B?<!859=B$$r;}$D MIN $NDs0F

<k >P4d 550f 5.G7 H9 IRGn E7Ln 1Q@2

{cissy, kamei, hanawa, hunga}@aa.cs.keio.ac.jp

7DXf5A=NBg3X M}9)3XIt

35MW

K\O@J8GO!"B?<!859=B$$r;}$D MIN!"$n$D-MIN $rDs0F$9$k!#$n$D-MIN $OB?<!852=$H=[4D%j%s%/$NIU2C$Khj!"FCDj$N%a%b%j%b%8%e!<%k$KBP9kE>Aw%9%F%C%W?t$r8:$i$7!"%"%/%;%9$N6I=j@-$rMxMQ$9k3H,G-$k!#

3NN(%b%G%kKh$k%7%_%e%l!<%7%g%s$N7k2L!"B?<!859=B$$r:GBg8B$KMxMQ$9$k<!85<+M3%k!<%F%#%s%0$rMQ$$$?>l9g!"%i%s%@%`E>AwK*$$$F$b!"DL>o$N MIN hjM%l?%"%/%;%9%l%$%F%s%7%#$r<B8=9k3H$,$G$-$k!#5i$K!"%"%/%;%9$K6I=j@-$,B8:_$9$k>l9g$O!"%"%/%;%9%l%$%F%s%7%#$r:GBg 24% 2~A1G-k3H,o+C?!#$^$?!"8N>c$d:.;($r1*2s9k%k!<%F%#%s%0J}K!KD$$$F$bDs0F$7$?!#

MIN with multi-dimensional structure

Abstract

In this paper, we propose a novel MIN (Multistage Interconnection Network) structure called the multi-dimensional MIN (nD-MIN). Unlike the conventional MINs, the nD-MIN can make the best use of access locality by its multi-dimensional structure and feedback lines.

According to the probabilistic simulation results, the latency is 24% better than that of traditional MINs under the traffic with communication locality, by using the dimensional free routing. Even without communication locality, the latency of the nD-MIN is better than that of traditional MINs if the size is appropriately matched. Faulty or congested elements or links can be bypassed with a simple modification of the routing algorithm.

1 O8aK

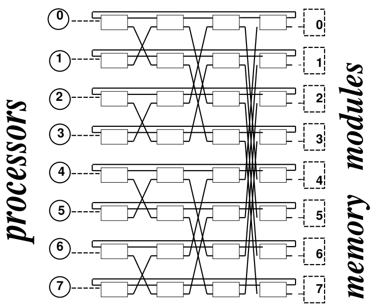
Bg5,LO$JJBNs7W;;5!$r9=@.9k:]$K!"PU (Processing Unit) 4V$"$k$$$O PU-%a%b%j4V$NAj8_7k9gJ}<0$O=EMW$J0LCV$r@jaF$*$j!"JBNs7W;;5!$N5,LO!"1~MQLdBj$N@-<AJI$K1~$8$?:GE,$J7k9gLV$r5a$a$k8&5f$,@Q6KE*$K?J$ail$F$$$k!#$=$NCf$G!"B?CJ7k9gLV MIN(Multistage Interconnection Network) $O%9%1!<%i%S%j%F%$$,9b$/!"E>AwMFNL$,Bg$-$$MxE@rbD?$a!"PU $H6&M-%a%b%j%b%8%e!<%k$r7k9g9kJ}K!H7$F!"8E$/$+$i8&5f5lF-$?$, [1]!"<B:]$N%^%7%s>e$G<BAu5l$?Nc$O:G6a>/J/JC$F$$$k!#

3l$O!"MIN $N;}$D9=B$>e$NLdBjE@$,$RHD0xHJCF$$$k!#9JoA!"=>Mh$N MIN GO!"PU$H%a%b%j%b%8%e!<%k$N4V$G8r49$5lk%Q%1%C%H$O!"I$:F1$8?t$N%9%F!<%8rDLC$FE>Aw$5lk!#3N9=B$

$O!"F1;~$KJ#?t$N%a%b%j%b%8%e!<%k$+$iJ#?t$N PU $KBgNL$K%G!<%?$rE>Aw$9kK$OJXMx$G$"$k$,!"PU $,%a%b%j%b%8%e!<%k$KBP7F9TJ&%"%/%;%9$K6I=j@-$,B8:_9k>l9g!"$=$NMxE@$r3h$+$9$3H,G-$J$$!#%7%9%F%`$,Bg5,LO$K$J$k$H!"$R$H$D$N%7%9%F%`>e$GB??t$N%8%g%V$d%W%m%;%9$,F0:n9kh&KJ$j!"$9YF$N PU $,$9YF$N%a%b%j%b%8%e!<%k$KBP7F0lMM$K%"%/%;%9$rH/@8$9$k3H$O9M$(K/$$!#$=$3$G!"MIN $NFCD'$rJ];}7?$^$^!"FCDj$N%a%b%j%b%8%e!<%k$KBP9k%"%/%;%9$r8zN(NI$/9TJ&3HNG$-$k9=@.$,M-Mx$KJk!#

K\O@J8GO!"6I=j@-$rMxMQ$9k3H,2DG=$GBg5,LO$N8Ns%7%9%F%`$K8~$/ n <!85 MIN(nD-MIN) $rDs0F$9$k!#$3$N MIN $O!"=[4D9=B$$HB?<!859=B$$r;}D3HG!"MIN $NFCD'$rJ]C?$^$^!"6I=j@-$r@8$+$9$3H,G-$k!#$5iK!"$=$N%l%$%F%s%7%#$K$D$$$F3N

