B?CJ7k9gLV$K4p$E$/JBNs7W;;5!$N$?$a$N %-%c%C%7%e@)8f5!9=$N<BAu

550f5.G7 H9 IRGn @>B<9n?. E7Ln1Q@2

7DXf5A=NBg3XM}9)3XIt

B?CJ7k9gLV (MIN:Multistage Interconnetion Network) $O!">.5,LO$J%9%$%C%A%s%0%(%l%a%s%H$r B?CJ@\B3$7$?7k9gLV$G!"Hf3SE*>/NL$N%O!<%I%&%'%"$GBg5,LO$J%7%9%F%`$r<B8=$G$-$k$,!"%-%c%C%7%e $N0lCW@)8f$,Fq$7$$$H$$$&LdBj$,$"$k!#0lJ}!"%-%c%C%7%e@)8f5!9=$r8zN(NI$/<BAuG-$kB?CJ7k9gLV MINC(MIN with Cache coherent mechanism) $,Ds0F$5$l!"%7%_%e%l!<%7%g%s$KhkI>2AKh$j!"9b $$@-G=$rF@$ilk3H$,<($5lF$$$k$,!"%G!<%?E>Aw$H%-%c%C%7%e@)8f$,0lBN2=$7$F$$$k$?$a!"8zN NI$/<BAu$9k3H,G-$J$$!#$=$3$GK\O@J8$G$O!"%-%c%C%7%e@)8f$N$_$r9TJ&%A%C%W$rDs0F$7!"$= $N<BAu$K$D$$$F=RYk!#3N%A%C%WGO MINC $K4p$E$$$?%-%c%C%7%e@)8f$r9T$J$&$,!"%G!<%?E>Aw$K OJLN%A%C%W$rMQ$$$k3H$,$G$-$k!#

Aj8_7k9gLV, VLSI <BAu, %3%R!<%l%s%H%-%c%C%7%e, JBNs7W;;5!

An implementation of cache control mechanism for MIN based multiprocessors

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Multistage Interconnection Network(MIN) has been used for connecting processors and memory modules in a large scale multiprocessor. While multiple memory modules can be accessed simultaneously with a reasonable amount of hardware in such a machine, coherent cache is difficult to be implemented. Although MINC(MIN with Cache coherent mechanism) is proposed for coherent cache with a small amount of hardware, an implementation is still difficult work, because a data and a cache control are transferred with the same network. Here, we propose a dedicated chip architecture for cache control. While cache control mechanism is based on MINC, the method for various types of switch can be used for data transfer.

Multistage Interconnection Network, VLSI implementation, coherent cache, multiprocessor

1 O8aK

%9%$%C%A7k9g7?%^%k%A%W%m%;%C%5$O!"%W%m%;%C%5$H%a%b
%j4V$rBg5,LO$J%/%m%9%P$^$?$OB?CJ7k9gLV (Multistage Interconnection Network: MIN) Kh$j@\B3$9kJ}<0$G
$"$k!#3NJ}<0$O!"F1;~$KJ#?t$N%W%m%;%C%5$,$=$l$>$l
O[JC$?%a%b%j%b%8%e!<%k$r%"%/%;%9$9$k3H$,$G$-!"
%P%97k9g7?KHfY$FB?$/$N%W%m%;%C%5$r7k9g9k3H$
G-$k!#6aG/$NMWAG%W%m%;%C%5$N@-G=8~>e$N7k2L!"%P%9
$G7k9g2DG=$J%W%m%;%C%5?t$O 4 DxEY$K@)8B5lk3H+
$i!"%9%$%C%A7k9g7?%^%k%A%W%m%;%C%5$O>-Mh$NCf5,LO!"
Bg5,LO$JHFMQ%^%k%A%W%m%;%C%5%7%9%F%`H7$F9-$/MxMQ
5l$k2DG=@-$r;}CF$$$k!#

7+$7!"%9%$%C%A7k9g7?%^%k%A%W%m%;%C%5$O!"FC$K5,
LO$,Bg$-$/$JkH!"6&M-%a%b%j$N%"%/%;%9;~4V$,Bg$-$/
Jj!"@-G=Dc2<$N860x$HJk!#$3$3$G!"<g5-21$KBP9k
%W%i%$%Y!<%H%-%c%C%7%e$r%W%m%;%C%5-%9%$%C%A4V$K@_$1
k3H,G-lP%"%/%;%9;~4V$NDc8:$KBg$-$J8z2L$,4|
BT5l$k!#$H3m$,!"%W%m%;%C%5-%9%$%C%A4V$K%-%c%C
%7%e$r@_$1$k>l9g!"$=$N0lCW@)8f$,LdBjHJ$k!#

%9%$%C%A7k9g7?%^%k%A%W%m%;%C%5GOF1;~$KJ#?t$N%W
%m%;%C%5$,6&M-%a%b%j$r%"%/%;%9$9$k$?$a!"6&M-%P%9$K
$*$1$k%9%L!<%W5!9=$rMQ$$$k3H$,$G$-$J$$!#$=$3$G!"
CC(Cache Coherent)–NUMA $GMQ$$$ilF$$$k%G%#%l
%/%H%jJ}<0$rMQ$$$kI,MW$,$"k,!"C1=c$K%G%#%l%/%H%j
$r6&M-%a%b%j$KCV$/J}<0$G$O!"%G%#%l%/%H%j$"%/%;%9$K
MW9k;~4VKh$k@-G=$NDc2<$,Bg$-$$!#

MIN $rMxMQ$7$?%9%$%C%A7k9g7?%^%k%A%W%m%;%C%5$K
$*$$$F$O!":G6a$N LSI =8@QEY$N8~>e$rMxMQ$7!"%9%$%C
%A%s%0%(%l%a%s%H$K9b$$5!G=$rM?$($F%G%#%l%/%H%jJ}<0
$N7gE@$rJd$&J}K!$NDs0F$,9T$Jol$F$$$k!#3liNJ}
K!GO!"%9%$%C%A%s%0%(%l%a%s%HFbIt$K%-%c%C%7%e$rAH
$_9~$s$@$j!"%G%#%l%/%H%jrAH_9~$`$3HKhj%-%c%C
%7%e@)8f$N8zN(2=$H%"%/%;%9%l%$%F%s%7%#$NDc8:$r?^$C
$F$$$k [4][5]!#7+$7!"=>Mh$NJ}K!GO%9%$%C%A%s%0%(
%l%a%s%HCf$K%-%c%C%7%eK\BN$d%G%#%l%/%H%jrAH_9~$s
$@$?$a!"A4BN$N5-21NL$,KDBg$HJk!#$^$?!"%(%l%a%s
%HKh$K30It%a%b%j$r%"%/%;%9$7$J1lPJiJ$$$?$a!"
%*!<%P%X%C%I$NE@$G$bITMx$G$"$k!#

