A-2)	%@!<%&%#%s7? (<B83 4)
	5,B'$,JQ2= (G$0UNAH_9go;)	%@!<%&%#%s7? (<B83 5)	

I= 5.1: %@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=$NHf3S ($^Ha)

MM!9$J>u67$rA[Dj7?<B834D6-$N2<$G!$%@!<%&%#%s7?$H%i%^%k%/7?$N0dEA5!9=$r;}$D%(!<%
%s%H=8CD$r GA $rMQ$$$F?J2=5;$F!$E,1~@-$*$h$S4h7r@-$K4X7FHf3SI>2A$r9T$C$?!%I= 5.1 $
A[Dj7?4D6-H=$N2<$GIAiN0dEA5!9=$,M-8z$G$"$k$+$K$D$$$F$N7k2L$r$^$Hak!%J*!
Ai$N0dEA5!9=$,M-8zG"k+$N4p='$O!$E,1~@-!$E,1~?J2=$NB.EY!$4h7r@-JINLL+$iAm9
$KH=CG$7$F$$$k!%J*F0E*$J4D6-$K$D$$$F$O!$K\J8GOHs@~7A@-NFq7$$5,B'$r;}$D4D6-$N2
$NI>2A7k2L$K$D$$$FN_<h$j>e$2$?$,!$@~7AJ,N%2DG=$J4JC1$J5,B'$r;}$D4D6-$K$*$$$FF0E*$
67$rA[Dj$7$?<B83 (<B83 A-1!$<B83 A-2) $b9T$C$F$$$k!%$3$1iN<B837k2LKD$$$F$O!$K\O@J8
Hx$N Appendix A KF4JC1$K<B83@_Dj$*hS7k2L$r<(7F$$$k!%

I= 5.1 $K<($7$?$H$*$j!$@EE*$J4D6-2<GO%i%^%k%/7?$N0dEA5!9=$NJ}$,%@!<%&%#%s7?$NbN
jb05E]E*$KM%$l$F$$$k$H8@$($k!%$3lO!$8DBN$Khk3X=,$H=8CD$Khk?J2=$NN>2aDx$rD>@
$KM;9g$7$F$$$k%i%^%k%/7?$N5!9=$rMQ$$$k=8CD$O!$FCDj$N4D6-$X$NE,1~$,B.$$$+iG$"$k!%$
m,!$%i%^%k%/7?$OFCDj$N4D6-$KBP7F?<$/E,1~$7F7$^$&NG!$0lEY?<$/O^CF7^$&$
3+$iH4$1=P$9$3HOHs>o$K:$FqHJ$k!%$7$?$,CF!$4D6-$,F0E*$KJQF0$9kh$&$J>u67K
FO!$$=$NJQF0$K9go;$FE,1~EY$bBg$-$/?6F0$7!$6KaFIT0BDj$J5sF0$r<($9!%0lJ}!$%@!<%
%s7?$N=8CD$O!$4D6-$,JQF0$7$F$b%i%^%k%/7?$N=8CD$[$I5sF0$,IT0BDj$KJk3HbJ$$!%

	C5:w6u4V	C5:w$N@:EY	C5:w$N%?%$%W
GA	9-$$	AF$$	Bg0hE*%5%s%W%j%s%0
BP K!	69$$	:Y$+$$	6I=jE*C5:w

I= 5.2: GA $H BP K! (%K%e!<%i%k%M%C%H$N3X=,) $NFC@-

8DBN$K3X=,$r9To;kH!$3X=,7k2L$,0dEA9k3H$,$J$/$H$b%\!<%k%I%&%#%s8z2L$KhC$
CD$N?J2=$,B%?J5lk3HO=RY?!%$^$?!$$3$N5?;w%i%^%k%/E*8z2L$,@8$8$k860x$O!$8DBN$
$&3X=,$KhC$F!$@8F@E*$J%M%C%H%o!<%/$N7k9g6/EY%Y%/%H%k$N<~JU$,6I=jC5:w5lk+iG$
3H$b=R$Y$?!%F0E*$J4D6-K*$$$F!$J#?t$N5,B'$N2<$GE,@Z$JE,@Z$J9TF0%Q%?!<%s$r@8$8$5$
h&$J%K%e!<%i%k%M%C%H%o!<%/$,B8:_7J$$!$$b7/$O3MF@$,:FqG$"$k>l9gKO!$$3$N6I=
:w$,Hs>o$K=EMW$JLr3d$r2L$?$9!%<B:]$K!$@836$N3X=,$,9Tolk3HN$J$$ GA-Only $N=8CD$
3Nh&$JF0E*4D6-2<$G$OA4$/$&$^$/5!G=$7$J$$$3Hr3NG'7F$$$k!%H3mG!$$3$3$G6=L
$$$3HO!$8DBN$N3X=,7k2L (9JoA6I=jC5:w$N7k2L) $rM[$K0dEA5;kh$&$J%i%^%k%/E*$J
EA5!9=$bF0E*4D6-2<$GO&$^$/5!G=7J$$E@G"$k!%0lJ}!$%@!<%&%#%s7?$N=8CD$N4h7r@-$N8
$O!$8DBN$N0l@8$Ko?$k3X=,$H@$Be4V$N2M166HJk0dEANFsD$N2aDx$rL@3N$KJ,N%$7$F$$$
HK5/0x9k!%GA Kh$k0dEAE*A`:n$H BP K!Kh$k%K%e!<%i%k%M%C%H%o!<%/$N3X=,K!KO!$
l>$lI= 5.2 $K<($9h&$JFC<A$,$"$j!$$=l>lN2aDx$OAjJdE*$JbNG"$k!%$D$^$j!$3F8D
$N%l%Y%k$G$O3X=,$KhC$F>\:Y$J5,B'$KBP1~$7DD$b!$=8CDA4BNH7FO$"$kDxEY$NHFMQE*$
G=@-$rJ]$C$?$^$^=y!9$KE,1~7F$$$/NG$"$k!%5i$K6=L#?<$$$3HK!$@8B8$KM-Mx$J5,B'$
E>9kh&$J>u67$dA4$/M=B,ITG=$GIT5,B'$KJQ2=$9kh$&$J6KaFF0E*FC@-$N6/$$4D6-2<K
Fb!$%@!<%&%#%s7?$N%(!<%8%'%s%H$O4h7r@-$KM%lk$@$1GJ$/!$@Ber=EMkKDlFE,1
$r=y!9$K>e>:5;$F$$$/!%D^$j%@!<%&%#%s7?$N=8CD$O!$$3Nh$&$JIT5,B'$J4D6-$N2<GbE
@-$rJ]$C$F$$$kNG$"$k!%%@!<%&%#%s7?$N0dEA5!9=$N2<GO!$%(!<%8%'%s%H=8CD$O!$MM!9$J5
KBP7FbE,@Z$K3X=,$r9T$($kh&$J=@Fp$J%K%e!<%i%k%M%C%H%o!<%/$r3MF@$7$F$$$/3H$,2
G"$k!%

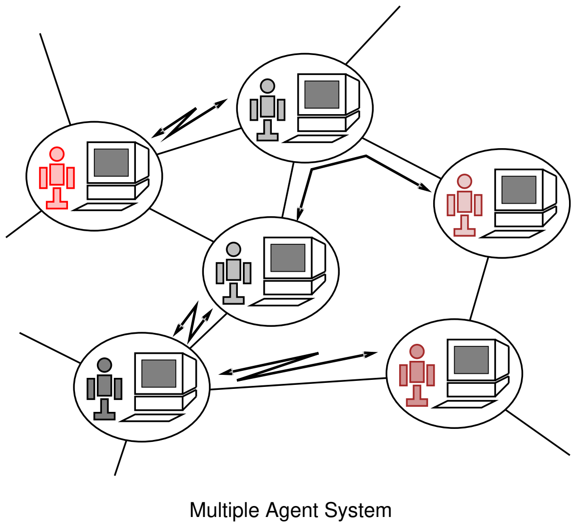
>e=RN3HH4XO"7F!$<B83 3!$<B83 4!$<B83 5 K*1k@$BeKh$N3X=,FC@-$NJQ2= (?^ 5.19
?^ 5.22!$?^ 5.25) KD$$$F?(lF$*$/Y-3H$,0lE@$"$k!%IaJWE*$J5,B'<+BN$,JQ2=$7$J$$<B8
3 K*$$$F$O!$@8F@E*$J%M%C%H%o!<%/$N=PNO8m:9$,@$Be$r=E$MkKDl$F8:>/$7$F$$$k (?^ 5.19
D^$j!$@8$^$lD-E,7?9TF0%Q%?!<%s$r<h$kh&$J8DBN$,@8$8$k!%0lJ}!$5,B'<+BN$,JQ2=$
7^$&<B83 4!$<B83 5 K*$$$F$O!$$`7m@8F@E*$J%M%C%H%o!<%/$N=PNO8m:9$O@$Be$r=E$Mk
lFA}2C7F$$$k (?^ 5.22!$?^ 5.25)!%$3N3HO!$F0E*FC@-$N6/$$4D6-GO!$FCDj$N5,B'2<$
E,@Z$K?6$kIq$&$3Hhjb!$MM!9$J5,B'$r3X=,$G$-$kh&$J=@Fp$J@-<A$NJ}$,=EMWG"k3$
0UL#7F$$$k!%D^$j‼$V$&$^$/9TF0$G$-$k!WFC@-$r0dEA$7h&H9$kD>@\E*$J%i%^%k%/7?$N0
GOJ/!‼V&$^$/3X=,G-$k!WFC@-$,0dEA7F$$$/%\!<%k%I%&%#%s8z2LKh$k4V@\E*$J5!9=$
$,=EMW$JLr3d$r;}$D!%

Bh **6** >O

5DO@$*$h$S:#8e$N2]Bj

Bh 5 >OKF!$%@!<%&%#%s7?$"$k$$$O%i%^%k%/7?$N0dEA5!9=$rHw$($?%(!<%8%'%s%H=8CD$,$I$N $&$J?J2=$N2aDx$rF'$`$N$+$r!$%7%_%e%l!<%7%g%s$K$h$jMM!9$J>u67$N2<$G:F8=$7!$$=$N7k2L$ $$$FI>2A$*$h$S9M;!$r9T$C$?!%K\>O$G$O!$$^$:!$6.1 @a$K$F!$$3$1$^$G$K9T$C$F$-$?<B83$K$ $FF@$i$1$?CN8+$,<B:]$K9W8%$r2L$?$7F@$k>1$H$7$F%^%k%A%(!<%8%'%s%H%7%9%F%`$N9=C[$N:]$ HrNc$r5s$2$F!$K\8&5f$N0U5A$r:F3NG'9k!%<!$K!$4V@\E*KGO"k,!$Bh 5 >O$K$F<($7$ 837k2L$rMxMQ$7F5iK6=L#?<$$5DO@$r9T$C$?>e$G!$:#8e$N2]Bj$r=R$Y$k!%