N(%b%G%k$rMQ$$$FI>2A$r9T$J$$!"8N>c$d:.;($N1*2s K!KD$$$F8!F$$r9TJ&!#



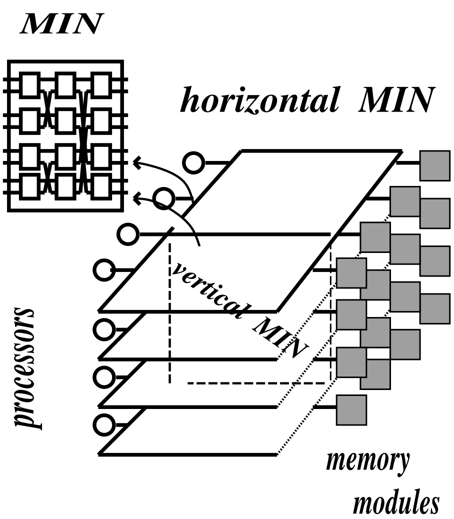
?^ 2: =[4D9=B$$rIU2C7?LV

2 B?<!85 MIN $NDs0F

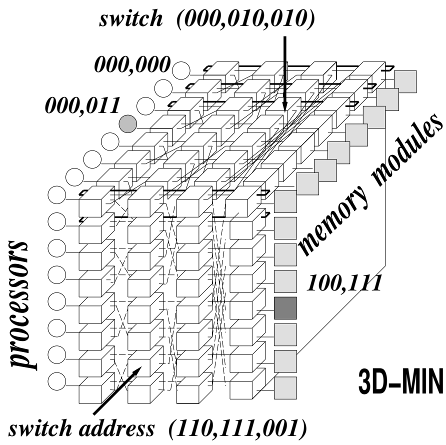
2.1 nD-MIN $N9=@.86M}

nD-MIN $O!"MIN $N%9%F!<%84V$N@\B3$rB?<!85J}8~$K3HD%9k3HKh$j9=@.$9$k!#$3$3$G$O!"4pK\$HJk MIN $K?^ 1Cf$K<($9 Banyan LV (Generalized Cube LV [4]) $rMQ$$$k!#3NLV$O!"$RHD$N%9%$%C%A%s%0%(%l%a%s%H$,!"=PNO$HF10lHV9f$NC<;R$KBP7F@\B3$5$l$?%j%s%/ (JB9T%j%s%/) $H S 2O%9%F!<%8HV9f) N%l?HV9f$NC<;R$KBP7F@\B3$5$l$?%j%s%/ (%/%m%9%j%s%/) $r;}$A!"D>@\LV$N%O%$%Q!<%-%e!<%V$KAjEv$9$kB?CJLV$r9=@.9k!#

D>J?LL>e$K%Q%1%C%H$rAw$j!"0lC6=[4D%j%s%/$rMQ$$$F=PH/COKLaC$?8e!"?eJ?J}8~$N MIN $rMQ$$$FL\E*CO$K%Q%1%C%H$rAwk3HKhj%"%/%;%9$9$k3H$,$G$-$k!#



?^ 1: 3 <!85 MIN $N9=@.86M}



?^ 3: 3 <!85 MIN $N9=@.

nD-MIN $O!"$3$N%/%m%9%j%s%/$rB?<!85J}8~KBP7Fb@_1k3HKh$j9=@.$9$k!#?^ 1$K 3 <!85 MIN $N9=@.86M}$r<($9!#$3$N9=@.$G$O!"PU $O!"<+J,$HF10l$N?eJ?$*hS?bD>J?LL>e$N%a%b%j%b%8%e!<%k$K7+%"%/%;%9G-$J$$!#$=$3$G!"Generalized Cube LV$K?^ 2$K<($9h&$K=[4D%j%s%/$rIU2C9k!#3N9=B$$O!"D>@\LV$NCf$N=[4DLV$KB0$9$k Circular Banyan LV [7] $N%H%]%m%8$r MIN $KMxMQ$7$?$bNH9M$($k3H$,$G$-$k!#

?^ 2$N9=B$$r4pK\$H7? 3D-MIN $r?^ 3$K<($9!#$3$N9=B$$OD>@\LV$G$"$k [2B3] $r MIN $K1~MQ$7$?$bNH9M$($k3HbG$-$k!#=[4D%j%s%/$r;}$D3HKh$j%O!<%I%&%'%"NL$OA}2C9k$,!"G$0U$N%a%b%j!<%b%8%e!<%k$K%"%/%;%9$9$k3H$,$G$-$k!#8@$$49$($k$H!"3 <!85 MIN GO?eJ?!"?bD>N=l>lNJ?LL>e$N%a%b%j%b%8%e!<%k$KBP7F$OD>@\$K!":G=i$K?bD>J}8~$N MIN $rMQ$$$FL\E*CO$HF10l$N?eJ?LL>e$N%a%b%j%b%8%e!<%k$KBP7F$O

?^ 3$K<($9 3D-MIN K*$$$F!"PU HV9f!"%a%b%jHV9fO=l>$l 1 <!85>/$J$$ 2 <!85$N:BI8 $P(X_0, X_1)$ $M(X_0, X_1)$ $GI=$9$3$H$,$G$-!"%9%$%C%A%s%0%(%l%a%s%HHV9fO3lK%9%F!<%8J}8~$r9g$o$;$? 3 <!85$N:BI8 $E(X_0, X_1, s)$ $GI=$9$3$H$,$G$-$k!#%(%l%a%s%H4V$N@\B3$O!"$E(X_0, X_1, s+1)$ KBP9$kJ?9T%j%s%/$H X_0, X_1 J}8~K=l>$l S 2N%l?%(%l%a%s%HKBP9$k%/%m%9%j%s%/KhCF@\B3$5lk!#

0J2<!"nD-MIN $N@\B3J}K!$rDj5A9k!#

2.2 nD-MIN $N@\B3

$a%b%j!"0J2<$Nh&$K PU!"%a%b%j!"%9%$%C%A%s%0%(%l%a%s%H$KHV9fIU$1$r9T$J$&!#$3$3$G!"<!85?t$r n H7!"3 <!85$NHV9f!"LV$N%[%C%W?t (F~NOB&$H=PNOB&$N5wN%=%9%F!<%8@?t) $r S H9$k!#j <!85K*1k%W%m%;%C%5?t (=%/%;%92DG=G"$k!#B>$N%a%b%j%b%8%e!<%kKBP7FO $r $L_j = 2^{l_j}$ $(0 \le j \le n-2, l_j \ge 1)$ GO!":G=i$K?bD>J}8~$N MIN $rMQ$$$FL\E*CO$HF10l$N?eJ?LL>e$N%a%b%j%b%8%e!<%k$KBP7F$O

%W%m%;%C%5?t$r N H9kH!"$\prod_{j=0}^{j=n-2} L_j$ $G I=$9$3$H$,$G$-$k!#3NH- $S = \max_j(l_j)$ G"$k!#

PU HV9f

$$P(X_0, X_1, \ldots, X_{n-2})$$

%a%b%jHV9f

$$M(X_0, X_1, \ldots, X_{n-2})$$

$3$3$G!"$X_0, X_1, \ldots, X_{n-2}$ $O3F<!85$N:BI8 $(0 \le X_j \le n-2)$ G"$k!#

$3$3GO!"PU $+$i%a%b%jXNC1J}8~$N MIN $r9M$($k!#$7$?$,CF!"PU HV9f$O MIN KBP9$kF~NO%i%Y%k!J=PH/COHV9f!K"%a%b%jHV9f$O=PNO%i%Y%k!JL$E*COHV9f!KHJ$k!#

%9%$%C%A%s%0%(%l%a%s%H HV9f

$$E(X_0, X_1, \ldots, X_{n-2}, s)$$

$3$3$G!"$X_0, X_1, \ldots, X_{n-2}$ $O3F<!85$N:BI8 $(0 \le X_j \le L_j)$ G"$j!"s $O%9%F!<%8HV9f $(0 \le s \le S-1)$ G"$k!#