3liNLdBjE@$r2r7h$9k?aK, MINC(MIN with Cache coherent mechanism) $,Ds0F$5l? [6]!#MINC
$OD6JBNs%^%7%s JUMP-1[2] MQ$K3+H/$5l?3,AX%G%#%l
%/%H%j=LLsJ}<0 [7][3] $r MIN $KF3F~$7!"5i$K MIN $N
@-<A$rMxMQ$7$F!"=LLsJ}<0$NLdBjE@G"$kL5BL%Q%1%C%H
$r8:$i9?aN;^4"$j%P%C%U%!$rbD!# 3,AX%G%#%l%/
%H%j=LLsJ}<0$H;^4"$j%P%C%U%!$NAH9g$;Kh$j!"$=l>
lN%9%$%C%A%s%0%(%l%a%s%H$O30It%a%b%j$r%"%/%;%9$9
kI,MWOJ/!"%Q%1%C%H$N%X%C%@$H;^4"$j%P%C%U%!$NFb
MF$K=>$C$?%^%k%A%-%c%9%H5!G=$N$_$G!"9bB.$+$D8zN($N
NI$$%-%c%C%7%e@)8f$,2DG=$HJk!#

7+$7!"Ds0F$5l? MINC $O!"C1=c$@$,9bB.F0:n$,
I,MW$J%G!<%?E>AwMQ MIN $HJ#;($JF0:n$r9T$J$&%-%c%C
%7%e@)8f5!9=$,0lBN2=$7$F$$$k$?$a!"8zN($NNI$$<BAu
$,:$FqG"C?!#$=$3$G!"K\O@J8$G$O!"%G!<%?E>AwMQ%9
%$%C%A$HFHN)7?%-%c%C%7%e@)8fMQ%A%C%W$rDs0F$7!"$=
$N<BAu$K4X7FJs9p9k!#3N%A%C%W$O MINC $N9M$(
J}$K4p$E$$$F%-%c%C%7%e@)8f$r9T$J$&$,!"0lDj$N>r7o$r
K~B-9kMM!9$J%G!<%?E>AwMQ%9%$%C%AHAH_9go;$FMQ
$$$k3H$,2DG=$G$"$k!#

2 MINC(MIN with Cache control mechanism)

$^$:!"K\O@J8$GDs0F$9$k%-%c%C%7%e@)8fMQ%A%C%W$N4p
K\$HJk MINC $r>R2p$9$k!#

2.1 MINC $N4pK\9=@.

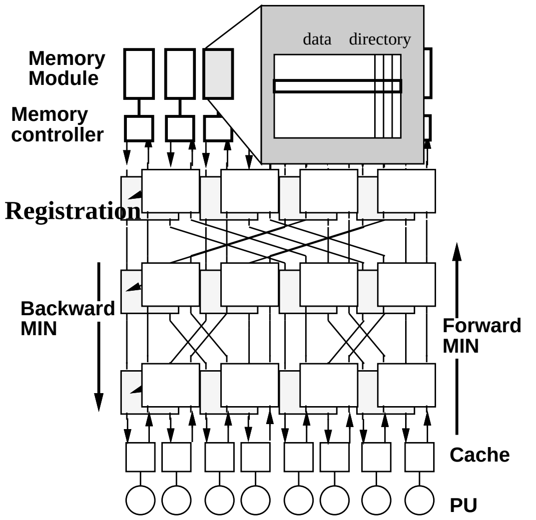
MINC $ODL>o$N%^%k%A%W%m%;%C%5K*1k MIN $HF1
MM!"?^1$K<($9h&$K!"%W%m%;%C%5$+$i%a%b%j$KBP$7
$F%Q%1%C%H$rAw$k Forward MIN $H!" %a%b%j$+$i%W%m
%;%C%5$K%Q%1%C%H$rAw$k Backward MIN $KJ,$+lF$$
$k!#$=$MhDs0F$5l?%-%c%C%7%e@)8f5!G=IU$- MIN HN
Aj0c$O0J2<$NE@G"$k!#

- 3,AX%S%C%H%^%C%W$O3F%9%$%C%A%s%0%(%l%a%s%H$K
CV$+$:!" 6&M-%a%b%j$K=LLs$5l?%S%C%H%^%C%W$N
7AGCV/!# L58z2=$d99?7%G!<%?$NJ|Aw;~KO!"$3
$N%S%C%H%^%C%W$r%Q%1%C%H$N%X%C%@$K3JG<$7!"$3$l
=>CF Backward MIN >e$G%^%k%A%-%c%9%H$9$k!#
- Backward MIN >e$K;^4"$j%P%C%U%!$r@_$1!"%-%c%C
%7%e%i%$%s$N%m!<%I;~$KEPO?$7!"%S%C%H%^%C%W$r
=LLs9k3HKh$jH/@8$9$kL5BL%Q%1%C%H$rKI$0!#

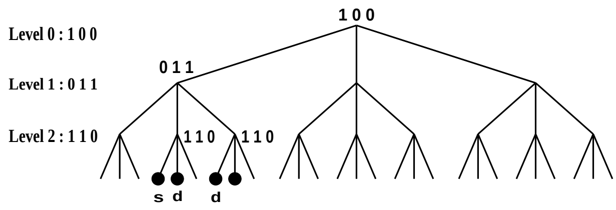
Forward MIN!" Backward MIN $N%H%]%m%8$K$D$$$F
OFCK@)8B$,$J$$$,!" MINC GO%W%m%;%C%5$N0LCV$K
hk6I=j@-$rMxMQ$G$-$kh&$K!" Baseline LV$rA[Dj$7
$F$$$k!#$^$?!" ?^ 1GO 2×2 $N%9%$%C%A%s%0%(%l%a%s
%H$r<($9$,!"<B:]$O LSI %A%C%WGN<BAu$r9M$(!"8×8
DxEY$N%5%$%:KJ$k!#

2.2 RHBD J}<0

3,AX%S%C%H%^%C%WJ}<0$O!" %W%m%;%C%5?t$,B?$/$J$k
$H%G%#%l%/%H%j$KI,MW$J%a%b%jNL$,KDBgKJ$j!" <B8=



?^ 1: %-%c%C%7%e@)8fIU$- MIN $N9=@.