6.1 K\8&5f$N0U5A: %^%k%A%(!<%8%'%s%H%7%9%F%`$N9=C[$K:]7F



?^ 6.1: %^%k%A%(!<%8%'%s%H%7%9%F%`

$3$3GO!$K\8&5f$N@.2L$,9W8%$7F@$k>1$N01DNNcH7$F!$%^%k%A%(!<%8%'%s%H%7%9%F%`$ $N:#8e$N3+J|7?J,;64D6-$G$N1?MQ$rA[Dj$7$?%7%9%F%`KD$$$F9M;!7F$_$k!%

:#F|$N7W;;5!4D6-$O!$%3%s%T%e!<%?%M%C%H%o!<%/$N5^B.$JH/C#$H7W;;5!$NIa5Z$KH<$$J,;6 3+J|2=$,?J$sG*$j!$%^%k%A%(!<%8%'%s%H%7%9%F%`$H$7$F$NMMAj$rDh$7;O$a$F$$$k (?^ 6.1)!% %k%A%(!<%8%'%s%H%7%9%F%`HO!$<+N'E*$J=hM}<gBNG"$k%(!<%8%'%s%H$,J#?tB8:_9kh&$ %9%F%`G"$k!%$3$3$G$O!$7W;;5!$N01Bf01Bf$r%(!<%8%'%s%HH_J9$3$H$b=PMh$k$7!$$"k %=%U%H%&%'%"%b%8%e!<%k$r%(!<%8%'%s%H$H$_$J$9$3Hb=PMh$k!%

$^$?!$$3Nh$&$K6KEY$KJ,;62=$7$?7W;;5!4D6-$O!$6K$a$FF0E*$KJQ2=9k!%8E$$7W;;5!$O? $$$bNKCV-49(i1$?$j!$%3%s%T%e!<%?%M%C%H%o!<%/$b$=$NB.EY$d%H%]%m%8!<$r;~!99o!9$ 2=5;$k!%?7$7$$%=%U%H%&%'%"$N3+H/$d?7$7$$>pJs$NDs6!$Khj!$$h$jNI$$%5!<%S%9$,F@$i hjM-Mx$J=hM}$r9T$($kh&KJ$k!%$3$1$i$NJQ2=$r%(!<%8%'%s%H$,;vA0$KM=B,9k3H$OI G=$G$"$k$7!$9-0h$KJ,;6$7$?4D6-$G$O8=:_JQ2=$7DD$"$k3H5(GD0.9k3H$O:$FqHJ

$"$k$$$O%(!<%8%'%s%H4V$NJ#;($JAj8_:nMQKhCF!$4D6-A4BN$H7FM=B,ITG=$J?6$kIq$$$,@
F@$k!%$7$?$,CF!$$3Nh$&$J3+J|7?J,;64D6-GN1?MQ$rA[Dj$7$?%(!<%8%'%s%H%7%9%F%`$r9
9k:]$K!$%7%9%F%`$,Ax6x$7F@k"if$k>u67$r$"$i$+$8$aA4$F@v$$=P7F$=$1ir9MN8$KF
$F%7%9%F%`$N@_7W$r9T$&$3$H$O:$Fq$G$"$k!%$=$3$G;O$a$+$i40A4$KF0:n$9$k%7%9%F%`$GOJ$
?J2=E*%(!<%8%'%s%H (*Evolutionary Agents*) $H$$$C$?E,1~7?$N%7%9%F%`$N35G0$,$^$9$^$9=EMW$K
JCF/$k!%Bh 5 >O$G$O!$$3Nh$&$J%7%9%F%`$N4D6-$X$NE,1~2aDx$r!$?J2=O@$J$I$NN`?d$+
8D!9$N%(!<%8%'%s%H8DBN$N!V3X=,!W$H%(!<%8%'%s%H=8CD$N!V?J2=!WNFsD$N0[$J$k%l%Y%k$K$
$k2aDx$NAjJdE*JbNG$"$k$HB*$($F!$Cj>]2=7?%b%G%k$rMQ$$$F%(!<%8%'%s%H=8CD$N?J2=$
Dx$rMM!9$J>u67$N2<$G4Q;!7F$-$?!%

K\O@J8GO!$3X=,$d?J2=!&0dEA$H$$$C$?@8J*3XE*$J8@MU$rMQ$$$F$-$?$,!$$3$1$i$r7W;;5!%
%H%&%'%"K*1k8@MU$G8@$$49$($k3H$b=PMh$k!%Nc$($P!$%=%U%H%&%'%"$JIN%(!<%8%'%s%
;HMQ4|4V$,!V0l@8!W$KAjEv$7!$$=$N0l@8$N4V$K%(!<%8%'%s%H$,>pJs$r<}=8$9k3$H!$$5iK$
iN>pJs$r85$KhjM-Mx$K=hM}$r<B9T=PMhkh$&$K<+J,$r2~A1$9k3H,!V3X=,!W$KBP1~$9
$^$?!$%P!<%8%g%s%"%C%W$KhC$F8E$$%(!<%8%'%s%H$r?7$7$$$bNXHCV-49$($k3H$,!V@$E
Be!W$KBP1~$9$k!%$"$k$$$O%P!<%8%g%s%"%C%W$,?M0YE*$K0Y$5$1kbNGJ/!$%(!<%8%'%s%H<+$
B>$NCg4V$N%(!<%8%'%s%H$H!V0dEA;R!W$r8r49$7$"CF;R%(!<%8%'%s%H$r:n$k3H$G<+F0E*$K%
%8%g%s%"%C%Wr7$F$$$/h&$J>u67$rA[Dj7F$b9=$o$J$$!%5i$K!$%P!<%8%g%s%"%C%W$H$$$
HK3@oi$:$K!$3F%(!<%8%'%s%H$,3MF@7?CN<1$r%(!<%8%'%s%H4V$GAj8_$K8r49$7$"$&h
>u67!$$"$k$$$O!$$"$k%(!<%8%'%s%H$,B>$NM%=($J%(!<%8%'%s%H$N9TF0%Q%?!<%s$r??;w9k2aD
9M$($F$bNI$$!%K\O@J8GO!$6K$a$FCj>]EY$N9b$$%l%Y%k$N%b%G%k>e$G$N5DO@$r7F-F*$j!
$?!$@8J*3XE*$JMQ8l$rB?MQ7F$-$?$,!$0dEA;R$d@w?'BN$JIOC1$K>pJsEAC#$NG^BN$K2a$.$:!
$?3X=,$b>pJs$N<}=8$*hS$=$N3hMQ$N2aDx$N0lDNJ}K!$K2a$.$J$$!%K\<AE*$K=EMW$JNO‼$V>
$N<}=8!&3hMQ!&<x<u!W$N2aDxG"$k!%?7$7$$%(!<%8%'%s%H$r%P!<%8%g%s%"%C%W$KhC$F:n@.$
:]$K8E$$%(!<%8%'%s%H$,3MF@$7$?>pJs$rINh&$K3h$+9+!$%(!<%8%'%s%H4V$G>pJs8r49r
:]KINh$&$J8r497ABV$,@-G=LL$"$k$$$O4h7r@-NLLGK>$^$7$$$+JI9MN8$9$Y$-$3HOB?
J*!$$3$N:]$K$O!$<B@$3&$N;}$DF0E*$JFC@-$r==J,$K9MN8$9$kI,MW$,$"$k!%K\O@J8$G$O!$F0E
@-<A$r;}$D4D6-$H;}$?$J$$4D6-N=l>lN2<K*$$$F!$%@!<%&%#%s7?$H%i%^%k%/7?$H$$$C$
DN0[Jk>pJs8r49$*$h$SEAC#$N7A<0$NHf3SI>2A$r9T$$!$$=l>lNFC@-$rL@$i$+$K7?!%K
J8K*1k8&5fKhCFF@il$?CN8+!$$"$k$$$O:#8e9Tol$k8&5f$KhC$FF@$ilk@.2L$O!
$&$7$?E,1~?J2=7?%7%9%F%`$N9=C[J}K!$d1?MQJ}K!$r9MN8$9$k:]$K2?$i$+$N<(:6$rM?$(Fkb
9M$($ilk!%

6.2 :#8e$N2]Bj

K\@aGO!$:#8e$N8&5f2]BjKD$$$F=RYk!%0J2<$K=R$Y$F$$$/8&5f2]Bj$O$$$:lb!$K\8&5

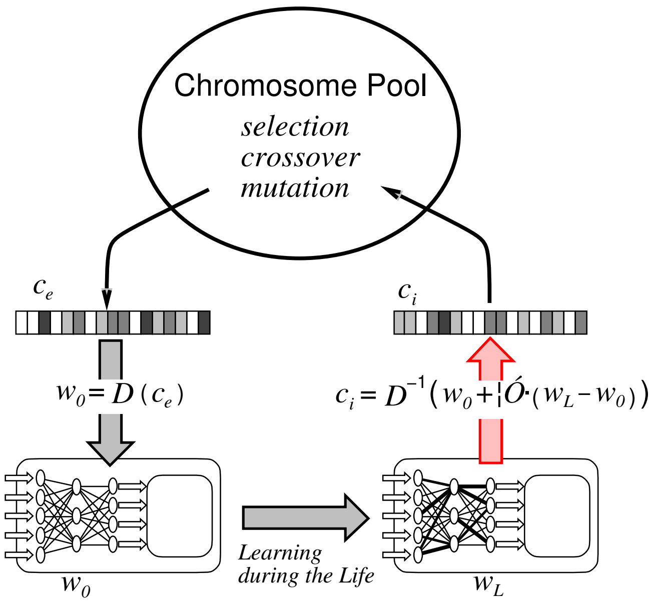
F@il$?CN8+$r3h$+$7$F!$<B:]E*$J%7%9%F%`$K1~MQ7F$$$/:]$K=EMW$KJCF/kbNG$"

6.2.1 3MF@7A<A$NCf4VE*$J0dEA5!9=$K4X$9$k5DO@

K\8&5fGO!$%@!<%&%#%s7?$H%i%^%k%/7?NFsD$N0[$J$k0dEA5!9=$K$D$$$FHf3SI>2A7F$-$?