>e5-$NHV9fIU$1KD$$$F!":B$8 X_j $7e$N 2 ?J?t

$$X_j = x_{j(l_j-1)} x_{j(l_j-2)} \ldots x_{j0} (0 \le j \le n-2)$$

$GI=$o5l$k!#

nD-MIN $N@\B3$O0J2<Nh$&$$KDj5A5l$k!#

$E(X_0, X_1, \ldots X_{n-2}, s)$ $r 1 K\$NJ?9T%j%s%/$H!"$n-1$ K\$N%/%m%9%j%s%/Kh$j!"0J2<$N%9%$%C%A%s%0%(%l%a%s%H$H@\B3$9$k!#

J?9T%j%s%/ (pl)

$$E(X_0, X_1, \ldots X_{n-2}, (s+1)\ mod\ S)$$

%/%m%9%j%s%/ $(cl_j\ (0 \le j \le n-1))$

$$cl_j : E(X_0, \ldots, rev(X_j, s), \ldots X_{n-2}, s+1)$$

$?$@$7!"$(s \le S-2)$ G"$j!"$rev_j(X)$ $O X $r 2 ?J?t$GI=7?>l9g$N s bit L\$rH?E>9k4X?tG"$k!#$9Jo$A!"

$$rev(X_j, s) = x_{j(l_j-1)} \ldots \overline{x_{js}} \ldots x_{j0}\ (0 \le s \le l_j - 1)$$

$S-1$ %9%F!<%8$9$JoA:G=*%9%F!<%8$N%j%s%/$O!"=[4DJ?9T%j%s%/$*$h$S%a%b%j%b%8%e!<%k$K@\B3$5$l$k=PNO%j%s%/$KJk!#

>e5-$N%9%$%C%A%s%0%(%l%a%s%H4V$N@\B3$K2C$($F!"0 %9%F!<%8$NF~NO$K%W%m%;%C%5 P, :G=*%9%F!<%8$N=PNO$K%a%b%j M $r@\B3$9kH!"C1J}8~$N nD-MIN $r9=@.$9k3H,G-$k!#$9Jo$A!"F~NO%j%s%/ inl !"=PNO%j%s%/ $outl$ $O!"

inl :
$P(X_0, X_1, \ldots X_{n-2}) \rightarrow E(X_0, X_1, \ldots X_{n-2}, 0)$
outl :
$E(X_0, X_1, \ldots X_{n-2}, S-1) \rightarrow M(X_0, X_1, \ldots X_{n-2})$

$N%j%s%/$G$"$k!#

2.3 %k!<%F%#%s%0

nD-MIN $N%k!<%F%#%s%0%"%k%4%j%:%`$O Generalized Cube F1MM!"GSB>E*O@M}OB$G9=@.$5lk%?%0$rMQ$$$k!#$?$@$7!"$n$D-MIN $OB?<!859=@.$G$"$kNG!"$=$l$>$lBP1~9k<!85F1;N$NHV9f$N%S%C%HC10L$NGSB>E*O@M}OB$r<hkI,MW,$"$k!#
%k!<%F%#%s%0%?%0

$$T(T_0, T_1, \cdots, T_{n-2})$$
$$= P(P_0, \cdots, P_{n-2}) \oplus M(M_0, \cdots, M_{n-2})$$
$$= T(P_0 \oplus M_0, \cdots, P_{n-2} \oplus M_{n-2})$$

$$P_j \oplus M_j = T_j$$
$$= p_{j(l_j-1)} \oplus m_{j(l_j-1)} \cdots p_{ji} \oplus m_{ji} \cdots p_{j0} \oplus m_{j0}$$
$$\equiv t_{j(l_j-1)} \cdots t_{ji} \cdots t_{j0}$$

2.3.1 J?LL%k!<%F%#%s%0

5F!"3N%k!<%F%#%s%0%?%0$rMQ$$$F2DG=$J!":G$b4pK\E*$J%k!<%F%#%s%0$O!"3F<!85$NJ?LL$K$D$$$FN_E>Aw$r9T$J$&J?LL%k!<%F%#%s%0$G$"$k!#0J2<!"3N%k!<%F%#%s%0K!$r C 8@8l$K;w$?I=5-K!$Khj<($9!#J?LL%k!<%F%#%s%0%"%k%4%j%:%`

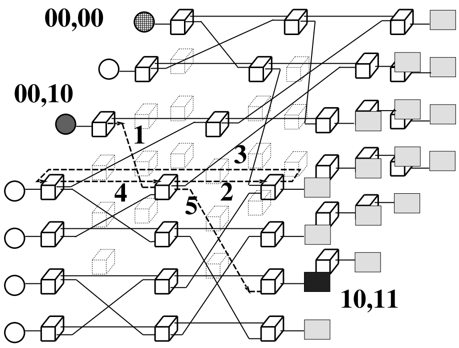
```
if (T == 0)
    for (i = 0; i < S − 1; i ++) Use pl;
else
    for (j = 0; j < n − 1; j ++) {
        if (T_j ≠ 0) {
            for (i = 0; i < S − 1; i ++)
                if (t_ji == 0) Use pl; else Use cl_j;
            if (j ≠ n − 2) Use pl;
        }
    }
Use outl ;
```

3NJ}K!$O, 2<$N<!85$+$i=g$K%?%0$, 0 GJ$$$+I&$+%A%'%C%/$7!"0 GJ1l$P%?%0$N2<$N%S%C%H$+$i=g$KH=CG$7!"0 G"lPJ?9T%j%s%/!"1 G"lP$=$N<!85$N%/%m%9%j%s%/$KE>Aw9kJ}K!G"$k!#C"$7!"j <!85GN%?%0 T_j $, 0 NH$-$O!"$=$N<!85GN%k!<%F%#%s%0$O>JN,G-$k!#=>CF!"%Q%1%C%H$O0lEYF1$8 J?LL>e$G%k!<%F%#%s%0$r;Oak$H!"$=$NJ?LL$+iO$:$lk3HO$J$$!#%Q%1%C%H$O $T_j \neq 0$ $N<!85?t$K Ey$7$$2s?t$@$1 MIN $NF~8}$+$i=P8}$^GrDL2a7FE>Aw5l$k!#$9Jo$A $T_j \neq 0$ $N<!85?t-1 2s$@$1=[4D%j%s%/$rMQ$$$k!#

2.3.2 <!85<+M3%k!<%F%#%s%0

J?LL%k!<%F%#%s%0$O<BAu$,MF0WG"k,!"%Q%1%C%H$, MIN $r0l2sDL2a$9k@1GE>Aw2DG=$J%a%b%j%b%8%e!<%k$O!"F10lJ?LL>e$K@)8B$5lk!#Nc$($P 3D-MIN GO?^ 4$K<($9h&$K!"%W%m%;%C%5 $P(00,10)$ $+

