HFMQJBNs OS N?aN;q8;>pJs$rMxMQ$7$?
%9%1%8%e!<%j%s%0J}<0$N8!F$

?.9qM[FsO:　>>K\>0　J?LZ7I

El5~Bg3X Bg3X1!M}3X7O8&5f2J >pJs2J3X@l96
") 113 El5~ETJ85~6hK\6? 7–3–1
Email: {nobukuni, tm, hiraki}@is.s.u-tokyo.ac.jp

$" $i $^ $7　%(%l%/%H%m%K%/%95;=Q$N8~>eKh$k%M%C%H%o!<%/<~JU$N@-G=8~>e$dJBNs4D6-2<$G$N3F<o:GE,2=5;K
<u$1!"J,;6%a%b%j4D6-$G$NJBNs=hM}$,8=<BL#rBSSF-$?!#K\9F$G$O!"#N#U#M#A7?JBNs7W;;5!$d%o!<%/%9%
%/%i%9%?>e$KHFMQJBNs OS $r9=C[$9k?aN%+!<%M%k%l%Y%k!&%9%1%8%e!<%j%s%0KD$$$F8!F$$9$k!#J,;6%a
$GJBNs%W%m%;%9$N8zN(E*$J<B9T$rK8$2$k3HJ/%^%k%A%f!<%6!?%^%k%A%8%g%V4D6-$r9=C[$9kK$O!"%a%b%
IN<B;q8;$N;HMQ>u67$r9MN8$7$?%9%1%8%e!<%j%s%0$r9T$J$$%7%9%F%`A4BN$N@-G=$r$"$2k3H,I,MWG"$
%m%;%9Kh$K=jM-$9$k<B%Z!<%8>pJs$r4IM}$7!"$=$N>pJs$K7?$,$C$F%9%1%8%e!<%j%s%0$r9TJC$?!#%7%_%e%
Kh$j!"4JN,2=$5l?%b%G%k>eGN%9%1%8%e!<%j%s%0K!$NHf3S$r9TJC$?!#

%-!<%o!<%I　NUMA, HFMQJBNs OS, %+!<%M%k%l%Y%k!&%9%1%8%e!<%j%s%0

Evaluation Of A Scheduling Method Using Resource Informations For General Purpose Parallel OS

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Abstract Parallel processing on parallel/distributed systems is showing greater availability as network-surrounding micro-electronics evolves and many optimization mechanisms are realized. This paper describes a kernel-level scheduling method to build a general purpose parallel OS on NUMA-type parallel machines. In a distributed memory environment, constructing a multi-user/multi-job world without decreasing high efficiency of parallel applicatoins can be achieved by managing resource informations and scheduling according to them. We simulated on a simplified model and evaluated four scheduling methods.

key words NUMA, parallel OS, kernel level scheduling

1 O8aK

NUMA 7?%7%9%F%`$O!"$h$jC1=c$Ghj0B2A$J9=@.MWAG rh$jB??t7k$SIU1F9b$$=hM}G=NO$rF@$k3H$,$G$-$kWC D'$r;}$D!#6aG/$N%M%C%H%o!<%/$<~JU$N@-G=8~>e$rGX7J$K!" JBNs%"%W%j%1!<%7%g%s$N$?$a$N<B9T;Y1g5!9= [1]!"JBNs4D6- 2<GN3F<o:GE,2=5;K!$N8&5f!?3+H/ [4][3] $O!" NUMA 7?% JBNs7W;;5!>eGN9b8zN($JHFMQ@-$r;}C?;HMQ7ABV$r2DG= H7DD$"$k!#$=3G!" NUMA 7?JBNs7W;;5!>e$KHFMQ$J 4D6-$rDs6!9kG=NOrHw($?%*%Z%l!<%F%#%s%0!&%7%9%F% $N3+H/$,5aailk!#