?^ 2: %G%#%l%/%H%j=LLsJ}<0

$,:$FqKJ$k!# $^$?!"%G%#%l%/%H%jO+JjBgMFNLKJk3H,M=A[5lkN$G!" %9%$%C%A%s%0%(%l%a%s%H$r9=@.$9$k%A%C%W$N30It$K@_$1kI,MW,$"$k!# 3N>l9g!"3,AXKh$K%G%#%l%/%H%j$r;2>H9kKO!"Bg$-$J;~4VrMW9$k!# $=$3$G%S%C%H?t$r=LLs9k RHBD(Reduced Hierarchical Bit-map Directory) J}<0$rF3F~$9$k!# 3NJ}K!$OD6JBNs%^%7%s JUMP-1 $N%G%#%l%/%H%j@)8fMQ$K9M0F5l$?J}<0 [7] [3] G"$j!"

- $"$k@a0J2<$O%V%m!<%I%-%c%9%H$H9k!#
- J#?t$N@a$GF10l$N%S%C%H%^%C%W$rMQ$$$k!%

$N$$$:l+!$$b7/$ON>J}$NAH$_9g$o$;$KhC$F!$3,AXKh$K n bit(n ?JLZ$G) $N%S%C%H%^%C%W$r0lD@$1;}$D3HH9$k!#>e5- 2 DNJ}K!$NAH9g$;Kh$j 3 DN%G%#%l%/%H%j=LLsJ}<0$,Ds0F$5lF$$$k [3] $,!" 8!F$$N7k2L!">.5,LO$J%7%9%F%`$G$O SM K!$,M-MxG"k3H,o+CF$$$k!#3NJ}K!GO!"3F3,AXKh$K!"$=$N3,AX$NA4FN@a$N=LLsA0$N%S%C%H%^%C%W$NO@M}OB$rHj!"$=$N3,AX$NA4$F$N@a$GMQ$$$k!#

?^ 2$K SM K!$N;0?JLZ$rMQ$$$?LN<0?^$r<($9!# 3N?^$G s $,Aw?.85$N%W%m%;%C%5!" d $,K\Mh$NAw$j@h!" • $,7k2LE*$K%Q%1%C%H$,Aw$jIU1ilk%W%m%;%C%5G"$k!# d $NL5$$ • NOL5BL$J%Q%1%C%H$r<u1H$k%W%m%;%C%5$r<($9!#

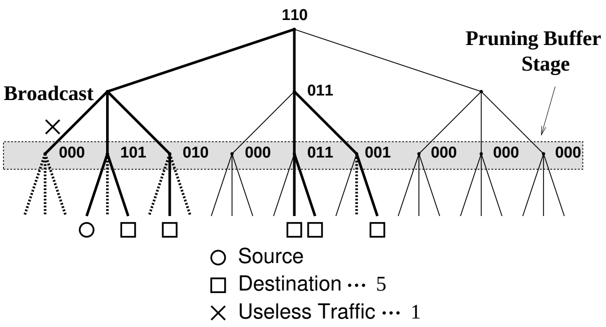
=LLsJ}<0$rMQ$$$?>l9g!"MIN $N%(%l%a%s%HFb$K%G%#%l%/%H%j$r;}$DI,MWOJ$/$J$j!"6&M-%a%b%j>e$KN_!"3F%9%F!<%8 (3,AX) $GMQ$$$k%S%C%H%^%C%W$rJ];}$9lPNI$$!# Backward MIN $rDL2a$9$k%Q%1%C%H$N%X%C%@K3$N3F%9%U%!>e$N%(%s%H%j$O!"Backward$... %F!<%8$GMQ$$$k%S%C%H%^%C%W$rF~$lF*$-!" Backward MIN Fb$GO3$N%S%C%H%^%C%W$K=>CF%Q%1%C%H$r%^%k%A%-%c%9%H$9$k!# 3NJ}<0GOL5BL$J%Q%1%C%H$,%W%m%;%C%5$KE~Ce$7F7$^$&$,!" A4$/%9%$%C%A%s%0%(%l%a%s%HFb$N%G%#%l%/%H%j$r%"%/%;%9$9kI,MW,J/Jj!"5-21MFNL$,@aLs$5lk$H6&$K!" L58z2=$N<B9TB.EY$b8~>e9k!#

2.3 ;^4"$j%P%C%U%!

=LLsJ}<0OBg-$JMxE@$r;}$D01J}!" L58z2=%Q%1%C%H$,I,MW0J30$N%W%m%;%C%5$K$bFO$$$F7^$&LdBj$,$"$k!# 3N%a%C%;!<%8$OFO$$$?%W%m%;%C%5$N%-%c%C%7%e%3%s%H%m!<%i$G<NFF7^$($P$h$$$N$G%W%m%H%3%k>e$N<B32OJ$$$,!"%i%$%s$r6&M-9k%W%m%;%C%5?t$,A}$(kH!" L5BL$J%Q%1%C%H$,A}$(Backward MIN $N:.;($,7c7/Jk!# %7%9%F%`$N%5%$%:$,Bg$-$/!"%G!<%?$N6&M-4X78$N6I=j@-$,>.$5$$$HM-8z%Q%1%C%H$N?tI4G\$NL5BL%Q%1%C%H$,H/@8$9$k2DG=@-$,$"$k [3]!#

3N$?$a!" Backward MIN >e$NFCDj$N%9%F!<%8$N%(%l%a%s%H$N$_$K!" %A%C%WFbIt$K<BAu$G$-$kDxEY$N>.$5$J;^4"$j%P%C%U%!$r@_$1$k!# ?^ 3$O!" LARP 7? MINC $K;^4"$j%P%C%U%!$rE,1~$5$;$?bNG"$k!#;^4"$j%P%C%U%!$O0J2<$Nh&$KF0:n$9$k!#