$i%a%b%j%b%8%e!<%k $M(10,11)$ $^$GE>Aw$r9T$Jk5$?t$,Bg$-$/Jk$H0l2s$N=d2sKMW9$k%9%F%C%W 9g!"1-2-3-4-5 $N=gHV$G%k!<%F%#%s%0$9$kI,MW$,$"j^$9!#$3N?$a!"J?LL%k!<%F%# MIN $r 2 2sDL2a$9kI,MW,$"$k!#H3m,!"E>Aw9G$O<!85$Khi$:$[$\0lDj$rJ]$A!"<!85<+M3%k!< $k<!85$rESCfGJQ(k3H,G-lP!"1-5 $N=gHV$G%k!<%F%#%s%0GO!"<!85?t$,Bg$-$/$JkH!">/$78:$k79 %j%s%/$rMxMQ$9lP!"0l2s$GE~Ce$9k3H,G-$k!#$3lO<!85<+M3%k!<%F%#%s%0$O!"<!85?t 3Nh&$KESCf$GMxMQ9k<!85rJQ(k3HNG-$kDx!"2DG=$J%k!<%F%#%s%0$NHO0O$,A}$(k? $k%k!<%F%#%s%0K!$G$"$k<!85<+M3%k!<%F%#%s%0G"$k!# 0F$9$k!#



?^ 4: J?LL!"<!85<+M3%k!<%F%#%s%0$NHf3S

<!85<+M3%k!<%F%#%s%0%"%k%4%j%:%`

if $(T == 0)$
    for $(i = 0; i < S-1; i{+}{+})$ Use pl;
else
    while $(T \neq 0)$ {
        for $(i = 0; i < S-1; i{+}{+})$ {
            for $(j = 0; j < n-1; j{+}{+})${
                if $(t_{ji} == 1)$ {
                    Use cl_j ;
                    $t_{ji} = 0$;
                    break;
                }
            }
            if $(j == n-1)$ Use pl ;
        }
        if $(T \neq 0)$ Use pl;
    }
Use $outl$;

3NJ}K!GO!"%9%F!<%8 i K*$$$F!"A4FN<!85 $N%?%0$N i bit L\$r%A%'%C%/9k!#$3$3$G!"1 KJCF $$$k%?%0$,$"lP$=$N<!85$N%/%m%9%j%s%/$K%Q%1%C %H$rE>Aw$7!"9YFN<!85$N%?%0$, 0 Ji$P J?LL %s%/$K%Q%1%C%H$rE>Aw$9$k!#%Q%1%C%H$,=P8}$KE~Ce 7?;~$KA4FN%?%0$, 0 KJCF$$$J1l$P=[4D$r %s%/rDL7$F%Q%1%C%H$rLa$7!"%k!<%F%#%s%0$r7+$j JV$9!#3NJ}K!$O!"JBNs$K n <!85$N%?%0$r%A%'%C%/ 9k%O!<%I%&%'%"$,I,MW$KJk$,!":GC;5wN%$N%k!< %F%#%s%0$,2DG=$G$"$k!#

I= 1$KJ?LL%k!<%F%#%s%0$H!"<!85<+M3%k!<%F%#%s%0 $NDL2a$9$k%(%l%a%s%H?t$NJ?6Q (J?6Q5wN%) $r%m%9%]

$O%W%m%;%C%5$"$k$$$O%a%b%j%b%8%e!<%k?t) KHfY$k $H!"%5%$%:$,$&$^$/9goJ$$>l9gOBg-$/$Jk,!"%5 %$%:$,9g$($P3l$r2<2s$k3H$,$G$-$k!#

<!85<+M3%k!<%F%#%s%0$rMQ$$$k3HKh$j!"J?LL %k!<%F%#%s%0$KHf$Y!":G>. 5%!":GBg 20%DxEYJ?6Q5w N%$r>.$5$/$9k3H,G-$k!#<!85<+M3%k!<%F%#%s %0$NJ?6Q5wN%$O!"=>Mh$N MIN $N5wN%$G$"$k log

I= 1: $=$l$>$l$NJ}K!$NJ?6Q5wN%

L	3D		4D		5D	
	J?LL	<+M3	J?LL	<+M3	J?LL	<+M3
64	5.30	4.73	4.53	3.97	5.03	4.28
128	7.28	6.31	7.15	5.95	5.52	4.61
256	7.52	6.73	7.51	6.14	6.01	5.10
512	9.54	8.42	7.88	6.62	9.38	7.65
1024	9.69	8.81	10.75	8.82	9.75	7.73

2.4 %O!<%I%&%'%"%3%9%H

<!$K nD-MIN $N%O!<%I%&%'%"%3%9%H$K$D$$$FI>2A 9k!#%W%m%;%C%5?t (%a%b%j%b%8%e!<%k?t) $r P !"MIN $N<!85$r n H7!"3F<!85J}8~$N%5%$%:rEy7$$$H$9 kH!"%9%F!<%8?t S $O

$$\lceil \frac{\log P}{n-1} + 1 \rceil$$

HJ$k!#$7$?$,CF%(%l%a%s%H?t$O!"

$$P \times \lceil \frac{\log P}{n-1} + 1 \rceil$$

HJ$k!#0lHL$N MIN K*1k%(%l%a%s%H?t$O!"2 !_ 2 $N%9%$%C%A%(%l%a%s%H$rMQ$$$k$H!"

$$\frac{P}{2} \times \log P$$

G"kN$G!"%(%l%a%s%H?t$K4X7F$O!"$n$D-MIN $O<!85?t$,A}$($kDx!"0lHL$N MIN KHfY$FM-MxG" k3H,o+$k!#

7?$,$7!"nD-MIN O=$NJ,F~=PNO$,A}$($k$?$a!" %m%9%]%$%s%H?t$GI>2A9k$H!"

$$P \times \lceil \frac{\log P}{n-1} + 1 \rceil \times n^2$$

HJCF!"0lHL$N MIN K*1k3F%(%l%a%s%H$N% %$%s%H?t$,>o$K 4 G"$k MIN KHfY$FITMx

G"k3H,o+$k!#$7$+$7!":G6a$N LSI 5;=Q$N%?
C#$r9M$(kH%/%m%9%]%$%s%H?t$,B?$/$F$b LSI%N
%s%M%C%/KJiJ$$HO0OGO0l35$KITMx$H$O$$$($J
%(%l%a%s%H$NG[CV!"%j%s%/$NG[@~N7d9$5Ey$b4^
$a8!F$$9kI,MW,$"$k!#