2f!9$,3+H/Cf$N SSS–CORE[2] $O!" NUMA 7?JBNs7W;; 5!>e$K;~J,3d HQ!<%F%#%7%g%K%s%0$rJ;MQ$7$F%^%k%A%f!< %6!?%^%k%A%8%g%V4D6-$rDs6!$7!"JBNs%"%W%j%1!<%7%g%s$N 8zN(NI$$<B9T$r<B8=$9k3HrL\I8H9$k!# NUMA 7? JBNs7W;;5!$G$O%a%b%j%"%/%;%9$N%3%9%H5Z$SMWAG%W%m%;% %54V$NDL?.%3%9%H$,0lMM$GOJ$$!#=>CF!"JBNs%"%W%j %1!<%7%g%s$r8zN(NI$/<B9T9kKO!"3F%9%l%C%I$rF1$8%9 %9%1%8%e!<%j%s%0$7!"3d$jEvFil?MWAG%W%m%;%C%5$r 5wN%!"5Z$S<B9T;~$N%a%b%j%Z!<%8$N0\F0$r:G>.8B$K$9 k3H,=EMWKJ$k!# SSS–CORE GO<B%a%b%j$N;HMQ>u 67$N%9%1%8%e!<%j%s%0XNH?1G!"%f!<%6%l%Y%k$+$i$N%9%1 %8%e!<%j%s%0@)Ls$NMxMQ!"$=$7$FM%@hEY$rMxMQ7?;q8;% 8xJ?$J3d$jEvFH$$$&#3DN%"%W%m!<%ArH$k!#

K\9FGO!"%/%i%9%?9=@.$G n CJ k 40A4LZ$N7A$r7? BP>N$+$D6Q<A$J%7%9%F%`$r4JN,2=7F%b%G%k2=$7!"Bf?t8G Dj@)LsN_$rMQ$$$?%9%1%8%e!<%j%s%0K!$r<BAu$7!"%7%_%e %l!<%7%g%s$r9T$JC?!#99$K!"<B%a%b%j$N;HMQ>u67$r%9%1 %8%e!<%j%s%0$XH?1G9k3H$NM-8z@-$N8!>Z$r9T$JC?!#

2 SSS–CORE

8=:_3+H/Cf$N SSS–CORE $O!" NUMA 7?JBNs7W;;5!$N BP>]H7$?HFMQJBNs#O#S$G$"$k!#BP>]H9$k NUMA 7?JB Ns7W;;5!$N%$%s%?!<%3%M%/%7%g%s%M%C%H%o!<%/$N7A>u$OLd oJ$$!#;~J,3d $H%Q!<%F%#%7%g%K%s%0$rJ;MQ7F%^%k%A %f!<%6!?%^%k%A%8%g%V4D6-$rDs6!$7!"JBNs%"%W%j%1!<%7%g %s$N8zN(NI$$<B9T$r<B8=$9k3HrL\I8H9$k!#

NUMA 7?$NJBNs7W;;5!%7%9%F%`$G$O!"%a%b%j%"%/%; %9%3%9%H5Z$SDL?.%3%9%H$,!"5wN%$K1F6A$5lk!#3li3 %9%H$,>.$5$$/M^$($ilkh&$K%9%1%8%e!<%j%s%0$9kH!" 8D!9$NJBNs%"%W%j%1!<%7%g%s$O8zN(NI$/<B9T$5lk!#$?$@ $7$3li%3%9%H$,M?$($k1F6A$O%W%m%;%9$K8GM-$NbNG" $j!"=>$C$F<u$1$k1F6A$b5^6^G"$k!#