- Backward MIN KhjFI_=P7?%i%$%s$rMW5a85$N%W%m%;%C%5$KE>Aw9k:]$K!" DL2a$9$k%(%l%a%s%H>e$N;^4"$j%P%C%U%!>e$K%i%$%s$"%I%l%9$rEP O?$7!" BP1~9kF~NO$N bit $r%;%C%H$9$k!# 4{$K%-%c%C%7%e>e$K%(%s%H%j$,B8:_9k>l9g$O!"%Q%1%C%H$N9T$-@h$KAjEv9k bit $r%;%C%H$9$k!#
- Backward MIN $r2p$7$F99?7%G!<%?$"$k$$$OL58z=%Q%1%C%HrAwk;~!"%9%$%C%A%s%0%(%l%a%s%HFb$N;^4"$j%P%C%U%!$r;2>H$7!" %"%I%l%9$,0lCW9l$P $=$N%G%#%l%/%H%j$N%S%C%H%^%C%W$rMxMQ7F!" 3F$KBP1~$9$k=PNO$KBP7FN_%Q%1%C%HrAwk!# L58z2=7?%W%m%H%3%k$rMQ$$$?>l9g$O!";^4"$j%P%C%U%!>e$N%(%s%H%j$O!"L58z2=%Q%1%C%HrAwC$?;~E@$G:o=|9k!#



?^ 3: ;^4"$j%P%C%U%!

L58z2=7?%W%m%H%3%k$G;^4"$j%P%C%U%!$O!"%9%$%C%A%s%0%(%l%a%s%HFb$K<BAu$9k3H,I,MW$G!"$J$*$+$D9bB.$J%"%/%;%9$,MW5a$5lk!#3Nh&$KMFNL$N@)8B$,87$7$$$?$a!"L58z2=%W%m%H%3%k$GIQHK$KL58z2=$,9TJolk>l9g$r=|$$$F!"%G%#%l%/%H%j%-%c%C%7%e$NEPO?;~$K$O%P%C%U%!$NNN0h$,$J$/$J$k>l9g$,IQHK$K5/$-kH9M$($ilk!#;^4"$j%P%C%U%!$NL\E*$OL5BL%Q%1%C%H$N:o8:K"kN$G!"$3Nh$&$J>l9g$O!"C1=c$KI3$+$N%i%$%s$rA*sG<NFF7^CFNN0h$r3NJ]$9$k!# IN%i%$%s$rA*V+$O!"LRU J}<0$rO8aH7F$$$/D+$NJ}<0$,9M$($ilk!#

2.4 MINC $N%-%c%C%7%e@)8f%W%m%H%3%k

MINC GO!"%G%#%l%/%H%j$,6&M-%a%b%j$K=8Cf7F$$$kJ, MHN[4] $d MIND[5] KHfY$F%W%m%H%3%k$O4JC1G"$k!#$?$@$7!"%G%#%l%/%H%j$r=LLs7?$?$a!"%i%$%s$N%3%T!<$rJ];}7F$$$k%W%m%;%C%5?t$r%+%&%s%H$9$k%+%&%s%?$r6&M-%a%b%j$N%G%#%l%/%H%j$K@_1kI,MW$,$"$k!#

3F%W%m%;%C%5$K@\B3$5l?%-%c%C%7%eKO!"$=$N%i%$%s$NM-8z/L58z（Valid:V / Invalid:I）$*$h$S!"%3%T!<$,B>$KB8:_$9$k/B8:_$7$J$$（Shared:S / Private:P）$N%?%0$,@_1ilF$$$k!# MINC $GMQ$$$k%W%m%H%3%k$O!" 3liNAH9g$;$Khj I!" P!" S $N 3 >uBV$r;}$D%i%$%H%9%k!<7?G"$j!" ?^ 4$K<($9>uBVA+0\$r9TJ&!# MINC GOL58z2=7? (?^ 4a)!"99?77? (?^ 4b) N>J}$N%W%m%H%3%k$NMxMQ$,2DG=$G$"$k!#

$^$:!"M-8z$J%-%c%C%7%e$KBP7FNFI_=P$7%"%/%;%9$,%R%C%H9l$P!"LdBj$J$/%-%c%C%7%e$+$i%G!<%?$rFI$_9~$`!# $=$NB>$N%"%/%;%9$O0J2<Nh$&$K=hM}5l$k!#

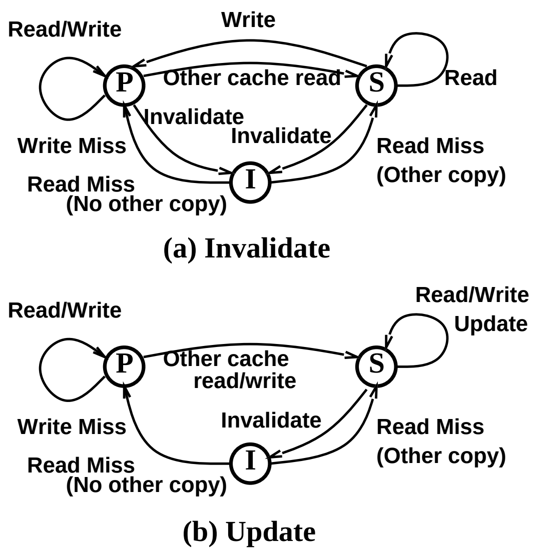
1. =q$-9~$_%_%9!?%R%C%H: Forward MIN $rMQ$$$F6&M-%a%b%j$K%G!<%?$rAw$j!"6&M-%a%b%j>e$N%G%#%l%/%H%j$K=>$C$F Backward MIN $rMQ$$$F!" L58z2=%Q%1%C%H$^$?$O99?7MQ$N%G!<%?$r%^%k%A%-%c%9%H$9$k!#

2. FI$_=P$7%_%9: %_%9$7$?%i%$%s$KBP1~9k%;%C%H$K I >uBV$,B8:_7J1l$P!"3!#$K=>CFEPO?>C5n$r9T$J$$$FI$_9~$_NN0h$r3NJ]$9$k!#<!$K Forward MIN $rMQ$$$F%i%$%sMW5a%Q%1%C%H$r6&M-%a%b%jKAwk!#$3$3$G!"6&M-%a%b%j$3%s%H%m!<%i$O!"6&M-%a%b%j>e$N%S%C%H%^%C%WNI,MWJ>l=j$K 1 $r%;%C%H$7!" %+%&%s%?$r%$%s%/%j%a%s%H9k!#$=$7$F!"Backward MIN $rMQ$$$FMW5a85$N%W%m%;%C%5$N%-%c%C%7%eKFI_=P7?%i%$%s$rAw$k!#$3$N;~!"$G%#%l%/%H%j>e$N%+%&%s%?$, 0!"9JoAB>$KF10l%i%$%s$r6&M-$9$k%W%m%;%C%5$,B8:_7J$$>l9g!"6&M-%a%b%jOFI_=P7?%i%$%s$rAw$k%Q%1%C%H$N%X%C%@Cf$N Private bit $r%;%C%H$7FAwj=P$9!#%Q%1%C%H$rAw$j=P$7$?8e!"6&M-%a%b%j%3%s%H%m!<%i$O%+%&%s%?$r%$%s%/%j%a%s%H$9$k!#MW5a$r=P7?%W%m%;%C%5$O!"%Q%1%C%H$r<u$1<h$j%X%C%@Cf$N Private bit $,%;%C%H$5lF$$$l$P P >uBV!"$=$&$GJ1lP S >uBVKJ$k!#