!V3MF@7A<A$N0dEAN(!W$H$$$&%Q%i%a!<%?$rF3F~$9kH!$$3liFsDN0dEA5!9=$r01$D$NE}01E

<0$GI=$9$3$H$,=PMh$kh&KJ$k!%



?^ 6.2: 0dEA5!9=

8DBNCB@8;~$N%K%e!<%i%k%M%C%H%o!<%/$N=i4|7k9g%Y%/%H%k$r w_0 H7!$8DBN$,01@8$N4V$K9T$&

3X=,KhCF=$@5$5l?8e$N%M%C%H%o!<%/$N7k9g%Y%/%H%k$r w_L H9$k!%$^$?!$8DBNH/@8;~$KMQ

$$$ilk@w?'BN$r c_e $!$=$N8DBN$,;R$r:n$k:]$KJ|=P$9$k@w?'BN$r c_i H9$k!%$=7F!$ D $r0d

EA;R7?$+$iI=8=7?XN<LA|H7!$ D^{-1} $rI=8=7?$+$i0dEA;R7?$X$N<LA|$H9k [1]J*!$$3$3$G w $r

%(!<%8%'%s%H$NJ];}$9$k>pJs$"$k$$$O%(!<%8%'%s%H$NFC@-$JIrI=8=7?NLG$"$kH9lP!

2<$N5DO@$O%K%e!<%i%k%M%C%H%o!<%/$K8BDj$5l?bNGOJ/!$$h$j0lHLE*$J5DO@XH3HD%$

3H$,$G$-$k!%

=i4|7k9g%Y%/%H%k w_0 $r;}$D8DBN$O@w?'BN c_e $i@8$8kN$G!$8DBN$NH/@82aDx$O0J2<$N<0$G

[1] 3.1 @a$G=R$Y$?J,;R@8J*3X$K$*$1$k%;%s%H%i%k%I%0%^$Khk$H!$DNA Kh$k0dEA5!9=$K4X7F$O!$ D^{-1} $J5U<LA|$O$J$$!%

I=$9$3H,=PMh$k!%

$$\boldsymbol{w}_o = \boldsymbol{D}(\boldsymbol{c}_e)$$

$^$?!$8DBN$,;R$r@8@.$9kN$KMQ$$$k@w?'BN$r $\boldsymbol{c}_i$ H9$k2aDx$O0J2<$N<0$GI=$9$3H,=PMh$k!%

$$\boldsymbol{c}_i = \boldsymbol{D}^{-1}\left(\boldsymbol{w}_o + \tau \cdot (\boldsymbol{w}_L - \boldsymbol{w}_o)\right) \tag{6.1}$$

τ $r!V3MF@7A<A$N0dEAN(!W$H8F$V3HK9$k!%(6.1) <0$K$*$$$F!$ $\tau = 0$ H7$?$H$-$O3MF@7A<A$
A4$/@w?'BN>e$N>pJs$KH?1G$7$J$$$N$G!$%@!<%&%#%s7?$N0dEA5!9=$rI=$9$3HKJk!%5U$K τ =
H9kH@w?'BN>e$K3MF@>pJs$,A4$FH?1G$5lk3HKJkN$G!$%i%^%k%/7?$N0dEA5!9=$rI=$
HKJk!%

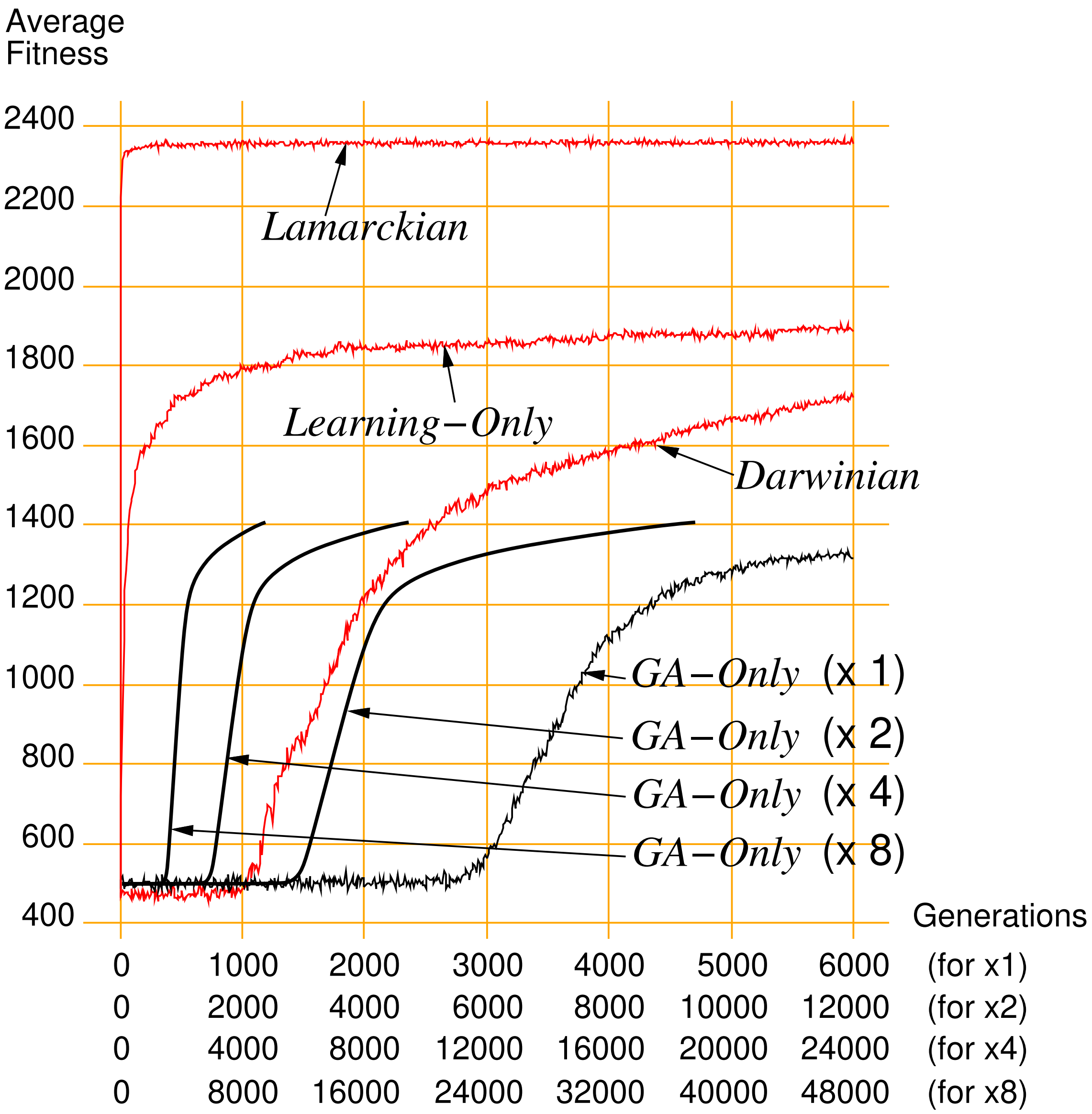
K\8&5fGO!$3MF@7A<A$N0dEAN(τ $, 0 $+ 1 NIAi$+!$$D$^$j!$3MF@7A<A$rA4$/0dEA$5$;$
$$$+A4$F0dEA$5$;$k$+$NIAi+N>6KC<$N>l9g$N$_$K$D$$$F$NHf3SI>2A$r9TCF$-$?!%$3$3
b7 τ $K 0 $H 1 $N4V$NE,EvJCMr@_Dj7F3MF@7A<A$rCf4VE*$K0dEA5;$k5!9=$rF3F~9l$
hjE,1~B.EY$,B.$/$+$D4h7r@-$KM%$l$?%7%9%F%`$r9=C[G-$k2DG=@-$,$"$k!%3Nh&$J0dE
BV$,@8J*3XE*$K$"$jF@kN$+$I$&$+$OJLLdBj$G$"$k$,!$9)3XE*$J1~MQ$N4QE@$+$iHs>o$K6=L#$
$?$l$kE@$G$"$j!$$^$?=EMW$G$"$k$H;W$olk!%

6.2.2 3X=,$N%3%9%H$H@$Be8rBe$N%3%9%H$K4X$9$k5DO@

Bh 5 >OGO!$%@!<%&%#%s7?!$%i%^%k%/7?!$GA-Only!$Learning-Only $N=8CD$NA4FK$*$$$F
@$Be8rBe$NB.EY$,Ey$7$$$bNH7FI>2A$r9T$CF-$?!%$3$3$G!$<B:]$N@8J*ObAm$s!$?M9
$J%(!<%8%'%s%H$KHCFb!$3X=,$*hS@$Be8rBe$KBP7F2?i+$N%3%9%H$,3]$+$k3H$OL@$
G"$k!%$3li$N%3%9%H$r9MN8$KF~$lkH!$GA-Only $N=8CD$,0l@8$N4V$N3X=,$r9T$o$J$$$J,
$1!$@$Be8rBe$K%(%M%k%.!<$r?6$jBX$($k@oN,$r<h$k3H$,2DG=$G$"$k$H9M$(k3HOM}K+$
$F$$$k!%$=$b$=$b!$GA-Only $N=8CD$KHCFO!$3X=,$r9T$&B>$N=8CD$HF1$8<\EY$GHf3S$5l
3HORI/IT8xJ?G"$k!%

Nc$($P!$4D6- 2 K*$$$F0l@8$, 400 3X=,%9%F%C%W$H7?H-$N<B83 (<B837k2L$O?^ 5.14) K
$$$F!$B>$N=8CD$N 2 G\!$4 G\!$8 G\$NB.5G@$Be8rBe$,2DG=$J GA-Only $N=8CD$NE,1~EY$N?d0
$rI=$96J@~$O!$?^ 6.3 $K<($9h&$J7A$r<hkH;Wol$k!%B>$N=8CD$N%(!<%8%'%s%H$, 400 2s$b
=,KhCF%K%e!<%i%k%M%C%H%o!<%/$r=$@5$9$k4V$K!$GA-Only $N=8CD$OA4$/3X=,$r9ToJ$$$
$G!$%3%9%H$N@_Dj$KhCFO!99Khj9bB.$J@$Be8rBe$r2>Dj$9k3Hb2DG=G"m&!%

<+A33&$r8+$F$_$F$b!$Nc$($PC1:YK&@8J*Nh$&$K9=B$$,C1=c$J@8J*$O:YK&J,NvKhk=$N
?#B.EY$OB.$/!$9bEY$J3X=,$r9T$&3H$,=PMh$kJ#;($J9=B$$r;}$D9bEy@8J*$[$I@$Be8rBe$NB.E
CY$/$J$k!%$3$3$G!$?J2=$N=i4|$NCJ3,$K$O3X=,$hjb@$Be8rBe$K=E$-$rCV$-!$CJ3,$,?J$`K
$F3X=,$NJ}$r=E;k$9kh$&$J@oN,$OM-K>$G$"$m$&!%$3Nh$&$K!$3X=,$H@$Be8rBe$KBP9k%(%



?^ 6.3: [4D6− 2] J?6QE,1~EY (@$Be8rBeB.EY$K4X9k;W9M<B83)