3 %7%_%e%l!<%7%g%sKh$k@-G=I>2A

M}O@E*$K5a$ak3HNG-$kE>Aw%9%F%C%W?t$O!"
%M%C%H%o!<%/FbItGN%Q%1%C%H$N>WFM$KhkCYl,
9MN8$5$l$F$$$J$$$?$a!"<B:]E*$GOJ$$!#$=$3$G!"3N
N(%b%G%k$K4p$E$-$d$d<B:]E*$J%7%_%e%l!<%7%g%s$r
9TJ&!#

3.1 I>2A>r7o

$3$3GO!"%m!<%+%k%a%b%j$^$?$O%-%c%C%7%e$r;}$D
%W%m%;%C%5$, nD-MIN $r2p$7$F%a%b%j%b%8%e!<%k$H
@\B3$5$l$F$$$k%7%9%F%`$rA[Dj$9$k!#L?Na$*hS%G
%?%C%/$O%m!<%+%k%a%b%j$^$?$O%-%c%C%7%e$K3JG<$5$l
$F$$$k$H9M$(!"3F%W%m%;%C%5$O!"0J2<$N%"%/%;%9$r
3F%/%m%C%/$G%G!<%?$KBP7FH/@8$9$kH7$?!#

- n_{br}: %V%m%C%/%"%/%;%9!#FI$_=P$7$^$?$OFI4|JQ ?t$X$N%"%/%;%9!#3F%W%m%;%C%5$O%G!<%?$,E~Ce$9 k^$G<!$N%"%/%;%9$rH/@8$9k3H,G-$J$$!#
- n_{nb}: %N%s%V%m%C%-%s%0%"%/%;%9!#=q$-9~$_%"%/ %;%9$G!"%W%m%;%C%5$O%"%/%;%9$rH/@8$7F9$0 <!$N7W;;$^$?$O%"%/%;%9$K0\$k3H$,$G$-$k!#

$3$3GO!"I>2A%G!<%?$,H/I=$5lF$$$k%9%$%C%A%7
9g7?JBNs7W;;5! SNAIL[5] $NI>2A$K4pE- n_{br} =
0.01, n_{nb} = 0.04 $K@_Dj$7$?!#%W%m%;%C%5?t$O
$(2^6, 2^7, 2^8, 2^9, 2^{10})$ H7!"100000 %9%F%C%W$r%7%_
%e%l!<%7%g%s7?!#J*!"%M%C%H%o!<%/$,0BDj$9k^
GN 10000 %9%F%C%W$O!"%7%_%e%l!<%7%g%s7k2L$+$i
=|$$$?!#

%9%$%C%A$N%b%G%k$O!"%(%l%a%s%HFbIt$K %Q%1%C%H
3JG<MQ%P%C%U%!$r;}$D0lHLE*$J MIN G"$j!"%P%C
%H$O 1 %/%m%C%/$G%(%l%a%s%H4V$rE>Aw$5lk!#FI$_
=P7G!<%?MQ$K!"%a%b%j%b%8%e!<%k$+$i PU $X
$&5"4TMQ$N MIN rJLK;}DbNH9k!#%9%$%C%A
%0%(%l%a%s%H$O!"F~NO%j%s%/$KBP7F FIFO $N
NO%j%s%/KBP7$F%Q%1%C%H 1 8DJ,3JG<$G$-$k%P
$r;}$D!#<!$N%9%F!<%8$N%(%l%a%s%H$N FIFO $N
$?>l9g!"%Q%1%C%H$O=PNO%j%s%/$N%P%C%U%!$GBT$A>uBV
KJ$k!#$3$3$G$O%7%_%e%l!<%7%g%s;~4V$H%a%b%j$N
4X78$G FIFO $G3JG<$G$-$k%Q%1%C%H$N:GBg?t$O 3 $H
7?!#%Q%1%C%H$NM%@h@)8f$O0J2<Nh$&$K9TJC$?!#

- J?9T%j%s%/$+$i$N%Q%1%C%H$K:G9b$NM%@h8"$rM? $(!"=g$K<!85?t$NDc$$%j%s%/$+$iMh$?%Q%1%C%H $[$I9b$$M%@h8"$rM?$($k!#
- >WFM7F!"0l2sBT$?$;il$?%Q%1%C%H$O$=$NE EYM%@h8"$r>e$2!"<!2s$NE>Aw$KM-MxKJkh$& K9$k!#

NH?!"%a%b%j$N%"%/%;%9;~4V$O 3 %/%m%C%/H7!"%a
%b%j%b%8%e!<%kFb$O%9%$%C%A%s%0%(%l%a%s%HF1MM%Q
%1%C%H 1 8DJ,$N FIFO $r;}$D!#

3.2 %"%/%;%9%l%$%F%s%7%#

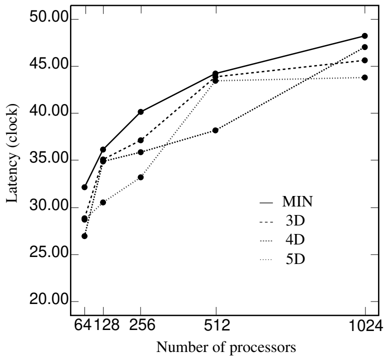
$3$3GO!"%W%m%;%C%5$,H/@8$7$?FI$_=P$7 (%V%m%C
%-%s%0%"%/%;%9) MW5a$KBP1~$7$?%Q%1%C%H$,LaCF$/
k^GN%/%m%C%/?t$r%"%/%;%9%l%$%F%s%7%#$H9M$(!"
%"%/%;%9$,6I=j@-$r;}CF$$$k>l9g$H;}$C$F$$$J$$
>l9gKD$$$F!"B,Dj$r9T$JC?!#

3F%W%m%;%C%5$,A4$/%i%s%@%`$K%a%b%j%b%8%e!<%k
KBP7$F%"%/%;%9$r9TJC$?>l9g$K4X7F!"<!85<+
M3%k!<%F%#%s%0K!$rMQ$$!"%W%m%;%C%5?t 64 $+$i 1024
GJQ($?>l9g $N%l%$%F%s%7%#$r?^ 5$K<($9!#?^ 5
KhkH!"6I=j@-NJ$$>l9gGb!"nD-MIN $ODL>o
$N 2 <!85 MIN KHfY!"%l%$%F%s%7%#$,>.$5$$$3H,
J,$+$k!#FC$K!"%5%$%:$,9g$&>l9g$O!"2 <!85 MIN $K
HfYFi+$KDc$$%l%$%F%s%7%#$r<B8=7F$$$k!#3l
$O!"$n$D-MIN $NJ}$,!"<!85<+M3%k!<%F%#%s%0$NMxMQ
Kh$j!"J?6Q5wN%$,>.$5$$$E@$K2C$(!"nD-MIN $O8r
49G=NO$N9b$$%9%$%C%A%s%0%(%l%a%s%H$rMQ$$$F$$$k
$?$a!";~Kb@-G=$,Dc2<$7$J$$$?aH9M$($ilk!#