5F!"6&M-%a%b%j%3%s%H%m!<%i$O!"%+%&%s%?$, 1 $N%i%$%sKBP9$k%i%$%sMW5a%Q%1%C%H$r<u$1<hkH!"6&M-2=%Q%1%C%H$r Backward MIN $rMQ$$$F%^%k%A%-%c%9%H$7!"$3$N%i%$%s$r6&M-$7$F$$$kb&0lDN%-%c%C%7%e%i%$%s$N>uBV$r S $KJQ99$9$k!#

3. EPO?>C5n: %G%#%l%/%H%j$r=LLs$7$?>l9g!"%S%C%H%^%C%WCf$N 1 $OJ#?t$N%-%c%C%7%e$N%3%T!<$rI=8=7F$$$k>l9g$,$"$k!# 7?$,CF!"4JC1$K3N%S%C%H$r%j%;%C%H$9k3HOG-$J$$!# %i%$%s$r<NFk>l9g$O!"Forward MIN $rMQ$$$FEPO?>C5n%a%C%;!<%8$r6&M-%a%b%j$KAw$j!"%G%#%l%/%H%jCf$N%+%&%s%?$r%G%/%j%a%s%H$9$k!#6&M-%a%b%j%3%s%H%m!<%i$O!"%G%/%j%a%s%H$N7k2L!"%+%&%s%?$, 0 KJC?;~KN$_%S%C%H%^%C%WCf$NA4FN bit $r>C5n$9$k!#

MINC $OL58z2=7?$H99?77?$NN>J}$rMQ$$$k3H$,$G$-$k$,!"99?77?$rMQ$$$k$H6&M-%G!<%?$N%^%k%A%-%c%9%H$d%V%m!<%I%-%c%9%H$r8zN(NI$/9T$J$&$3H,G-$k!#$3$N>l9g!"%-%c%C%7%e$N%R%C%HN($,>e$,iJ$$>l9gGb!"1BP1E>AwN_$K5!G=$,8BDj5l$k=>Mh$N MIN KHfYkH9b$$@-G=$rF@$k3H$,4|BT$G$-$k!#



?^ 4: %-%c%C%7%e$N>uBVA+0\

3 %-%c%C%7%e@)8f5!9=

3.1 MINC $NLdBjE@

MINC $O=>MhDs0F$5lF$$$?J}K!HHfY$F!"%O!<%I%&%'%"NL$r8:i7!"<BAu$r9MN8$7$?9=B$$rHC$F$$$k$,!"<B:]$K LSI $K<BAu$9kK$OLdBj$,$"$k!#

$^$:<BAu$rA0Ds$H7F!"MINC K*1k%-%c%C%7%e@)8fKI,MWJ4pK\F0:n$r8+D>$9$H!"

- %i%$%H%9%k!<$,4pK\$JNG!":G?7$N%G!<%?$OL,$:6&M-%a%b%j$KB8:_9k!#
- %G!<%?E>Aw$H6&M-%a%b%j$+$i 1 %i%$%sJ,$N%G!<%?$rE>Aw$7!"F1;~$K;^4#$j%-%c%C%7%e$X$NEPO?$r9TJ&!#
- %i%$%H$7$?>l9g!"6&M-%a%b%j$K%G!<%?$r=q$-9~s@8e$K!"F1$8%i%$%s$r6&M-7F$$$k PU $KL58z2=!"$"$k$$$O99?7%G!<%?%Q%1%C%HrAwk!#

HJ$k!#MINC GO!"%a%b%j%b%8%e!<%k$H%W%m%;%C%54V$r@\B3$9$k%M%C%H%o!<%/$O!"9T$- (Forward) $H5"$j (Backward) K^Hail$F$$$k$?$a!"3N MINC $N;EMM$K=>CF<BAu7?>l9g!"%M%C%H%o!<%/KBP7$F!"1$D$N08@h$KD9$$$%-%c%C%7%e%i%$%s$rE>Aw9k5!G=$H!"J#?t$N08@h$KC;$$%-%c%C%7%e@)8f%Q%1%C%H$rE>Aw$9$k5!G=$rF1;~$KK~$?5J$/$FOJiJ$$!#7+$7!"N>J}$N5!G=$rF10l$N%M%C%H%o!<%/>e$G<B8=$7h&H9kH!"%Q%1%C%H$N@)8f$,J#;(KJ$j!"@-G=$,Dc2<7F7^$&!#

5i$K!"MINC $N%-%c%C%7%e@)8f5!9=$r$=$N$^$^<BAu9k$H!"<!$K5s2kLdBj$,@8$8$k!#

%^%k%A%-%c%9%H%Q%1%C%H$N>WFM %-%c%C%7%e0lCW@)8f$N%Q%1%C%H$r Backward-MIN >e$G%^%k%A%-%c%9%H7?;~!"E>Aw$NESCf$G%Q%1%C%H$,>WFM$7!"L\E*$N%W%m%;%C%5$N$&$A$N0lIt$N%W%m%;%C%5KN$_%Q%1%C%H$,FO$$$F!";DjN0lItKOFO$+$J$$$3H,$"$jF@$k!#$3$N>l9g!"FO$+J+C?%W%m%;%C%5KBP7$F:FAw$9kI,MW,$"$k$,!"=LLs$7$?%G%#%l%/%H%j$K4p$E$$$F%^%k%A%-%c%9%H9k$?$a!"%"%/%N%j%C%8?.9f$@$1GOFO$+$J$+$C$?%W%m%;%C%5$r@53N$KFCDj$G$-$J$$!#$=$3$G!"%M%C%H%o!<%/$NESCf$GH/@8$7$?%Q%1%C%H$N>WFM$K4X$9$k>pJs$r!"6&M-%a%b%jB&KCNi$;$kI,MW$,$"$k!#