%.!<$NG[J,$rF0E*$KD4@a$9kh$&$J@oN,$O!$@8J*3XE*$J%"%J%m%8!<0J>e$K9)3XE*$J1~MQ$K:]$
$bHs>o$K6=L#$,;}$?lk!%

$^$?!JLN6=L#?<$$OCBjH7$F!$?M9)G>JI$N?M9)E*$JCNE*%7%9%F%`9=C[$NMxE@$N0lDH$
<wL?$N@)Ls$,B8:_7J$$$$3H,7P7P5s2ilk$,!$K\8&5f$GF@$$il?CN8+O3$NAGKQ$JD
KBP7$F:F9M$rB%$9!%K\O@J8$G9M$($F$$$k%i%^%k%/7?$N0dEA5!9=$G$O!$<+A3EqBA$d0dEA;R$N8
$dFMA3JQ0[$JIN8z2LO"kbNN!$?F$N3X=,7k2L$r;R$,$=$N$^$^<u$17Q$0$H$$$&Bg;(GD$J0
GO!$8+J}$rJQ$($k$H<wL?$rL5$/$73X=,$r1J1s$KB3$1$k3H$r2DG=$K9k;EAH$_$H7FB*$($
Hb=PMh$k!%$H3m$,K\9F$G$N<B837k2L$Khk$H!$F0E*$J4D6-2<$GO3$&$7$??M9)E*$J%7%9%
$K<wL?$,B8:_7J$$$$3HO5QCFITMxHJ$jF@$k3H$,M=A[$5lk!%$`$7mE,EvK@$Be8rBe$
jJV9$3$H$,=EMW$G$"$j!$$7$+$b$=$N:]$N>pJs$NEAC#$O%@!<%&%#%s7?$N5!9=$K4p$E$$$?bN$
1lPJiJ$$!%

6.2.3 %b%G%k$N0lHL@-$K4X9k5DO@

%(!<%8%'%s%H=8CD$N?J2=E*$J2aDx$r:F8=$9k?aKK\O@J8$GMQ$$$?%b%G%k$O!$@8L?$N86M}$
A[$rF@$?bNGO$"$k$,!$@8J*3XE*$K=EMW$J$$$/D+$NB&LL$rL5;k7?6KaFCj>]EY$N9b$$$
HJCF$$$k!%Nc$($P!$@w?'BN$+$i8DBN$N%K%e!<%i%k%M%C%H%o!<%/$r@8@.$9kK$"$?CFD>@
%s%3!<%IK!$rMQ$$$?$,!$<B:]$N@8J*$NG>GO3F%K%e!<%m%s4V$N7k9g6/EY$NA4F,D>@\E*$K0dE
$+$i7hDj5l$F$$$kHO9M$($K$/$$!%$^$?9)3XE*$JN)>l$+ib!$$h$jBg5,LO$J$K%e!<%i%k%M%
%o!<%/$r?J2=E*$K3MF@9k3H$r9M$($?$H$-$K$O!$$3$3$GMQ$$$?D>@\%(%s%3!<%IK!GOIT==J
$"$k!%3N:]KO!$%0%i%U=q$-49$(5,B'$r:F5"E*$KMQ$$$kJ8K!%(%s%3!<%IK! [Kit90, KLLn 93] $
h&$J5!9=$,M-MQKJk3HO3N$+$G$"$k!%$^$?!$$=$N5!9=$O@8J*$NH/@8$N%a%+%K%:%`Kh$
$$%b%G%kGb$"$k!%7+$7!$$3N3HOK\O@J8K*1k3X=,$H?J2=$K4X9k5DO@$NK\<A$rJ$$
NGOJ$$!%

0J>e=RYF$-$?h&$K!$K\8&5fGN@.2Lr=N^$^@8J*3X$K%U%#!<%I%P%C%/9k3HOFq
$,!$5U$KCj>]EY$N9b$$%b%G%k>eGN5DO@$O%^%k%A%(!<%8%'%s%H%7%9%F%`$N9=C[K!$JINMM!9$
BjK^$G1~MQHO0O$r9-2ilk2DG=@-$,$"$k!%%(!<%8%'%s%H$KhkLdBj2r7h$"$k$$$O$=$N$?$
8z2LE*$J@oN,3MF@$N2aDx$H$$$&4QE@$+$i$O!$K\O@J8$GMQ$$$?!V3X=,!W$H!V?J2=!W$H$$$&MQ8l$
l>lO!$3F8DBN$,FH<+$K9T$&C5:w$H=8CDA4BN$Khk6(D4C5:w$KBP1~$9$k!%$3NH$-$K$=$l$
$N2aDx$N2M$166 — >pJs$NEAC#$*$h$S8r49 — $NLr3d$rC4$&$N$,!V0dEA!W$N5!9=G"$k!%

0lJ}$G!$K\O@J8$GMxMQ$7F-$?%b%G%k$N0lHL@-$dBEEv@-$K4X9k8!>Z$O=EMW$G$"$k!%Nc$(
$3$3GO!$%(!<%8%'%s%H$N3X=,H7$F%K%e!<%i%k%M%C%H%o!<%/$N%b%G%k$r:NMQ$7$?!%%K%e!<%
%M%C%H%o!<%/$N3X=,$N?J$_J}$OA2?JE*G"$j!$;~H7$F6I=j2r$KJaiolF3X=,$,$,<sHxNI$/?
$J$$$$3Hb$"$k$H$$$&@-<A$r;}$C$F$$$k!%3liN@-<A$O!$3+J|7?J,;64D6-Nh$&$JJ#;($J4

2<GN%(!<%8%'%s%H$N3X=,2aDx$rE,EY$K%b%G%k2=$G$-$kbN$H;W$olk$,!$K\O@J8$GF@$il
8+$,$=N^$^B>$N3X=,%Q%i%@%$%`$KBP7F@.$jN)$D$+$I$&$+KD$$$F$O:#8e$N3NG'$,BT$?$l
$^$?!$K\8&5f$K$*$1$k%b%G%k$O!$4D6-Cf$K%(!<%8%'%s%H$N?)NH$HJkJ*;q$,==J,$K$"$j!$8B$
$??)NH$ra0CF$N%(!<%8%'%s%H4V$N6%Ah$H$$$C$?D>@\E*$J%(!<%8%'%s%H4V$NAj8_:nMQ$r9MN
F~l?bNHJCF$$$J$$!%7+$7!$<B:]$N@8J*$N@$3&$d7W;;5!4D6-JI$r9MN8$9kH!$8B$
$?;q8;$r=dCF@8J*$d%5%V%7%9%F%`$,6%9g9k3H$,>o$G$"$k!%5i$K!$%(!<%8%'%s%H$NAj8
MQHO>e5-Nh$&$J6%Ah$K8B$C$?$bNP$+$jGO$J$$!%%(!<%8%'%s%HF1;N$O!$8_$$$NMx1W$r>
k?aK6(D4$9$k3Hb"$k [MT93]!%$7$?$,CF!$$3Nh$&$J9-$$0UL#GN%(!<%8%'%s%H4V
Aj8_:nMQ$r9MN8$KF~l?%b%G%k$rMQ$$$?I>2AbI,MWKJCF/$k!%$^$?!$$3$&$7$?%(!<%8%'%
4V$KAj8_:nMQ$N%M%C%H%o!<%/$,B8:_$9$k>l9g!$%7%9%F%`A4BNKOhjJ#;($GM=B,ITG=$J?6$kI
$,@8$8kG$"$m$& [KI92]!%$3$N?6$kIq$$$rM}2r9kNK!$%+%*%9$JINJ#;(7O$N2J3X$K4p$E$$
2r@ObI,MWHJk$H;W$olk [Tok94, =j 95]!%

6.2.4 %_%/%m$J0dEA;R%l%Y%k$G$N2r@O

K\8&5fGO!$<g$KE,1~EY$d3X=,FC@-$NJQ2=$NMM;R$JIH$$$C$?Hf3SE*%^%/%m$J%l%Y%kGN2
rbHK5DO@$r?J$aF-$?!%$3l^GKF@il$?CN8+$r3h$+$7$F!$<B:]$N%7%9%F%`$K1~MQ7
$/:]$K$O!$$5iK0dEA;R%l%Y%kGN%_%/%m$J2r@O$K4p$E$$$?5DO@$r2!$7?Jak3H$,=EMW$G$
$&!%FC$K!$6K$a$FF0E*FC@-$N6/$$4D6-K*$$$F!$%@!<%&%#%s7?$N=8CD$,I$Nh&K7$FM-1W$
Js$r;RB9$KEA$($F$$$kN+!$%@!<%&%#%s7?$"$k$$$O%i%^%k%/7?$N=8CD$N@w?'BN%W!<%kKOI
$&$J>pJs$,C_@Q$5lF$$$/N+JI$r!$%_%/%m$J%l%Y%k$G4Q;!9kI,MW,$"$k!%

Bh **7** >O

7kO@

K\8&5fGO!$F0E*$GM=B,ITG=$J?6$kIq$$$rDh9k3+J|7?J,;64D6-K*$$$F$O?J2=E*%(!<%8%
%H$N35G0$,=EMWKJkH$NN)>l$+$i!$3X=,$N8z2L$H0dEA5!9=$,%(!<%8%'%s%H=8CD$N?J2=$KM?$
1F6AKD$$$F!$Cj>]E*$J%b%G%k$rMQ$$$?%7%_%e%l!<%7%g%sKh$jI>2A$7$?!%

Hs@~7A@-$N6/$$4D6-GN1?MQ$rA[Dj$7$?CNE*%7%9%F%`$O!$EAE}E*$J%H%C%W%@%&%s$N%"%W%m!
$G9=C[$9k3HOFq$7$$!%K\8&5fGO!$<+A33&$N@8J*$N3X=,$d?J2=JI$N2aDx$KJiCF?M9
L?E*$J%\%H%`%"%C%W$N%"%W%m!<%A$G%7%9%F%`$,4D6-$KE,1~$7$F$$$/2aDx$K>GE@$rEvF?!%6qE
KO!$3X=,$9$k%(!<%8%'%s%H$r%K%e!<%i%k%M%C%H%o!<%/H7$FCj>]2=$7!$?J2=!&0dEA$N86M}$
>]2=7?0dEAE*%"%k%4%j%:%`$rMQ$$$F%(!<%8%'%s%H=8CD$r?J2=$5$;$k%7%_%e%l!<%7%g%s$r9T$
F@il$?7k2L$OBg$-$/0J2<NDLjG"$k!%