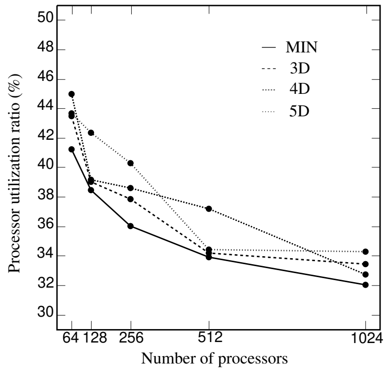
<!$K!"%"%/%;%9$K6I=j@-N"$k>l9g$N%l%$%F%s%7%#
rB,Dj7$?!#$3lO!"%"%/%;%9$N 50%$,$=$l$>$l<!
85?t$N0lCW$9$k%a%b%j%b%8%e!<%k$KBP7F9TJo$l
kH2>Dj7?!#3N>l9g!"DL>o$N 2 <!85 MIN $KBP
7F%"%/%;%9$N6I=j@-$rM?$($k$H!"$+$($C$F%[%C%H%9
%]%C%H$r7A@.$7$F@-G=$,Dc2<9k$?$a!"DL>o$N MIN
KBP9$k%"%/%;%9$O6Q0l%"%/%;%9$rMQ$$$?!#3N>l
9g!"?^ 6$K<($9h&$K!"6I=j@-$r@8$+$9$3$H$,$G$-$k
nD-MIN $,$5iKM-MxKJ$j!":GBg 24%2~A1$5lk!#

3.3 %W%m%;%C%5MxMQN(

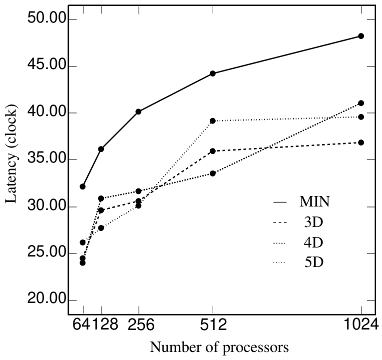
%M%C%H%o!<%/$N:G=*E*$J@-G=$O!"$3lr2p7?%"
%/%;%9Kh$j%W%m%;%C%5$,Il@$1BT$?5lk+$K
hC$F7h$^$k!#$=3G!"A4<B9T;~4VCf!"%"%/%;%9N?
aKBT$?$5lk;~4V$N3d9g$NJ?6Q$r!" %W%m%;%C%5Mx
MQN(H7FB,Dj7$?!# %"%/%;%9$,6QEy$KJ,;6$7$F$$
$k>l9g$N<!85<+M3%k!<%F%#%s%0$N>l9g (6I=j@-L5$7) $N7k
2L$r?^ 7$K<($9!#%W%m%;%C%5?t$,A}2C9k$H!"%l%$%F
%s%7%#$,A}2C$9k?$a!"%W%m%;%C%5MxMQN($,>.5/
Jk!#3lKBP7!"%"%/%;%9$K6I=j@-$,B8:_9k>l
9g$N%W%m%;%C%5MxMQN($r?^ 8$K<($9!#%"%/%;%9%l%$%F
%s%7%#$,>.$5$$$7k9gLV$[$I%W%m%;%C%5NBTA;~4V$,
8:k?$a!"%W%m%;%C%5MxMQN($K$D$$$F$b nD-MIN $N
J}$,M-Mx$G$"$k!# nD-MIN K*$$$F$O!"<!85?t$,9g
$&>l9g!"<!85$NBg$-$$ MIN $NJ}$,@-G=$,2~A1$5lF$*
$j!"%5%$%:$,Bg$-$$>l9g!"DL>o$N MIN KBP7$F:GBg
20%DxEYMxMQN($r2~A1$9$k8z2L$,$"$k3H$,$o$+$k!#



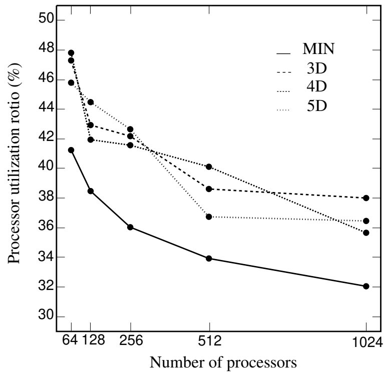
?^ 5: %l%$%F%s%7%#(6I=j@-L5$7)



?^ 7: %W%m%;%C%5MxMQN((6I=j@-L5$7)



?^ 6: %l%$%F%s%7%#(6I=j@-M-$j)



?^ 8: %W%m%;%C%5MxMQN((6I=j@-M-$j)

4 $=$NB>$NFC@-$HB>$N **MIN** HN Hf3S

4.1 %Q!<%F%#%7%g%K%s%0

nD-MIN $O!"Generalized Cube $K%j%s%/$rDI2C$7 $?9=B$$r<hk?$a!"3FJ?LL$N%9%F!<%8J}8~$K4X$7$F %Q!<%F%#%7%g%K%s%0$,2DG=G"$k [4]!#?^ 9$K<(9h $&$K!"3FNs$O 2^n C10L$G%Q!<%F%#%7%g%sK^$Hak 3H$,G-!"3F%Q!<%F%#%7%g%sFb$NDL?.$OB>$N%Q!< %F%#%7%g%s$K=P$k3HOJ$$!#

3N@-<AO=l>lNJ?LLKBP7$FM-8z$G$"$k$? $a!"$n$D-MIN $O3F<!85J}8~$K 2^m $N%/%m!<%:%I%Q!< %F%#%7%g%s$r7A@.$9k3H,G-$k!#$3$N%Q!<%F%# %7%g%s$O!"FHN)7F$?J#?t$N%8%g%V$r<B9T$9$k>l9gEy $KM-8z$G$"$k!#

4.2 8N>c$*$h$S:.;($N2sHr

nD-MIN $O!"=[4D9=B$$r;}D?$aFCDj$N%9%$%C%A %s%0%(%l%a%s%H$"$k$$$O%j%s%/$N8N>c$"$k$$$O:.;($r1*2s$9k3H,G-$k!#