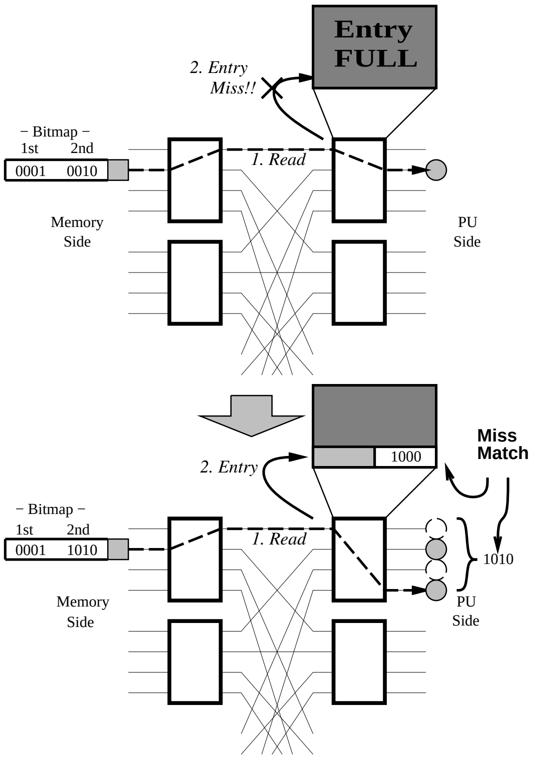
;^4#$j%P%C%U%!$N%(%s%H%j%_%9 ;^4#$j%P%C%U%!$K%(%s%H%j9k;~$K!"4{$K;^4#$j%P%C%U%!$,Kd$^$C$F$$$F%(%s%H%jG-$J$$>l9g!"4{K"$k%i%$%srEG-=P9+!"%(%s%H%j$rD|$ak7$+$J$$!#7+$7!"$$$:lNJ}K!rHC?>l9gGb!";^4#$j%P%C%U%!$K%G%#%l%/%H%j$,$J$$$N$K!"$=$N;^4#$j%P%C%U%!$N4IM}2<$K$"$k%W%m%;%C%5$,%i%$%s$r;}$C$F$$$k3H$,$"$jF@$k!#3N>l9g!";^4#$j%P%C%U%!$H6&M-%a%b%jK"$k%G%#%l%/%H%j$N4V$G!">pJs$K?)$$0c$$$,@8$8$F7^$$!"%-%c%C%7%e$N0lCW@)8f$K<:GT7F7^$&!#;^4#$j%P%C%U%!$N%(%s%H%j$rD|a?>l9gNNcr?^ 5$K<($9!#$"$k%W%m%;%C%5$,6&M-%a%b%j$N%G!<%?rFIs$@;~$K!"%-%c%C%7%e%i%$%s$O%G!<%?E>AwMQ$N%M%C%H%o!<%/$rDLCF%W%m%;%C%5KAwilk$,!";^4#$j%P%C%U%!$,Kd$^CF$$$k$H%(%s%H%j$G$-$J$$ (?^ 5>e)!#$=$N8e!"=q$-9~$_$NH/@8$JIG;^4#$j%P%C%U%!$K6u$-$,G-$?8e!"@h$[$I%G!<%?$rFIs@bNHOJL$N%W%m%;%C%5$,!"F1$8%-%c%C%7%e%i%$%s$N%G!<%?$rFIs@;~!";^4#$j%P%C%U%!$K$O8e$GFI$_$@7?r9TJC$?%W%m%;%C%5$N$_$,EPO?5l$k!#$=CF!"<B:]$K%-%c%C%7%e%i%$%s$N3%T!<$r;}$D%W%m%;%C%5$H!";^4#$j%P%C%U%!$N;X$7<($9>pJsHN4V$K?)$$0c$$$,@8$8$k (?^ 52<)!#

3N>l9g!"6&M-%a%b%jB&$N%G%#%l%/%H%j$K$O@5$7$$>pJs$,$"k3H+$i!";^4#$j%-%c%C%7%e$K%_%9$7$?;v$r6&M-%a%b%jB&KCNi$;!"0J8e;^4#$j%-%c%C%7%e$K%(%s%H%j$7$J$$$h$&$K9kI,MW$,$"$k!#

3.2 Ds0F9k%-%c%C%7%e@)8f5!9=

$=$3$G!":#2s!"%G!<%?E>Aw5!9=$H%-%c%C%7%e@)8f5!9=$rJ,N%$7!"%-%c%C%7%e@)8f5!9=$@$1$rFHN)$7$F9T$J$&J}K!$rDs0F9k!#Ds0F9kJ}K!$O!"4pK\E*$J@)8f<jK!$O MINC $HF1$8$@$,!"<!$NE@$G2~A1$r9T$JC?!#

- %-%c%C%7%e@)8f5!9=$@$1$rJ,N%$9k3HKhj!"%-%c%C%7%e@)8f$KE,$7$?5!G=$@1r;}$?$;$F%O!<%I%&%'%"$rC1=c2=9k3H$,2DG=$G!"@-G=8~>e$r



?^ 5: ;^4#$j%-%c%C%7%e$N%(%s%H%j%_%9

4 |BTG-$k!#$^$?!"MM!9$JB>$N%G!<%?E>AwMQ%9%$%C%AHAH_9go;k3H,2DG=G"$k!#

- %^%k%A%-%c%9%H%Q%1%C%H$N>WFM$H;^4#$j%P%C%U%!$N%(%s%H%j%_%9KBP7!"%"%/%N%j%C%8$r%Q%1%C%H$K9k3HKh$j!"ESCf$N>WFM>u67$H;^4#$j%P%C%U%!$N%(%s%H%j%_%9$r6&M-%a%b%j$B&$N%-%c%C%7%e%3%s%H%m!<%iKCNi$;$k3H$,$G$-$k!#$^$?!"6&M-%a%b%j$N%G%#%l%/%H%j$K$O!";^4#$j%P%C%U%!;2>H%S%C%H$r 1 %S%C%H@_$1k3HKhj!";^4#$j%P%C%U%!$K%(%s%H%jG-J+C?>l9g$K%S%C%H$r%;%C%H$7!"0J8e;^4#$j%P%C%U%!$K%(%s%H%j$7$J$$$h$&$K9k!#