SSS–CORE GO!"7W;;5!$N%$%s%?!<%3%M%/%7%g%s%M%C%H %o!<%/$N3,AX9=B$$H0lCW7?9=B$$N;q8;4IM}9=B$$rMQ0U$7 $F;q8;>pJs$N4IM}r9$k!#$^$?!"3F%W%m%;%9$O%9%1%8%e!< %j%s%0KBP7$F@)Ls$rDs<(G-$k!#%+!<%M%k%l%Y%k!&%9 %1%8%e!<%i$O;q8;>pJs$H!"%W%m%;%9$+$iDs<(5l$?%9%1 %8%e!<%j%s%0@)Ls$K7?$,$C$F!"%W%m%;%9C10L$K;q8;$N3d Ev$r9TJ&!#;q8;>pJs$rMxMQ$9k3HG!"%?%$%`%9%i%$%9

Kh$N;q8;$N3djEvF>u67$r%9%1%8%e!<%j%s%0$KH?1G9k$3 H,2DG=HJ$k!#99$K!"Ds<(5l$?%9%1%8%e!<%j%s%0@)Ls $K=>$C$F%9%1%8%e!<%j%s%0$9k3HG!"%W%m%;%9Kh$K0[$J $k;q8;$XNM_5arK~$?$9$3$H$,$G$-$k!#;q8;4IM}9=B$$OJB Ns7W;;5!$N9=B$$HF1$8$G$"$k$?$a$K!"3d$jEvFr9TJ&%W %C%54V$NDL?.%3%9%H$rGD0.7?$&$(GN%9%1%8%e!<%j %s%0$,2DG=$G$"$k!#$?$@$7!"%W%m%;%9Fb$G$N;q8;3d$jEv$F %f!<%6%l%Y%k!&%9%1%8%e!<%i$K0lG$$5lk!# %9%1%8%e!<%j%s%0$5$l$?%W%m%;%9$O!";HMQ7?;q8;NLH %9%1%8%e!<%j%s%0@)Ls$K=>$$M%@hEY$,%($%%8%s%0$5$l!"% $$`%9%i%$%9Kh$KM%@hEY=g$K%9%1%8%e!<%j%s%0$5lk!#$9 lKhj8xJ?$J%^%k%A%f!<%6!?%^%k%A%?%9%/4D6-$rC#@.$9 $k!#

SSS–CORE GO3NB>Kb!"%7%9%F%`$N@-G=8~>e$N$? $a$N5!9= [2] $r<h$j9~$`!#BP>]JBNs7W;;5!GOFs<!5-21$X $N?"%/%;%9$O%W%m%;%C%5%Q%o!<$r>CHq$7$J$$$G9TJ($k A[D$$KJC$F$$$k!#$=$N$?$a!";~J,3d$N7W;;Cf$K<!$N;~J 3d$G%9%1%8%e!<%k5l$k%W%m%;%9$N$?$a$NFs<!5-21$N%W 1j$N'%C%A$r9TJ&!#3l$r;Y1g$9k?$a!"%f!<%6%l%Y% $$$+!<%M%k%l%Y%kXI,MWJ%G!<%?NN0h$N%R%s%H$r<($9!# %^%M%k%l%Y%k!&%9%1%8%e!<%j%s%0$r 1 %?%$%`%9%i%$%9J, @h9T$7F*3J$$!"0J>e$N5!9=$rMxMQ9k!#

3 %9%1%8%e!<%j%s%0K!