1. =>Mh$+$i$N$$$/D+$N8&5f$KhC$F3NG'$5lF$$$?%\!<%k%I%&%#%s8z2L$O!$Hs@~7A@-$r
   DFq7$$4D6-K*$$$FFC$K3X=,$,==J,KJ5l$J$$$H$-$K$O@8$8$J$$$3H,L@i+KJ
   $?!%$`7m5U$K8DBN$Khk3X=,$,=8CD$N?J2=$rK832$9kNcb4Q;!5l$?!%
2. @EE*$J4D6-$N2<GO!$%@!<%&%#%s7?$N0dEA5!9=$r;}$D%(!<%8%'%s%H=8CDhj$b%i%^%k%/
   $N5!9=$r;}$D=8CD$NJ}$,E,1~?J2=$NB.EY$,:G$bB.$/!$$+$D!$E,1~8e$N@.@S$bM%=(G"$C
3. F0E*$J4D6-$N2<GO!$5U$KB?MM@-$rJ]$C$?$^$^=y!9$KE,1~?J2=7F$$$/%@!<%&%#%s7?$N
   EA5!9=$r;}$D%(!<%8%'%s%H=8CD$NJ}$,%i%^%k%/7?$N5!9=$r;}$D=8CD$KHfYF!$4D6-$NJQ
   KBP7$F0BDj$7$?5sF0$r<($7!$4h7r@-$KM%$lk3H,3NG'5l$?!%
4. F0E*$J4D6-$N2<GO!$%@!<%&%#%s7?$N0dEA5!9=$r;}$D%(!<%8%'%s%H=8CD$O4h7r@-$KM%$l
   $$$k$@$1GJ$/!$=y!9$KJ?6QE*$JE,1~EY$r>e>:$5$;$F$$$/E,1~@-$r;}$C$F$$$k3H$,L@
   $+$KJC$?!%$7$+$b!$4D6-$,A4$/IT5,B'$KJQF0$9$kKb4Xoi$:!$@Ber=EMk4H$K
   1~EY$r>e>:$5$;$F$$$/$H$$$C$?6C$/Y-7k2L$rF@$?!%

K\O@J8GO!$<g$KF0E*@-<A$r;}$D4D6-$H;}$?$J$$4D6-N=l>lN2<K*$$$F!$%@!<%&%#%
$H%i%^%k%/7?$H$$$C$?Fs$D$N>pJs8r49$*hSEAC#$N7A<0$K>GE@rEvF!$$=li$NFC@-$NHf3SI
$r9T$C$?!%:GBg$N9W8%$O!$$3l^GFCK0Y5lF3J+C?F0E*$J4D6-2<$G$N%@!<%&%#%s7?$
%^%k%/7?$N0dEA5!9=$NHf3SI>2A$r9T$C$F!$$=$NFC@-$rL@i+K7$?$3HG$"$k!%

:#8e$N7W;;5!$N$_$Ji:!$<B@$3&NI$N%l%Y%k$N7O$b!$F0E*$J3+J|7?J,;64D6-$H7F$NMMA
Dh9k!%7?$,$C$F!$K\8&5fKhCFF@il$?CN8+$O!$:#8e$N3+J|7?J,;64D6-K*1khj9
$NCNE*LdBj2r7h%7%9%F%`$N9=C[K!$d1?MQK!$K$D$$$F9MN8$9$k:]JI$K!$2?i+$NM-1W$J<(:6$
$($kbNG"$k!%

<U<-

K\8&5f$O!$B?$/$NJ}!9$N@K$7$_$J$$1g=u$*$h$S7cNe$NbH$K@.$jN)CF$$$k!%

$^$:O8aK!$F|:"$+$i:)@Z$J;XF3$rD:$-!$K\8&5f$N@Z$C3]$1JiSK8&5f$N5!2q$rM?$($
5C$?7DXf5A=NBg3XM}9)3XItEE5$9)3X2J65<x =j??M}M: Gn;N$K:GBg$N46<U$N0U$rI=$9!%

<!$K!$K\8&5f<<F~<<Ev=i$+$iKDBgJk;dE*$J;~4V$r3d$$$F$^$G=i4|$N8&5f$K4X7F:)@ZCzG
;XF3$rD:$-!$3XLdC55f$N3Z7_!$8&5f$KBP9k;Q@*JIB?$/$r$465<($7$F2<$5C?K\8&5f<<E
@8 @iB<J8I' Gn;N$K?4$+$i46<U$9$k!%

$^$?!$K\8&5f$r9T$&$K$"$?$j!$>oF|:"$+$iM-0U5A$J8f<(:6$JiS$KK\O@J8$N::FIJI;~4V$
o:BgJQK*@OCKJC$?K\8&5f<<Gn;N2]Dx >>NS7D;a$K?<$/46<U9k!%5i$K!$EY=EJk3
JFO@rDL8$F5.=E$J=u8@r7$FD:$$$?K\8&5f<<Gn;N2]Dx FbF#9d?M;a!$=$;N2]Dx 1 G/ CfN$=
;a!$K\8&5f<<3X2J 4 G/ CSC+D>5*;a!$F1$8$/3X2J 4 G/ 7,@^N4G7;a$K46<U9k!%$=$7$F!$K\8&5f
F~<<;~0JMh!$8x;d$KEOCF6l3Z$r6&$K7F$-$?K\8&5f<<=$;N2]Dx 2 G/@8 Fb3$=(2p;a!$LZA>N4
;XLnFF;J;a!$Hu8}BY2p;a!$J!ED7r2p;arO8a!$K\8&5f<<$G$N@83h$r<Bj"kbNH7F2<$
$?K\8&5f<<$N=t;a$K?4$+$i46<U$9$k!%

:G8e$K!$@d$($6$k2fPV$rJ9$$$F2<5j!$$^$?3X6H$KM}2r$r<($7$FD:$$$?N>?F!$2HB2$K46<U$9

J?@. 8 G/ 2 7n

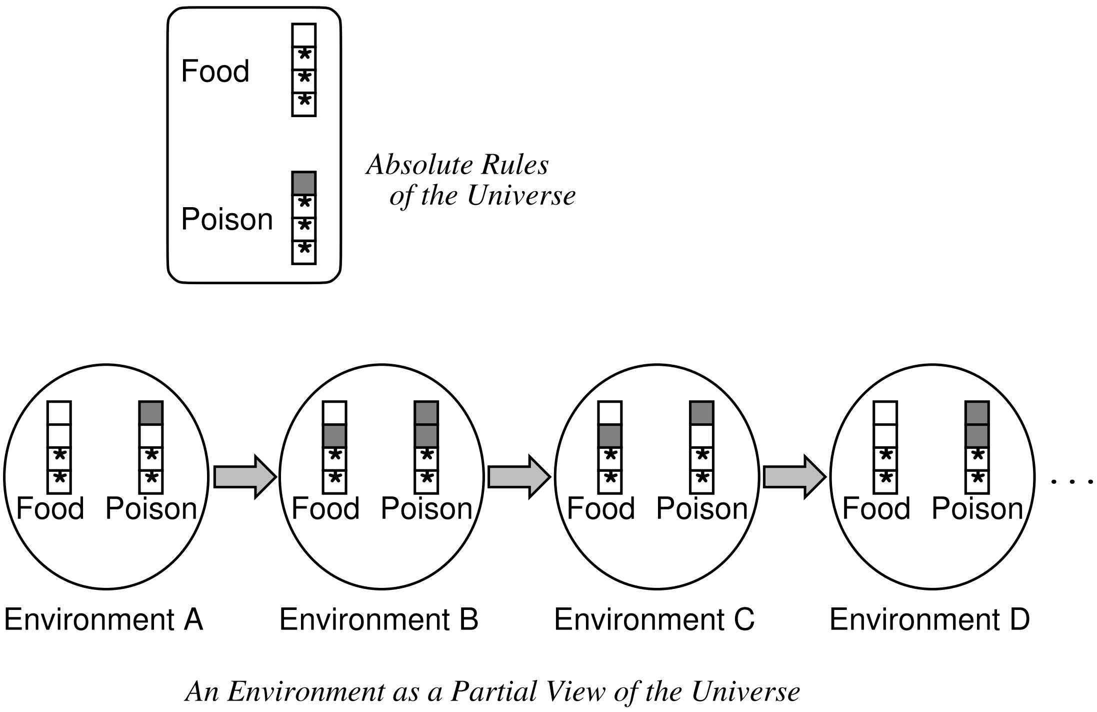
Appendix

`$=$NB>$N<B83$N7k2L`

$3$3GO!$K\J8$G$O?($lJ+C?<B837k2L$r7G:\$9$k!%

A.1 <B83 A-1

5.3.1 @a$N<B83 3 GO!$%(!<%8%'%s%H$N3MF@G-$k>pJs$,ItJ,E*G"$k>u67$rA[Dj7?<B83$ 9TC?!%H3mG!$<B83 3 K*$$$F$OIaJWE*$J5,B'$,Hs@~7AE*$G$"$kh&JbNr07C?$,! 3G$O!$$=$NIaJWE*$J5,B'$,@~7AJ,N%2DG=$G$"$k>l9gKD$$$F9TC?<B837k2L$N0lIt$r<($9! A.1 Nh$&$K!$4D6-$KB8:_9kJ*<A$,JQ2=9k>u67$r9M$($k!%?^ A.3!$?^ A.4 $O!$$=l>$l 2 @$BeKh!$100 @$BeKh$K4D6-$rJQ2=5;$?$H$-$N7k2L$r<($9!%J*!$?^$O%(!<%8%'%s%H$N0l@8$r 3X=,%9%F%C%WH7$?$H$-$N7k2L$r<($7$F$$$k!%



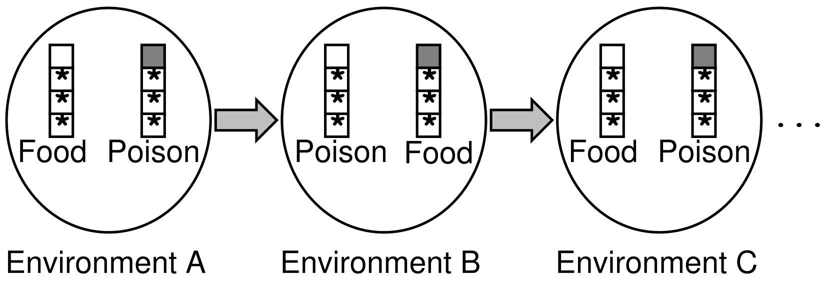
?^ A.1: 4D6- A-1

A.2 <B83 A-2

5.3.2 @a$N<B83 4 GO!$IaJWE*$J5,B'$,H?E>$9kh$&$J4D6-$rA[Dj7?<B83$r9TC?!%H3$ $G!$<B83 4 K*$$$FO=$N5,B'$,Hs@~7AE*G"kh$&$JbN$r07$C$?$,!$$3$3$G$O!$$=$N5,B @~7AJ,N%2DG=$G$"$k>l9gKD$$$F9TC?<B837k2L$N0lIt$r<($9!%?^ A.2 Nh$&$K!$?)NHG"$k FGJ*G"k+$r<1JL9k5,B'$,;~BeHHbKH?E>9kbNH9$k!%?^ A.5!$?^ A.6 $O!$$=l