0J>e$G!"MINC K*1k%-%c%C%7%e@)8f5!9=$r<BAu$9$k>e$G$NLdBj$O2r7h9k3H$,$G$-$?NG!"B3$$$F<B:]$K%A%C%W$X<BAu$r9T$J$&!#

4 @_7W$H<BAu

:#2s$N<BAu$G$O!";n838&5f (B)!VVLSI @_7W650f$+$j%-%e%i%`$N3+H/!W$N0l4DH7$F9T$Jol!"%W%m%;%9$O 0.4$\mu$m!"10 K|%2!<%HAjEv $N LPGA(Laser Programmable Gate Array) $r;HMQ$9$k!#

:#2sDs0F9k MINC $K4p$E$/%-%c%C%7%e@)8fJ}K!$G$O!"%-%c%C%7%e%i%$%s$N=jM->pJs$,6&M-%a%b%jB&$K!"%-%c%C%7%e%i%$%s$N%3%T!<$,%W%m%;%C%5B&$KB8:_$9$k!#=>$C$F!":#2s<BAu$9$k%A%C%W$O!"?t%P%$%H$NC;$$%Q%1%C%H$r9bB.$K!"Bt;3$N08@h$KAwk3H,I,MWHJ$k!#$=3G!"%-%c%C%7%e@)8f5!G=$r8zN(NI$/<BAu9k$?$a$K!"9=B$$H5!G=$NE@$+$i8!F$$r9TJ&!#

4.1 9=B$$N8!F$

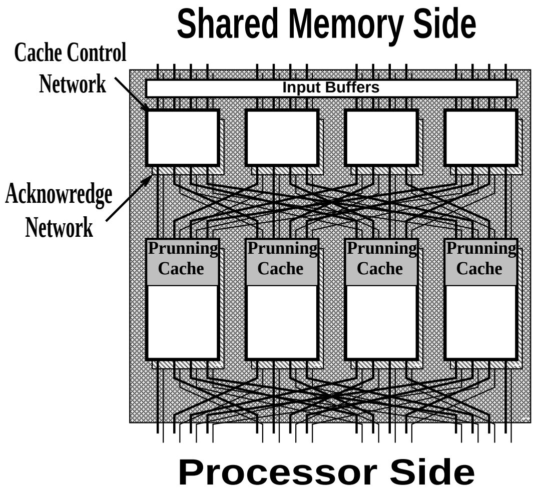
%M%C%H%o!<%/$N5,LO F1$85,LO$N%M%C%H%o!<%/$r<B8=9k>l9g!"1 %A%C%W$KF~$l$k%M%C%H%o!<%/$N5,LOrBg-$/$7$?J}$,!"Bt;3$N>.5,LO%M%C%H%o!<%/%A%C%W$r;HMQ$9khjbM-MxG"$k!#$7$+$7!"%M%C%H%o!<%/$N5,LO$,$"$^jKbBg-$$$H!"%2!<%H?t$d%T%s?t$NITB-$r>7$/!#$^$?!"E>AwJ}K!KO SSS J}<0 [1] $r:NMQ$9k,!"%A%C%WNCfK;^4#$j%P%C%U%!$,$"$k$?$a!"J#?t$N%A%C%W$r%S%C%H%Q%i%l%k$K;HMQ$9k3HOG-$J$$!#=>CF!"1 F~=PNO$"$?jN%S%C%HI}$,692a$.kH!"%Q%1%C%H$NE>Aw$K;~4V$,$+$+$j@-G=$NDc2<$r>7$$$F7^$&!#

$3$3$G2>$K 16 F~=PNOH7$?>l9g!"1 F~=PNO$"$?$j$N%Q%1%C%HE>AwMQ$K 4 K\!"%"%/%N%j%C%8MQ$K 2 K\$N?.9f@~$r3d$jEvFk$H!"%G!<%?%Q%9$@1G 192 K\!"@)8fMQ$b9g$o$;$F 200 K\6/$N?.9f%T%s$,I,MWHJ$j!":#2s<BAu$9$k%A%C%W$G;HMQ2DG=$J%T%s?t$.j.jG$"$k3H$,$o$+$C$?!#$=3G!":#2s$N<BAu$G$O%M%C%H%o!<%/$N5,LO$r 16 F~=PNO$H7?!#

%/%m%9%P%9%$%C%A$NBg$-$5 %9%$%C%A$,Bg$-$/Jk$H!">WFM$N:]$N@)8f$,J#;(KJ$j!"F0:nB.EY$,Dc2<7F7^$&!#$7$+$7!"%9%$%C%A$r>.5/7F7^$&$H!"%^%k%A%-%c%9%H5!G=$r3h$+$9$3H,G-$J$$!#$=$3$G!"%M%C%H%o!<%/$N5,LO$, 16 F~=PNO$G$"$k3HrF'^$(!"1 %/%m%9%P%9%$%C%A$N%5%$%:$r 4×4 H7!"%*%a%,LV$G@\B3$9$k!#

;^4#$j%P%C%U%!$NG[CV ;^4#$j%P%C%U%!$K$O!"%"%I%l%9$rJ];}9kHf3S4o$H%Q%1%C%H$NN.lr@)8f9k2sO)$,I,MW$HJj!"%/%m%9%P%9%$%C%A$KHfYF$O!<%I%&%'%"NL$,B?$/$J$k!#=>$C$F!"A4$F$N%9%$%C%A$K;^4#$j%P%C%U%!$rG[CV$9kN$O:$FqG"$k!#$^$?!"%7%_%e%l!<%7%g%s$KhkI>2A [9] $+$i!"J#?t$N%9%F!<%8$K@_1F$b!";^4#$j%P%C%U%!Kh$kL5BL%Q%1%C%H$N8:>/$O>.$5$/!"8z2L$,>e$,$i$J$$$3H,o+CF$$$k!#$=$3$G!"%7%_%e%l!<%7%g%s$KhkI>2A$K=>$$!"bCHb%W%m%;%C%5$K6a$$B&$N%9%F!<%8$KN_G[CV9k3HK7$?!#