:G$b4pK\E*$J1*2sK!H7$F!"$^$:!"$n$D-MIN NG 0U$NJ?LL>eGN1*2s$r9M$($k!#F10lJ?LL>eGO!"$9 YF$N%"%/%;%9$O!"8N>c$"$k$$$O:.;($,$J1l$P=[4D%k!<%W$r7PM3$7$J$$$GL\E*H9$k%a%b%j%b%8%e!< %k$KE~Ce9k!#%W%m%;%C%5$KD>@\@\B3$5l?%9%$%C %A%s%0%(%l%a%s%H$,8N>c7?>l9g!"$^$?$O!"%a%b%j $KD>7k$7$?%9%$%C%A%s%0%(%l%a%s%H$,8N>c$7$?>l9g $O!"$=$N%W%m%;%C%5$^$?$O%a%b%j$O!"%7%9%F%`$+$i@Z $jN%$5lk[1]!#>e5-$N%(%l%a%s%H$,:.;(7?>l9g$O!" C1=c$K%P%C%U%!$,6u$/$^$GBTD3HKJk!#

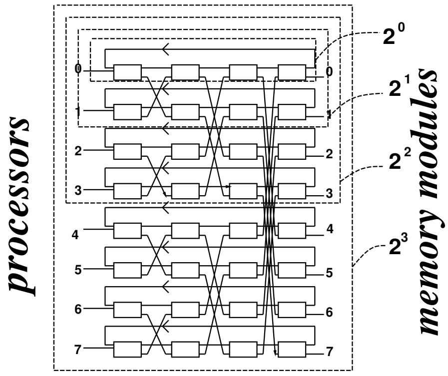
F10lJ?LL>eGN1*2s%k!<%F%#%s%0

%9%$%C%A%s%0%(%l%a%s%H $E(F,fs)$ $NF~NO%j%s%/$^ $?$O%P%C%U%!$,8N>c$7$?$j:.;(7F$$$k>l9g ($?$@$7 F $N 2 ?J?tI=<($r $F=f_{n-1}\dots f_0$ H9$k)!"$=$N%9 %$%C%A%s%0%(%l%a%s%H$K%G!<%?$rE>Aw9k%(%l%a%s %H $E(F,fs-1)$, $E(rev(F,fs-1),fs-1)$ $O!"

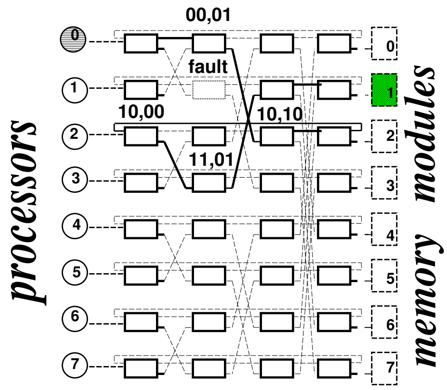
1. fs %9%F!<%8GO!"8N>c$"$k$$$O:.;(7F$$$k%9 %$%C%A%s%0%(%l%a%s%H$K@\B3$5$l$F$$$J$$$J$}$N %j%s%/$rMQ$$$F%Q%1%C%HrAwk!#

2. $fs+1$ %9%F!<%8$G!"%/%m%9%j%s%/$rMQ$$$?E>Aw $r(1 2s9T$J$&!#$fs+1$ %9%F!<%80J9_GOG$0U$N %k!<%F%#%s%0$r9T$J$&!#

[1] $[$HsI$NBQ8N>c@- MIN K*$$$F!"F1MM$N2>Dj$r7F$$$k



?^ 9: %Q!<%F%#%7%g%K%s%0



?^ 10: 1*2s$NMM;R

3. =[4D%k!<%W$r7PM3$7$F!"2 =dL\$OJ?LL%k!<%F%#%s%0$K4p$E$$$?%k!<%F%#%s%0$rMQ$$$k!#

>e5-$N<jK!$G8N>c$^$?$O:.;($7$F$$$k%(%l%a%s%H$r1*2s$G$-$kNO0J2<$NM}M3$Khk!#

1*2s%k!<%F%#%s%0$N@5Ev@-

1*2s%k!<%F%#%s%0$G 1 =dL\$KE~Ce9k:G=*%9%F!<%8$N%9%$%C%A%s%0%(%l%a%s%H $E(X,n-2)$ $N%i%Y%k X $O!"$fs+1$ %9%F!<%8$G%/%m%9%j%s%/$rMQ$$$k3H$+$i0J2<Nh$&$KI=$9$3H,G-$k!#

$$X = x_{n-1}\dots x_{fs+2}\overline{f_{fs+1}}\;\overline{f_{fs}}f_{fs-1}\dots f_0$$

HJ$k!#$?$@$7!"$x_{n-1}\dots x_{fs+2}$ OG0U$N 2 ?J?t$G$"$k!#

$3$3$G!"=[4D%j%s%/$rMQ$$$F 2 =dL\$N%k!<%F%#%s%0$r9T$J$&$?$a!"2 =dL\$N=PH/CO$N%(%l%a%s%H$N%i%Y%k$O!"$E(X,0)$ HJ$k!#4pK\%k!<%F%#%s%0J}K!$K=>CF%k!<%F%#%s%0$r9T$J$&>l9g!"=PH/CO$N $fs+1$ 7eL\$N%i%Y%k$\overline{f_{fs+1}}$ G"k3H+$i!"2 =dL\$NDL2a%9%$%C%A%s%0%(%l%a%s%H$N%i%Y%k$O!"$fs+1$ %9%F!<%8$^$G$O 1 =dL\$H0lCW9k3HOJ$$!#9JoA!"2 =dL\$N%Q%9$O8N>c$"$k$$$O:.;(7?%9%$%C%A%s%0%(%l%a%s%H $E(F,fs)$ rDLk3HOJ$$!#

?^ 10$K!"PU0 $,%a%b%j%b%8%e!<%k 1 KBP7$FMQ%1%C%H$rAwC?;~!"8N>c7?%9%$%C%A%s%0%(%l%a%s%H (fault 0u) $r1*2s$9$kMM;R$r<($9!#8N>c%(%l%a%s%H$rHr1?<!$N%9%F!<%8$G%/%m%9%j%s%/$rMQ$$$F$$$k$?$a!"2 =dL\$N%Q%9$O 2 =dL\$N%Q%9$H8N>c$"$k$$$O:.;(7?%(%l%a%s%H$NB8:_$9$k%9%F!<%8$^GO$$JC?%Q!<%F%#%7%g%sFb$r?J$`!#3N$?$a 2 =dL\$N%Q%9$,:F$S8N>c$"$k$$$O:.;(7?%(%l%a%s%HrDLk3HOJ$$!#