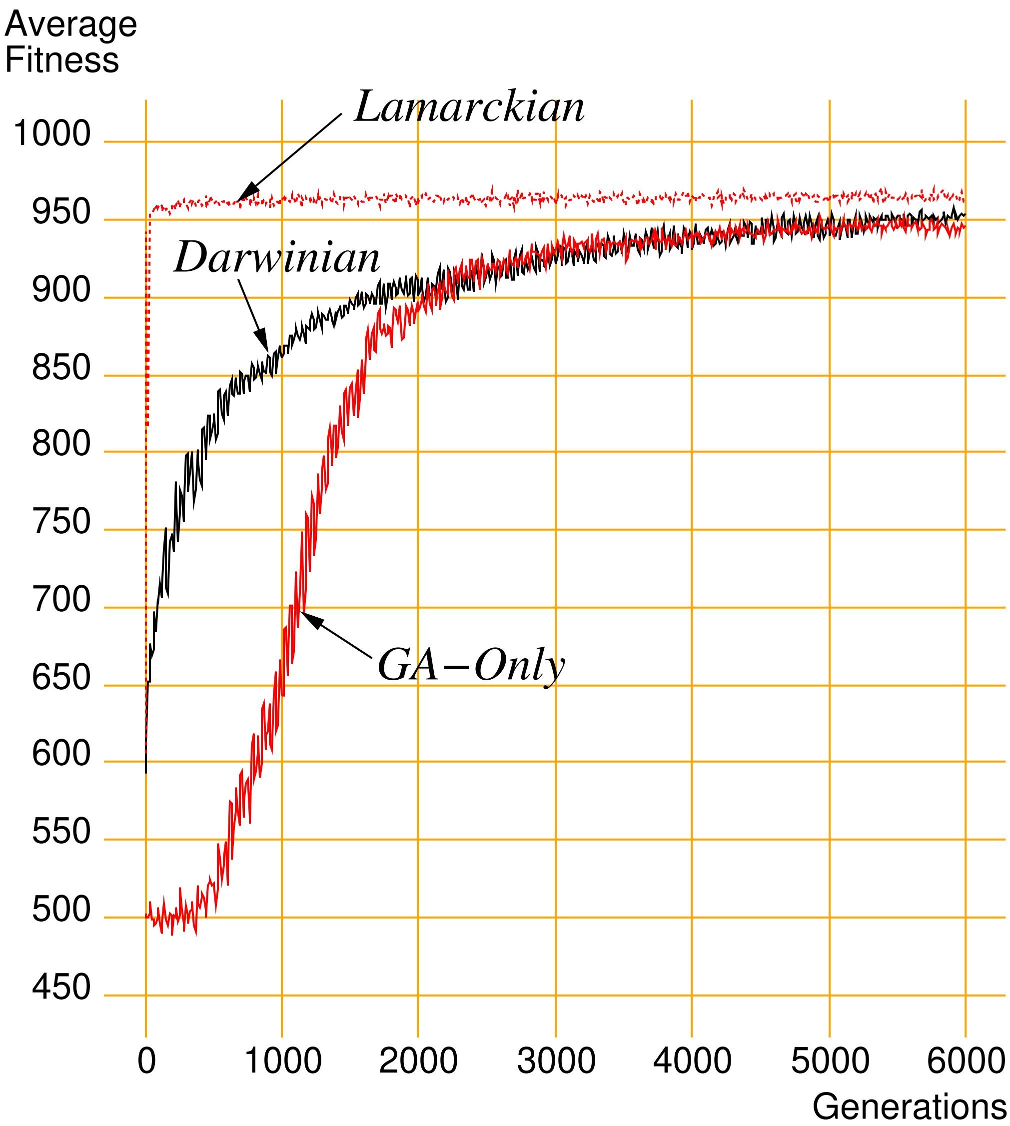
$l 50 @$BeKh!$200 @$BeKh$K4D6-$rJQ2=5;$?$H$-$N7k2L$r<($9!%J*!$?^$O%(!<%8%'%s%H$N