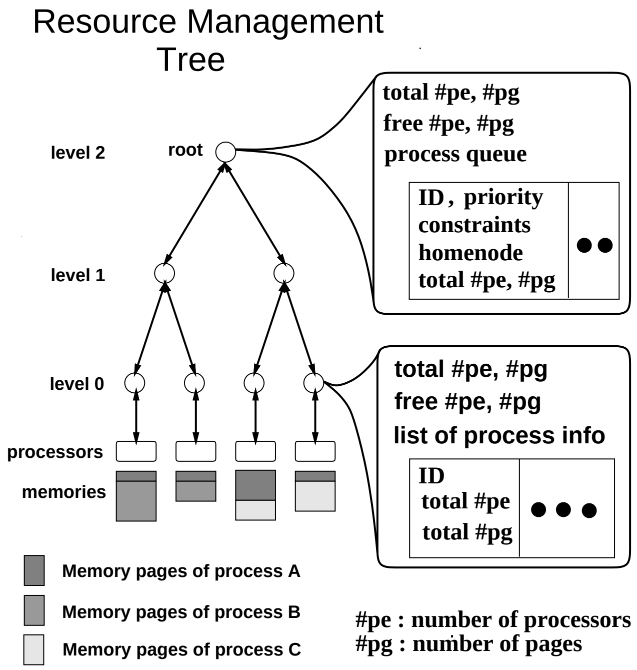
SSS–CORE GO%?%$%`%9%i%$%9$N4V3V$r 100msec $+ $i?tICDxEY$NHf3SE*Bg$-$JC10L$r2>Dj$7$F$$$kNG!"%9 %1%8%e!<%j%s%0KI,MWH5l$k=hM}%3%9%H$OL5;kG-$k NH2>Dj9k!#=>CF%7%_%e%l!<%7%g%sGO%9%1%8%e!< %s%0$O<B9T;~4V$r 0 H7$F<B9T$5$l!"%7%_%e%l!<%7%g%s$N I>2AKO4^$^$l$F$$$J$$!#$^$?3N2>DjN?$a!";q8;4IM} LZ$N%G!<%?9=B$$N<B%a%b%j>eXN%^%C%T%s%0$d%9%1%8%e!< %j%s%0$N7W;;J}K!!"5i$K%+!<%M%k$X$N%f!<%6%l%Y%k$+$i $N%9%1%8%e!<%j%s%0@)Ls$N3+<(K!!J$$%s%?%U%'!<%9!"<BAu K!K$OK\9F$G$OM}A[E*$JbN$r2>Dj$9$k!#

3.1 ;q8;4IM}LZ

2>A[E*$J;q8;4IM}9=B$$rMQ0U$7!"$3lK%7%9%F%`$N3,AX 9=B$$HF10l$NLZ9=B$$r;}$?$;$k!#K\9F$GO3$N9=B$$N$3 Hr;q8;4IM}LZ$H8F$V!#;q8;4IM}LZ$N3F%N!<%IGO!"$=$N %N!<%I0J2<$K4^$^lk%W%m%;%C%5$H<B%Z!<%8$NAm?t5Z$S!" %U%j!<$J%W%m%;%C%5$H<B%Z!<%8$NAm?t!"JiSK%W%m%; Kh$K ID 5Z$S;HMQ$5lF$$$k%W%m%;%C%5$H<B%Z!<%8$NAm?t $r5-21$9$k!#$^$?%k!<%H%N!<%I$KO3$NB>$K!"%W%m%;%9Kh $K%9%1%8%e!<%j%s%0@)Ls!"M%@hEY!"%[!<%`%N!<%I!J8e=R!K $r;}$D!#?^ 1$K 4 %W%m%;%C%59=@.%7%9%F%`$N>l9g$NNc$r<($9!#

3.2 %9%1%8%e!<%j%s%0@)Ls

!#2s$N%7%_%e%l!<%?$K<BAu7?%+!<%M%k%l%Y%k!&%9%1 %8%e!<%j%s%0K!GO!"Bf?t8GDj@)Ls N_$r07$&!#Bf?t8GDj



?^ 1: ;q8;4IM}LZ

@)LsGO!"3F%W%m%;%9$O%+!<%M%k$KBP7F<+J,$,I,MW$H9kMWAG%W%m%;%C%5$N0lDj$N?t$r;XDj$9k3H,G-$k!#$3$N%7%_%e%l!<%7%g%s$G$O!"%W%m%;%9$K%9%1%8%e!<%j%s%0$,Ls$rJQ99$9$k3H!JBf?t8GDj@)LsGO4uK>9k0lDjBf?t$rJQ99$9k3$H!K$rG'aF$$$J$$$N$G!"%W%m%;%9$O@8@.;~1F$+$i>CLG9k$^$GF1$8JBNsEY$r;}$D!#