>e5-$N1*2s%k!<%F%#%s%0$O!"nD-MIN N9YF$N<!85$NJ?LL$G2DG=$G$"$j!"1 =dL\$@1GJ/!"2 =dL\0J9_KBP7FbE,MQ9k3H$,$G$-$k!#7?$,$C$F!"$n$D-MIN $O!"4pK\%k!<%F%#%s%0%"%k%4%j%:%`KBP7$F!"8N>c$"$k$$$O:.;($,5/$-$?>l9g!"=d2s?t$,Nd9@1G!"1*2s2DG=$J%Q%9$, n K\B8:_9k3H$,$o$+$k!#3FJ?LL$O!"%(%l%a%s%H$, 2 8D8N>c7?>l9gDL2aG-$J$$%(%l%a%s%H$,@8$8MxMQ9k3H$,$G$-$J$/$J$k!#$7$?$,CF!"nD-MIN $O $2n-1$ 8D$N%(%l%a%s%H8N>c$KBP=hG-k3H,o+$k!#

I=2$K%9%F!<%8 1 $N%(%l%a%s%H$, 1 8D8N>c$,@8$8$?>l9g$N!"J?6Q5wN%$NA}2C$r<($9!#I=2$rI=1Cf$NJ?LL%k!<%F%#%s%0$NJ?6Q5wN%$HHf3S$9kH!"8N>cKh$kJ?6Q5wN%$NA}2COo$:$+G"$k!#>e5-$N@-<A$O!"8N>c2sHr$@1GJ/!":.;($r2sHr$9kE,MQ7?%k!<%F%#%s%0$rMQ$$$k>l9gKbM-MxG"$k!#

I=2: 1*2s7?>l9g$NJ?6Q5wN%

	3D	4D	5D
64	5.31	4.54	5.04
128	7.29	7.15	5.52
256	7.52	7.51	6.01
512	9.54	7.88	9.38
1024	9.69	10.75	9.75

%(5+$N5DO@$O4JC1N?aKJ?LL%k!<%F%#%s%0$K4X$7$F9T$JC?$,!"<!85<+M3%k!<%F%#%s%0$K$D$$$F$bF1MM$NJ}K!$,E,MQ2DG=$G$"$k!#

4.3 B>$N8&5f$H$NHf3S

B>Kb%k!<%W9=B$!"3<!859=B$$r;}C? MIN $,Ds0F$5lF$$$k!#Kumar iKhk ASEN[9] $O!"=[4D%k!<%W$r;}$D MIN G"k,!"3N=[4D%k!<%W$O=DJ}8~K"$j!"<g$K8N>c2sHrN?aKMQ$$$ilF$$$k!#

$^$?!"Lea iN Multi-Log_2N %M%C%H%o!<%/ [10] H9FKhk PBSF[5] $O 3 <!859=B$$r;}C? MIN G"k,!"3N MIN GO 3 <!85E*$J@\B3$O 1 <!85E*KJB5CF PU $H%a%b%j$r7ksG$*$j!"7k9gLV$NDL2aN($r8BP$7$9k?aKMQ$$$ilF$$$k!#7?$,$C$F!"F10l$t$N PU-%a%b%j$r@\B3$9$k>l9g$O!"3D-MIN KHfY3HO,k$+$KBgNL$N%O!<%I%&%'%"$rI,MWH9$k!#$^$?!"nD-MIN $N<g$?$kL\E*$G$"$k6I=jE*$JMxMQ$,G-$J

$/$J$k!#

B<EDiKhk MDX[11] $O!"B><!85J}8~$K%9%$%C%A$r;}$DE@$G nD-MIN $H6&DLE@$,$"$k!#7+$7 MDX O=l>lNJ}8~$N@\B3$OC1CJ@\B3G"$j!"B?CJ@\B3$N MIN 9=B$$r;}$D nD-MIN $NJ}$,%5%$%:$KBP9k3HD%@-!"%Q%1%C%HE>Aw$N=@Fp@-$K$*$$$FM%lF$$$k$H9M$(il$k!#$7$+$7!"3NE@$K4X$7FO:#8eNj>\:Y$JI>2A$HHf3S$,I,MW$G$"$k!#

5 $^$H$a

K\O@J8GO!"6I=j@-$rMxMQ$9k3HNG-$k MIN G"$k nD-MIN $rDs0F$7!"E>Aw%l%$%F%s%7%#!"%W%m%;%C%5MxMQN(KD$$$F4JC1$J3NN(%b%G%k$Khk2r@O$r9T$JC?!#$=$N7k2L!"%i%s%@%`E>AwK*$$$F$b=>Mh$N MIN hjM-MxG"$j!"%"%/%;%9$K6I=j@-$,$"$k>l9g$O%l%$%F%s%7%#$r 24% 2~A1G-k3H,o+C?!#$^$?!"%(%l%a%s%H$N8N>c$"$k$$$O:.;(KBP7$F1*2s$9$k%k!<%F%#%s%0$r<($7!"Bg$-$J@-G=$NDc2<J7$K1*2s$,2DG=G"k3H,o+C?!#

:#8e!" 4pK\E*$J@-G=$K4X7Fhj<B:]E*$J>r7o$N2<$G!"%7%_%e%l!<%7%g%s$r9T$J$$I>2A7F$$$/0lJ}!"E,1~7?%k!<%F%#%s%0Kh$k:.;($N2sHr$N8z2L$K$D$$$F$b6qBNE*$KI>2A$r9T$JCF$$$/M=DjG"$k!#$^$?!":#2s$NI>2A$O!"MIN $O 2!"$n$D-MIN $O<!85?t$K1~8?%/%m%9%]%$%s%H?t$G9TJCF*$j!"8xJ?$5$r7g$/LL$,$"$k!#LSI $N%T%s?tEy$r2>Dj7F!"F10l%3%9%H$r2>Dj$7$FI>2A$9kI,MW,$"$k!#

;29MJ88%

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[2] 2#ED!"B>!VD6JBNs7W;;5! RWC-1 $NAj8_7k9gLV!W >p=h8&Js 93-ARC-101

[3] 2#ED!">>2,!"2,K\!"9-Ln!":d0f!"VD6JBNs8~$1Aj8_7k9gLV MDCE $NDs0F$HI>2A!W >pJs=hM}3X2qO@J8;o!"Vol.36,No.7, Jul.1995.pp.1600-1609

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[5] H9!"E7Ln!VB?=E=PNO2DG=$J MIN $N@-G=I>2A!W>pJs=hM}3X2qO@J8;o Bh 36 4, Bh 7 9f 1995 G/ 7 7n

[6] :{86!"B>!V*SSS* 7? *MIN* $K4p$E$/%^%k%A%W%m%;%C%5 *SNAIL* $N<BAu$HI>2A!W>pJs=hM}3X2qO@J8;o Vol.36,No.7,Jul. 1995. pp.1640-1651

[7] ;y6L!":d0f!";38}!V9bJBNs7W;;5! EM-4 H=$NJBNs@-G=I>2A!WEE;R>pJsDL?.3X2qO@J8;o ,J75-D-I,No.8,1992. pp.607-614

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