@8$r 100 3X=,%9%F%C%W$H7?H-$N7k2L$r<(7F$$$k!%

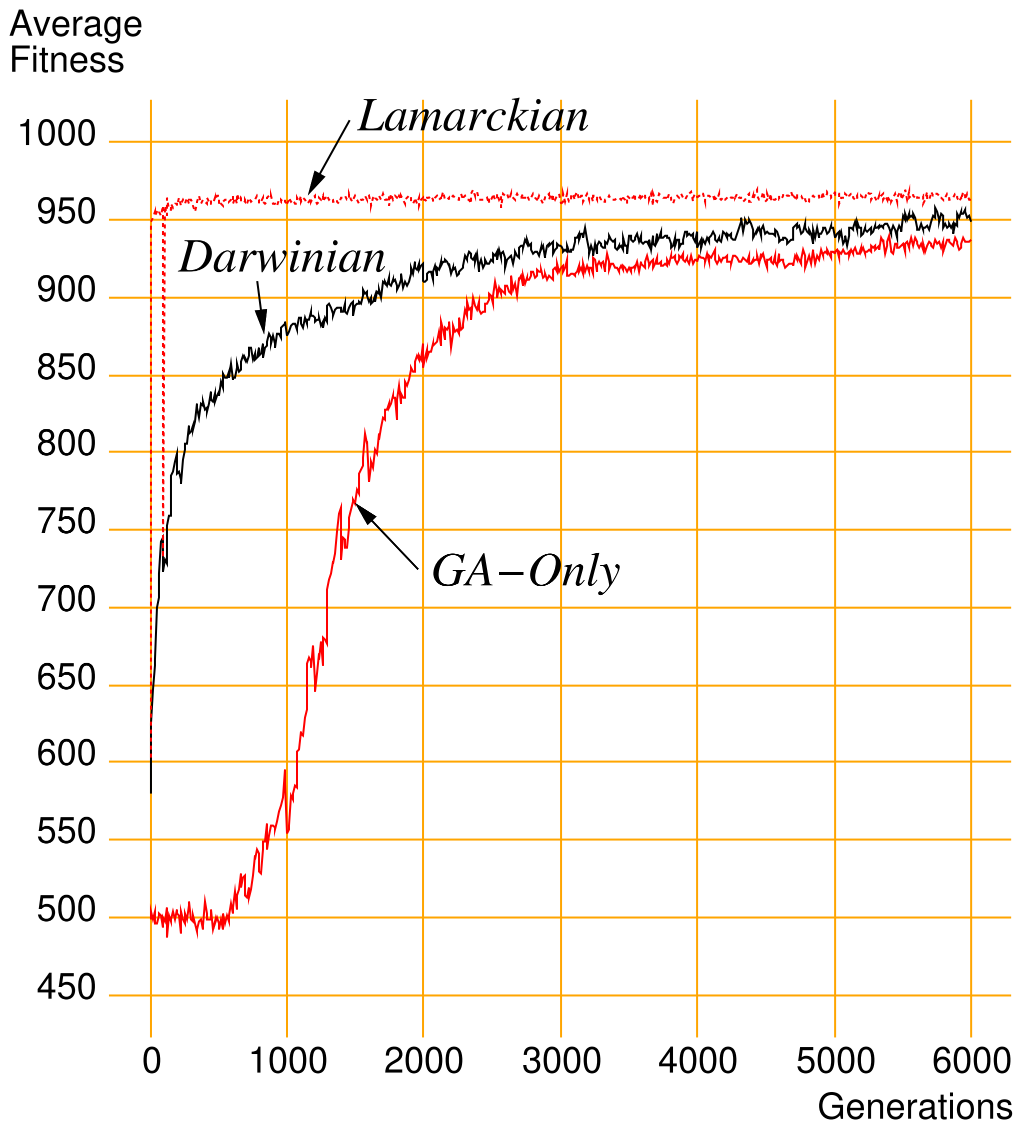


Dynamic Change of the Rules of Universe

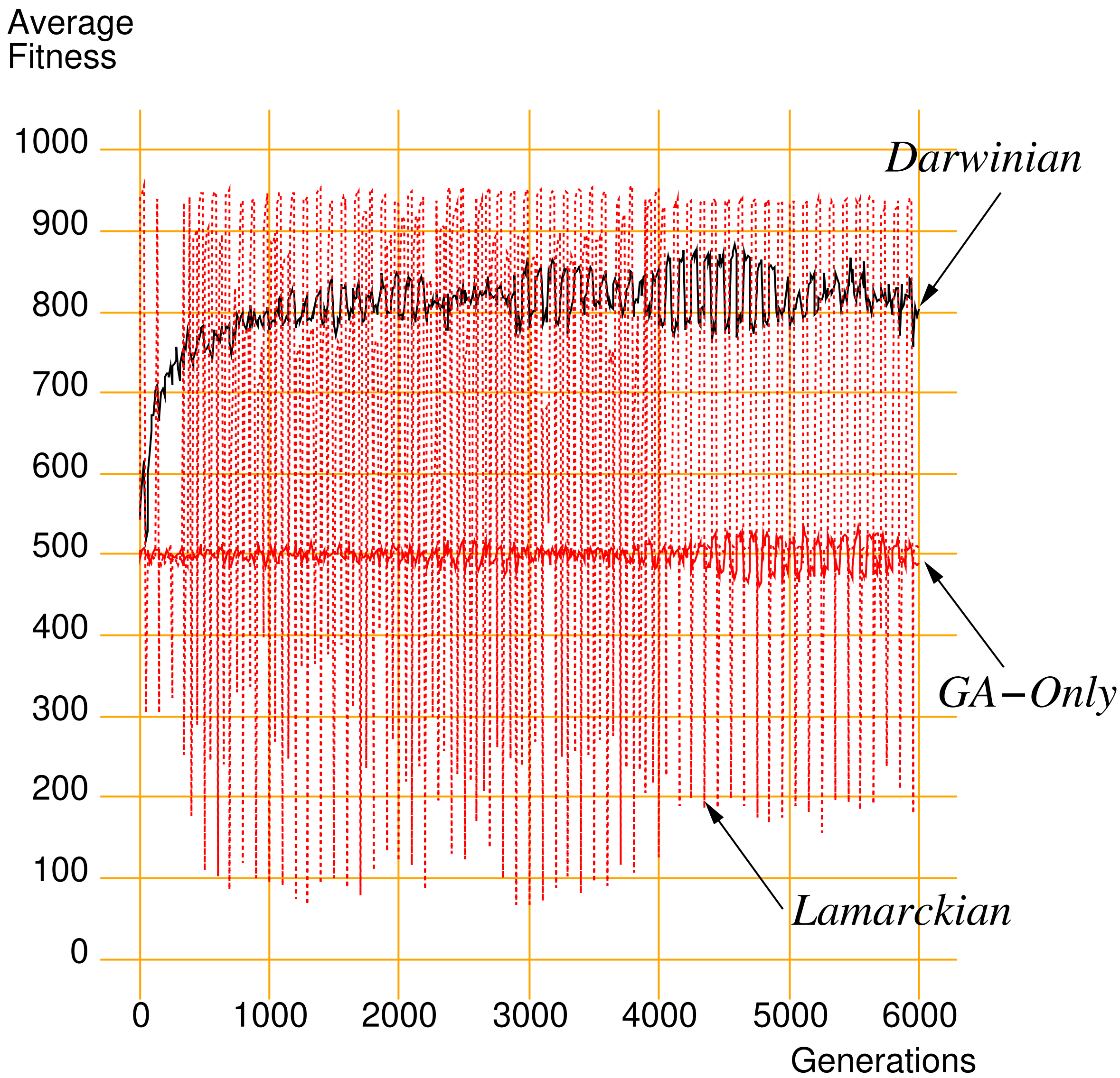
?^ A.2: 4D6- A-2



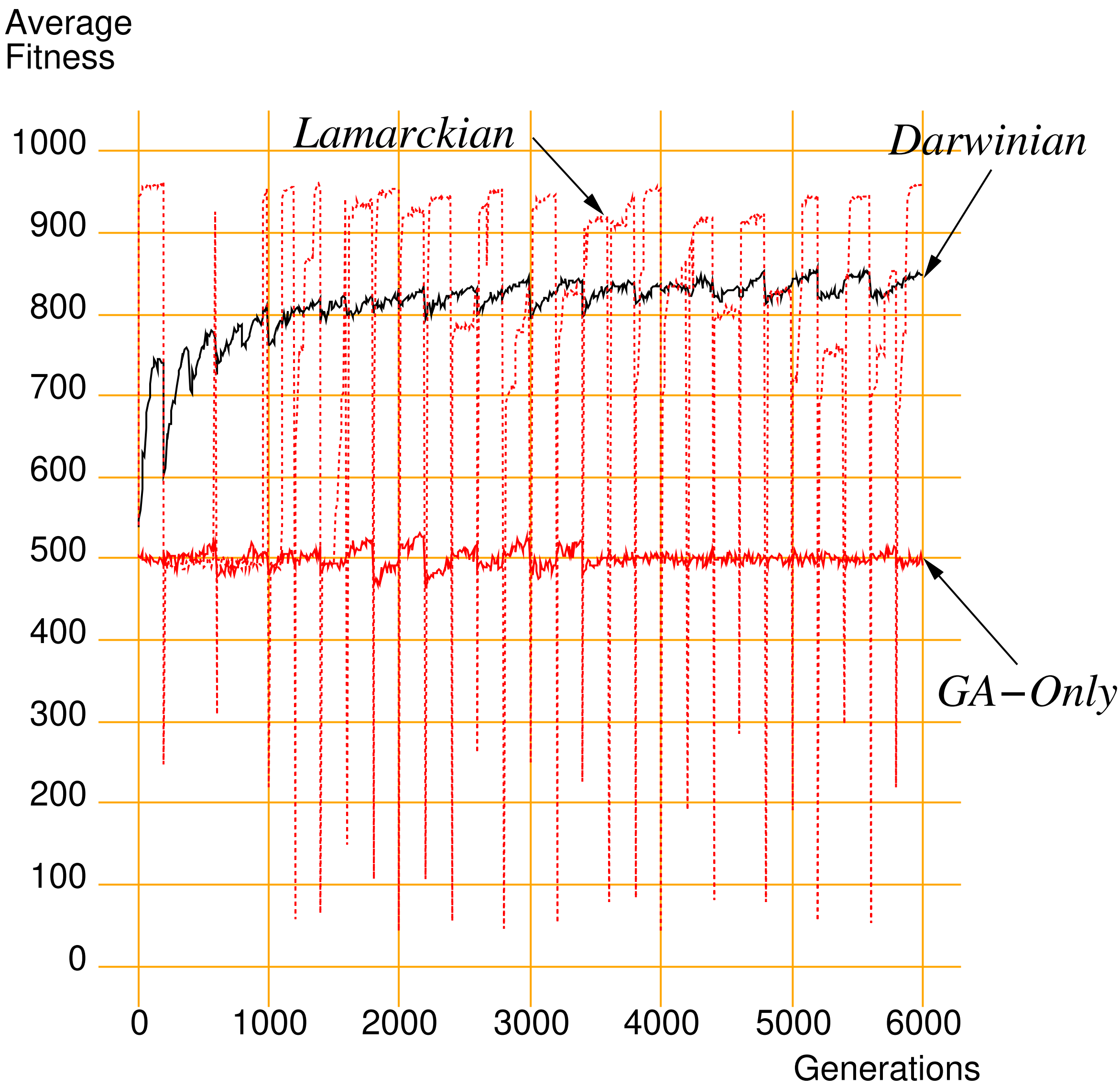
?^ A.3: [4D6- A-1] J?6QE,1~EY (01@8 = 100 3X=,%9%F%C%W!$4D6-$NJQF0 = 20 @$BeKh)



?^ A.4: [4D6- A-1] J?6QE,1~EY (01@8 = 100 3X=,%9%F%C%W!$4D6-$NJQF0 = 100 @$BeKh)



?^ A.5: [4D6- A-2] J?6QE,1~EY (01@8 = 100 3X=,%9%F%C%W!$4D6-$NJQF0 = 50 @$BeKh)



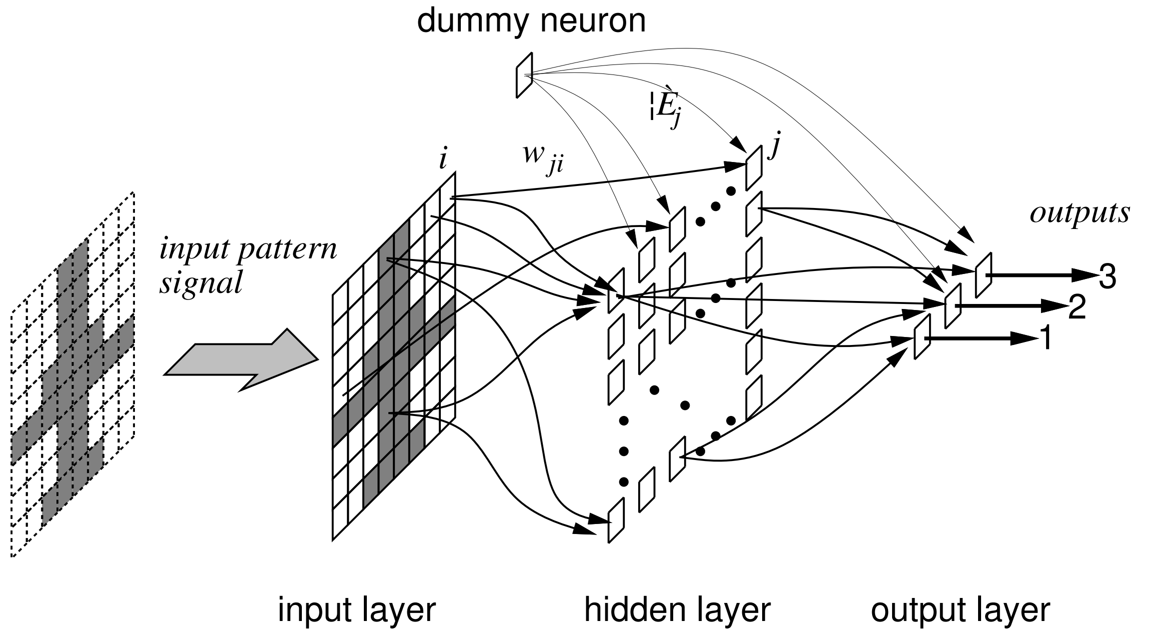
?^ A.6: [4D6- A-2] J?6QE,1~EY (01@8 = 100 3X=,%9%F%C%W!$4D6-$NJQF0 = 200 @$BeKh)

Appendix

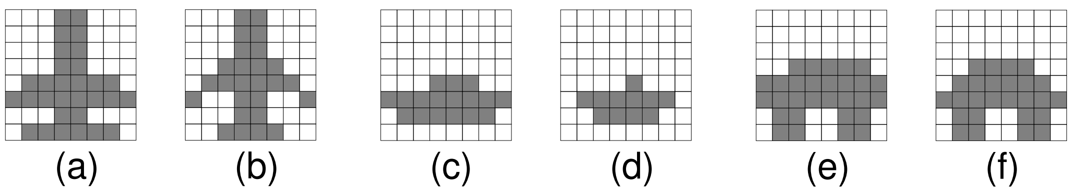
8m:95UEAHB3X=,K!Kh$k%Q%?!<%sG’<1

$3$3GO!$8m:95UEAHB3X=,K! (BP K!) $N0l$D$N1~MQNc$H7F%Q%?!<%sG'<1LdBj$r07$$!$$=$l
$D$$$F9TC?<B837k2L$r<($9!%

?^ B.1 $K<($9h&$J!$F~NOAX 64 %K%e!<%m%s!$1#$lAX 32 %K%e!<%m%s!$ =PNOAX 3 %K%e!<%m%s
$N;0AX$+iJ$k3,AX7?%U%#!<%I%U%)%o!<%I7?%K%e!<%i%k%M%C%H%o!<%/$K!$?^ B.2 $N 8 × 8 $N%S
%H%Q%?!<%s$GM?$(il$k 6 <oN'$N71N}MQ%Q%?!<%s$rM?$($k!%?^ B.2 K*$$$F!$(a)!$(b) $O!VHt9
5!!W!$(c)!$(d) $O!VA%!W!$(e)!$(f) $O!V<V!W$rI=9bNH9k!%3NH-!$M?$(il$?F~NO%Q%?
%s$,!VHt9T5!!W$+!VA%!W$+!V<V!W$+$r<1JL$7!$$=lK1~8F=PNO%K%e!<%m%s 1!$=PNO%K%e!<%
2!$=PNO%K%e!<%m%s 3 $,$=l>$lH?1~$9kh$&$J%K%e!<%i%k%M%C%H$rF@$?$$$$bNH9k!%



?^ B.1: 3 AX%U%#!<%I%U%)%o!<%I$N%K%e!<%i%k%M%C%H



?^ B.2: 71N}%Q%?!<%s

2.3.3 @a$G@bL@$7$? BP K!$K=>CF!$?^ B.2$G<(7?F~NO%G!<%?$r (a) $+$i (e) $K0lDj$N=g=x$G
7+jJV7Dh<(7?H-$N=PNO%K%e!<%m%s 1!$2!$3 $N=PNOCM$NJQ2=$NMM;R$r?^ B.3$+$i?^ B.5$K<