3.3 M%@hEY$N7W;;K!

M%@hEYOCM,>.$5$$$[$I9b$$!#M%@hEY$N7W;;K!$r0J2<$K<($9!#$^$:0J2<NCMr7W;;9k!#

- ;HMQ7?;q8;NL!' $U_r = C_p *$;HMQ%W%m%;%C%5Am?t$+C_m*$;HMQ%Z!<%8Am?t
- @)Ls>r7o$N87$7$5!' $R_c =$ MW5a%W%m%;%C%5Bf?t/Am%W%m%;%C%5?t
- @)Ls>r7o$NK~B-EY!' $S_c = 0$ or 1
- L5BLK7$?;q8;NL!' $W_r = C_{wp} * nwp *$MW5a%W%m%;%C%5Bf?t/Am%W%m%;%C%5?t
- BT$A%W%m%;%9$NM-L5!' $f_w = 0$ or 1
- <cJV$j7O?t!' C_r

$3$3$G!" nwp $OD>A0$N;~J,3d$G;HMQ$5lJ$+$C$?%W%m%;%C%5$N?t$G!"D>A0$^$G%9%1%8%e!<%k$5lF$$$?%W%m%;%9$N4V$G2C=EG[J,7?CM W_r $r%Z%J%k%F%#!<$H7F$$$k!#3liNCM$r!J0lIt$O%W%m%;%9Kh$K!K7W;;$9kH!"<!$N<0$Khj$=$N%W%m%;%9Kh$N%(%$%8%s%0NCM,5aailk!#

$$aging = (U_r R_c S_c + W_r) f_w * t - C_r(1 - t)$$

%7%_%e%l!<%7%g%sCf$N%W%m%;%9$O!"%?%$%`%9%i%$%9;~$K%9%1%8%e!<%k$5lk$+!"$5lJ$$$+N?$a!" $t = 0$ or 1 G"$k!#

$^$?!"M%@hEYNCMNH/;6rKI0$?$a$K!"D>A0$^$G%9%1%8%e!<%k$5lF$$$?%W%m%;%9$N%(%$%8%s%0$NAmOB$r!"BT$A>uBV$@C?%W%m%;%9$K<cJV$jJ,H7$F6QEy$KJ,G[9k!#

3F78?tNCMH7F%7%_%e%l!<%7%g%sGO!"I= 1K"kh$&$K4JC1JCMrMxMQ7?!# C_m NCMO!" 1 %a%b%jEv$?$j$N%Z!<%8?t$r 400 H7$?%7%_%e%l!<%7%g%s$GNCMG$"$k!# 1 %a%b%j$NH>J,$N 200 %Z!<%8$r@jM-$9k3HHMWAG%W%m%;%C%5 1 Bf$r;HMQ$9k3HH$, 1:1 KJkh$&$KD4@a5l$F$$$k!#