0J>e$+$i!":#2s<BAu9k%-%c%C%7%e@)8f%A%C%W$N9=B$ $O?^ 6$Nh&KJC?!#



?^ 6: %-%c%C%7%e@)8f%A%C%W$N9=B$

4.2 5!G=$N8!F$

B3$$$F!"5!G=LLKD$$$F8!F$$r9TJ&!#

$^$:!"%G%#%l%/%H%j$N=LLsJ}<0$K$D$$$F$O!"@h$N3NN(%b%G%k$K4p$E$/I>2A [9] $+$i!":#2s<BAu9k%A%C%WGO!"SM K!$rMQ$$$?%G%#%l%/%H%j=LLs$K4p$E$$$F%^%k%A%^%c%9%H$r9T$J$&$h$&$K7?!#

$^$?!"SSS J}<0$rMQ$$$?>l9g!"%9%$%C%A$NF~NOKBP7$FM%@hEY$,8GDj5lk?$a!"%Q%1%C%H$KM%@hEY$r;}$?$;$kI,MW$,$"$k [8]!#%-%c%C%7%e@)8f%Q%1%C%H$O!"%W%m%;%C%5$,%j!<%I%_%9r7$?;~$KH/@8$9$k;^4#$j%-%c%C%7%e$H!"EPO?9k%Q%1%C%H$H!"%i%$%H7?;~$KH/@8$9$kL58z2=(99?7) %Q%1%C%H$N 2 <oN`$,$"k,!"4 CJ3, (2bit) $NM%@hEY@)8f$r9TJ&$H!"%/%m%9%P%9%$%C%A$N@)8f2sO)$,J#;(KJCF7^$&$?$a!"2 CJ3, (1bit) $NM%@hEY$rMQ$$$k3HK7$?!#

4.3 <BAu

:#2s$N<BAu$G$O!"A4$F Verilog-HDL $G2sO)$N5-=R$r9T$J$$!"E15~Bg3X VDEC $+$iB_M?5l$?D!<%k$rMQ$$$FO@M}9g@.!&%l%$%"%&%H$^Gr9TJ&!#8=:_$N=j!"O@M}@_7W$^$G=*N;$7F*$j!"L58z2=7?%W%m%H%3%k$r:NMQ7?>l9gKO!"%-%c%C%7%e@)8f%Q%1%C%H$r 38 %/%m%C%/$GE>AwG-$k!#%G!<%?E>AwMQ$K!"@h$K<BAu$5l? SSS-PBSF %A%C%W [8] $r:NMQ$7$?>l9g$r2>Dj9k$H!"%A%C%W$r%S%C%H%Q%i%l%k$K 8 8D;HMQ$7Fb!"1 %P%$%H$NE>Aw$K 1 %/%m%C%

$?$a!"F1$8F0:nB.EY$GF0$+$;$P!"1%i%$%s$N%G!<%?E>AwCf$K%-%c%C%7%e@)8f$r9T$J$&$K$O==J,$JF0:nB.EYG"kH$$$($k!#$7$+$7!":#NH3m!":#2s$N<BAu$K;HMQ9k LPGA $d%Q%C%1!<%8$K4X9k>\:Y$J;qNA$rF~<jG-$F$$$J$$$?$a!"2sO)5,LO$HF0:nB.EY$r@53N$K7Wk3H,G-$J$$!#$=$3$G!"@-G=$rM=B,9k$?$a!"Cadence <R$NO@M}9g@.%D!<%k$H Altera <R$N FPGA(Flex–8000 %7%j!<%:) MQ$N%i%$%V%i%j$rMQ$$$FO@M}9g@.7?!#

$^$:2sO)5,LO$rI= 1$K<($9!#$3NCfK$O!"%-%c%C%7%e%a%b%j$KI,MW$JJ,$O>J$$$F$"$k!#$^$?!"$3$3$G4pK\%2!<%H$H$O!"1 %2!<%H$"$?$j 2 %2!<%HAjEv0J2<NbNG!"J#9g%2!<%HO=$10J>e (J?6Q 5 %2!<%H)!"%U%j%C%W%U%m%C%W$O 10 %2!<%HAjEv0J>e$NLL@QrI,MWH9k!#:#2s$NO@M}9g@.$N7k2L$+$i!"%M%C%H%o!<%/A4BN$G!"35;; 4 K|%2!<%HAjEv$N2sO)HJk3H,o+C?!#%a%b%jNNLO3N?t;z$K4^$^lF$$$J$$$,!";^4#$j%P%C%U%!$NMFNL$OHs>o$K>/$J$$$N$G!":#2s;HMQ$9$k LPGA $K==J,<BAu2DG=$G$"$k$H9M$(il$k!#

<oN`	F~NO%P%C%U%	%9%$%C%A	;^4#$j	%A%C%WA4BN
4pK\%2!<%H	3	393	337	4560
J#9g%2!<%H	4	32	282	1448
Flip Flop	25	48	429	2450

I= 1: M=A[%2!<%H?t

$^$?!"F0:nB.EYKD$$$F!"%/%m%9%P!<%9%$%C%A$r Altera <R$N%D!<%k$G FPGA $KG[CVG[@~$7$?8e$K!"F0:nB.EY$r%D!<%k>e$N%3%^%s%I$G7WB,$7$?=j!"40MHz $GF0:n$9k3H,o+C?!#FPGA $N>l9g!":#2s;HMQ$9kh$&$J%;%9%? LSI KHfY$F01HL$KH>J,0J2<$NB.EY$KJkNG!":GDcGb 80MHz $N9bB.F0:n$,4|BTG-$k!#

5 $*$ojK

K\O@J8GO!"B?CJ7k9gLV$K%-%c%C%7%e@)8f5!9=$rN;$? MINC $N<BAu>e$NLdBjE@$r9MN8$7$?!"%-%c%C%7%e@)8f5!G=$N$_$r;}$D%A%C%W$rDs0F$7!"$=$N@_7W$H<BAuKD$$$FJs9p7?!#

8=:_!"%A%C%W$OO@M}@_7W$,=*N;$7!"LSI $K<BAu$9k?aN%l%$%"%&%H:n6H$KF~C?=jG"k,!";n83E*$K FPGA KBP7$FO@M}9g@.$r9TJC$?7k2L!"16 F~=PNO$N%M%C%H%o!<%/$r 10 K|%2!<%H$N LSI 1 DK<}ak3H$,G-!"80 MHz $N9bB.F0:n$r4|BTG-k3H,o+C?!#:#8e$O!"<B:]$N LPGA $N%G!<%?$K4pE/@-G=I>2A$r9T$JC?8e!"VLSI %A%C%W$K<BAu$9$kM=Dj$G$"$k!#

;29MJ88%

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