$9!%$J$*!$(2.7) <0K*$$$F!$η = 0.75!$α = 0.8 H7$?!%

90 2s$N3X=,8e$K3F=PNO%f%K%C%H$N=PNOCM$O$[$\01Dj$K<}B+$7 ‼$VHt9T5!!W((a)!$(b)) ‼$VA%!W((c

(d)) ‼$V<V!W((e)!$(f)) $,M?$(i1$?$H$-$K=PNO%K%e!<%m%s 1!$2!$3 $,$=1>$1:GBgH?1~$7!$E,@

$K%Q%?!<%s<1JL$,=PMhkh$&$J%K%e!<%i%k%M%C%H%o!<%/$,3X=,$KhC$F9=C[$5$1$F$$$k3H$

G'$5$1$k!%

?^ B.3 KhkH!$3X=,2s?t$, 40!A50 2s$N6aJU$G ‼$VHt9T5!!W$rM?$($?H-$K2C$($F!V<V!W$rM

$($?H-$N=PNO%K%e!<%m%s 1 $N=PNOCM$,01;~E*$K>e>:$7$F$$$k!%$3$1$O!$71N}%Q%?!<%sH7$

$($?!VHt9T5!!W$H!V<V!W$H$,N`;w$7$F$$$k$?$a$H;W$o1k!%?^ B.4 KhkH ‼$VA%!W$OB>$NF

N`$N%S%C%H%Q%?!<%s$H$NN`;wEY$,Dc$$$?a+!$=PNO%K%e!<%m%s 2 $O3X=,$N=i4|$NCJ3, (3X=,2

$, 20!A30 2s) $G4{$K!VA%!WH=$NB>$N%S%C%H%Q%?!<%sHr<1JLG-$F$$$k3H$,J,$+$k!%5U

?^ B.5KhkH ‼$V<V!W$r<1JLG-kh$&$KJkNO:G$bCY$$$H$$$&3H$,J,$+$k!%$7$+$b!$M

=PNOCMXN<}B+$NEY9g$b:G$b0-$$!%

<!$K!$3X=,8e$N%K%e!<%i%k%M%C%H$K?^ B.6 $K<($9h&$J%F%9%H%Q%?!<%s$rF~NO7F$_$?7k

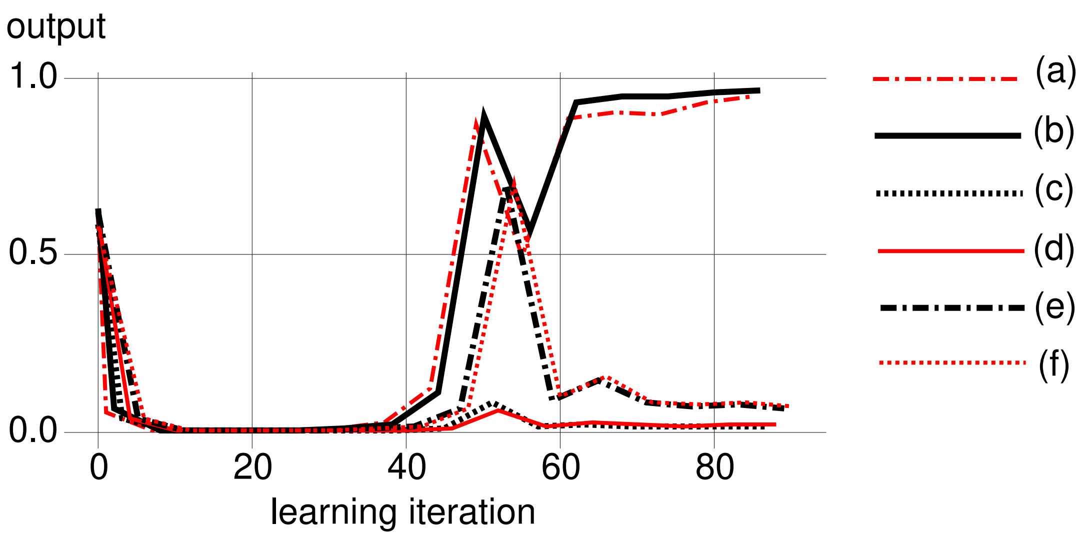
$rI= B.1 $K<($9!%J*!$I= B.1 $O?^ B.2 $N7k2L$bF1;~$K<($7$F$$$k!%I= B.1 $N7k2L$h$j!$(g),

(h) $O!VHt9T5!!W$H7F!$(i), (j) $O!VA%!W$H7F!$(k), (l) $O!V<V!W$H7FBEEv$K<1JL$5$1$F$$$k

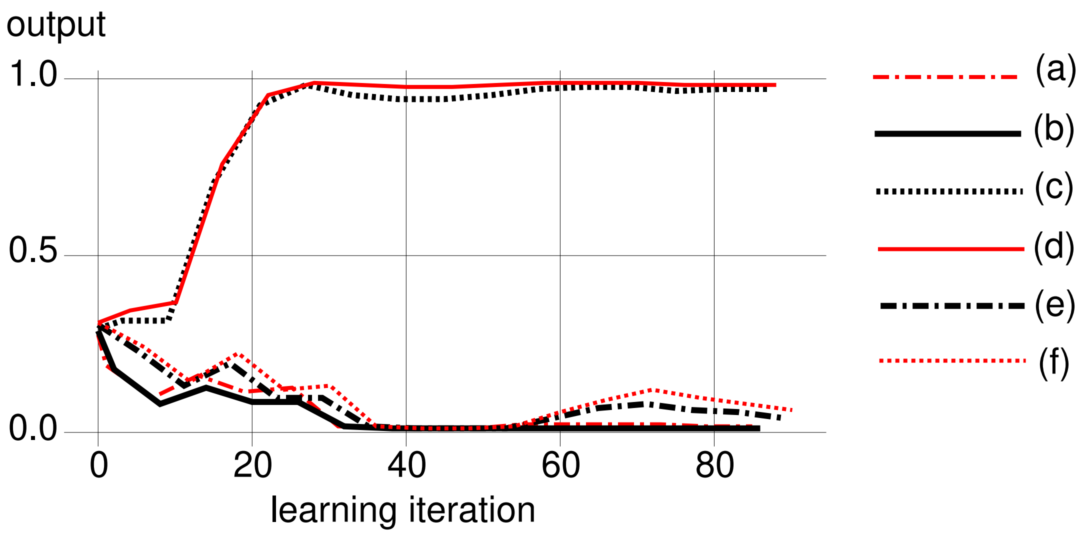
3H$,J,$+$k!%$^$?!$(m) $O!VHt9T5!!W$H7F$NFCD'$H!V<V!WH7FNFCD'$NN>J}$rHw$($F$

$?$a ‼$VHt9T5!!W$r8!CN9k=PNO%K%e!<%m%s 1 $H!V<V!W$r8!CN9k=PNO%K%e!<%m%s 3 $,$Ag

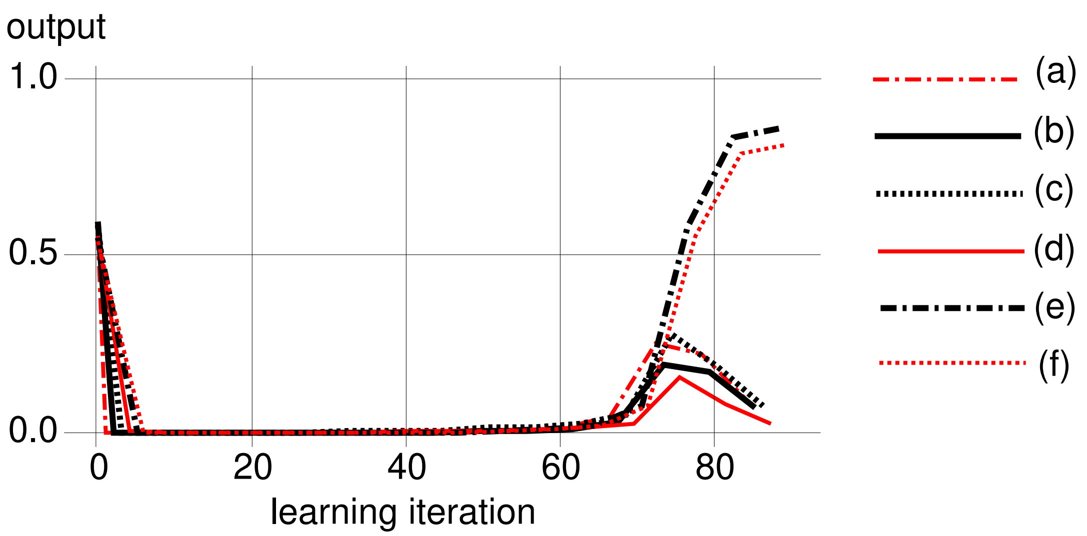
F1DxEY$KH?1~$7$F$$$k3H$,3NG'$5$1$k!%



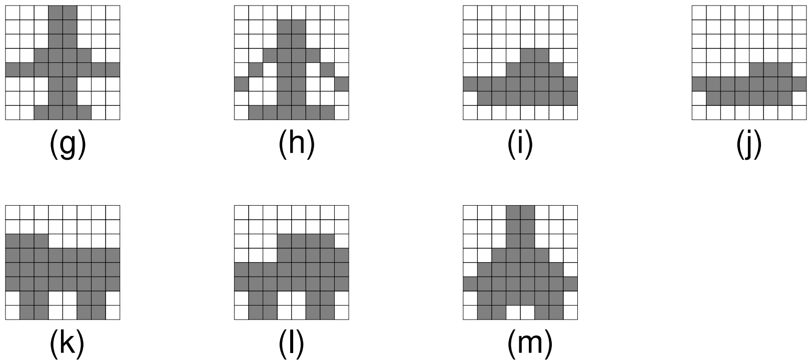
?^ B.3: =PNO%K%e!<%m%s 1 $N=PNOCM



?^ B.4: =PNO%K%e!<%m%s 2 $N=PNOCM



?^ B.5: =PNO%K%e!<%m%s 3 $N=PNOCM



?^ B.6: %F%9%H%Q%?!<%s

pattern	output neuron 1	output neuron 2	output neuron 3
(a)	0.949	0.014	0.092
(b)	0.968	0.008	0.074
(c)	0.014	0.974	0.080
(d)	0.018	0.985	0.030
(e)	0.063	0.042	0.866
(f)	0.073	0.061	0.819
(g)	0.961	0.008	0.080
(h)	0.949	0.006	0.115
(i)	0.023	0.894	0.184
(j)	0.016	0.965	0.087
(k)	0.078	0.040	0.853
(l)	0.109	0.036	0.811
(m)	0.490	0.052	0.550

I= B.1: %F%9%H%Q%?!<%sF~NO7k2L

;2 9M J8 8%

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