I= 1: M%@hEY7W;;N?aN78?t$NCM

M%@hEY7W;;MQ78?t	CM
C_p	1.0
C_m	0.005
C_{wp}	1.0
C_r	1.0

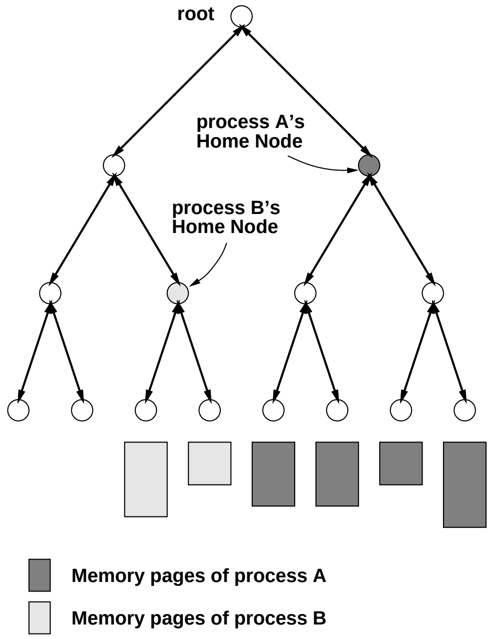
3.4 %9%1%8%e!<%j%s%0!&%"%k%4%j%:%`

%s$N%7%_%e%l!<%?$K<BAu7?%+!<%M%k!<%l%Y%k!&%9%1%8%e!<%j%s%0K!$N7W;;K!$r@bL@9k!#$^$:!"8@MU$rDj5A$9$k!#

%[!<%`%N!<%I %W%m%;%9$,A02s$N%9%1%8%e!<%j%s%0$G3d$jEv$F$i$l$F$$$?A4$F$N%W%m%;%C%5$r4^$`h&$J%N!<%I$N3H!J?^ 2!K!#3F%W%m%;%9$O;q8;4IM}LZ$N%N!<%IN&$A0l$D$r<+J,$N%[!<%`%N!<%IH9$k!#

%?%$%`%9%i%$%9$,Mh$kEY$K 3.3@a$K<($7$?J}K!$G!"3F%W%m%;%9$NM%@hEY$r7W;;$7D>$9!#?7$7$$M%@hEY$,9b$$%W%m%;%9$+$i=g$K!"0J2<$K<($9%"%k%4%j%:%`$K=>CF%9%1%8%e!<%j%s%0$r9T$J$&!#

1. ?7$7$$%W%m%;%9Kt$O<B%Z!<%8$r#1%Z!<%8$b;}$?$J$$%W%m%;%9$N>l9g$O!"$^$:%[!<%`%N!<%I$r7hDj$7!"$=$N%N!<%I$K0\F0$9$k!#$=$l$K$O;q8;4IM}LZ$N%k!<%H%N!<%I$+$i;O$a$F!"MW5aBf?t0J>e$N%W%m%;%C%5$r;}$A$+$D%U%j!<$J%Z!<%8$r0lHVB?$/$b$D;R%N!<%I$r9_$j$F$$$/!#5?;w%3!<%I$K$9$k$H?^ 3$N$h$&$K$J$k!#$=$10J30$N%W%m%;%9$N>l9g$K$O!";q8;4IM}LZ$N%k!<%H%N!<%I$r8+$F<+J,$N%[!<%`%N!<%I$K0\F0$7!"<!$N%9%F%C%W$K?J$`!#
2. b78=:_$N%N!<%I0J2<$K==J,$J%U%j!<%W%m%;%C%5$,J1lP!"3djEvF$O<:GT!##0$rJV7F=*N;!#$=$&GJ1l$P<!$N%9%F%C%W$X!#
3. 8=:_$N%N!<%I$NFb!"IN;R6!K=l>$l2?Bf$:$D3dEv$r0MMj9k$+7hDj$9$k!#$=$N:]!"$=$N%W%m%;%9$,%Z!<%8$r@jM-$9$k%N!<%I$rM%@h7F0MMj9k!#



?^ 2: 4IM}LZK*1k%[!<%`%N!<%I$NNc

```
NODE
FindHomeNode(
   int reqPEs,
   NODE this_node)
{
   NODE cand; /* CAndidate NoDe */

   if (this_node is a leaf node)
      return this_node;

   if (reqPEs > total PEs of a child)
      return this_node;

   cand = child[0];
   for each child[i]
      if (child[i]'s free PEs > reqPEs &&
         child[i]'s free pages > cand's free pages)
         cand = child[i]
   return FindHomeNode(reqPEs, cand);
}
```

?^ 3: %[!<%`%N!<%IC5:w%"%k%4%j%:%`

4. 3F;R6!KBP7$F!"$=l>$l7h$ail$?Bf?t$G3dEv$r ;n$_$k!#B($A3F;R6!KBP7$F!"Bh#2%9%F%C%W0J9_$r <B9T9k!#
5. ;n$_$?A4FN;R6!$G3dEv$,@.8y7?Ji!"3djEvF $K@.8y!#$3$N%N!<%I0J2<$K3djEvF$?Bf?t$rJV7F =*N;!#b7!"#1DG$b<:GT$7$?$i3djEvF<:GTJN $G!"#0$rJV7F=*N;9k!#

0J>e$r5?;w%3!<%I$GI=9H?^ 4Nh$&$KJk!#

4 %7%_%e%l!<%7%g%s!&%b%G%k

%7%_%e%l!<%7%g%s<+BN$N<B9T;~4V$X$N@)Ls$+$i4JN,2=$5 l?%b%G%k$r9=C[$7$?!#%9%1%8%e!<%j%s%0$N@-G=I>2A$N0l ;XI8$H7F!"%Z!<%8%U%)!<%k%H$,860x$N%Z!<%8BTAHF14|BT$A0J30$KMxMQ5l$?%/%m%C%/$N3d9g$rD4::$G$-$kh&$K 7?!#K\9FGO%Z!<%8BT$A!?F14|BT$A0J30$NF0:n$rM-8z<B 9T$H8F$S!"$=$Nh&$JF0:n$r5/$3$7$?%/%m%C%/!J;~4V!K$N 3H$r!"M-8z<B9T%/%m%C%/!J;~4V!K$H8F$V!#

4.1 %M%C%H%o!<%/%b%G%k

3,AX@-N"$kLZ9=B$$r7?%$%s%?!<%3%M%/%7%g%s%M%C%H %o!<%/$r;}$C$?%7%9%F%`$r%b%G%k2=9k!#%$!<%5%M%C%H$d ATM %9%&%#%C%AGDJ,l?3,AX9=B$$r;}C?%o!<%/%9 %F!<%7%g%s%/%i%9%?$d!"J#?t$N%/%i%9%?%\!<%I$rAX>u$K$D J.9go;$?JBNs7W;;5!$,3lKEv?$k!J?^ 5!K!#%7%_%e %l!<%?$O%M%C%H%o!<%/$NLZ9=B$$N3,AX$N?<$5$H!"3,AXFb$N %/%i%9%??t$r%Q%i%a!<%?$H9k!#D^$j!"#nCJ#k40A4LZ$r 07$&$3H,G-$k!#$7$?$,CF%M%C%H%o!<%/$N7A>u$OBP>N @-$r;}$A!"4JC1K9k?$aMWAG%W%m%;%C%5$OA4$FF10l$N$b NH2>Dj9k!#:#2s$N<B83GO#4CJ9=@.$N#2J,LZ!J9J$c $A!"3F3,AX$G#2DN%/%i%9%?$r;}$D!K$G!"#1#6Bf$NMWAG%W %m%;%C%5$r;}$C$?%7%9%F%`$r%7%_%e%l!<%7%g%s7?!#

<B:]$N%7%9%F%`$G$O!"#1$D$N7k9g@~>e$rF1;~$KJ#?t$N%Q %1%C%H$,N.$l$k$3$H$O$G$-$J$$!#=>$C$F%M%C%H%o!<%/$r8 L)$K%7%_%e%l!<%H$9$k$K$OA4$F$N7k9g@~$r%W%m%0%i%`$9$ I,MW$,$"$k!#$3lK$OB?Bg$N7W;;;~4V$rMW5a$7!"J,;6!?J Ns4D6-GN#O#S%1%Y%k$N%7%_%e%l!<%7%g%s$r<B%a%b%j$N? Iq$$$KCmL\$7$F9T$J$&>l9g!"$=$l0J30$N7W;;NL$,Bg$-$$$ aKU5o7$/$J$$!#$=$3$G:#2s$O!"%M%C%H%o!<%/>eG 6%9g$OA4$/L5;k7?!#7?$,$CF3$N%b%G%k$G$O!"%Z!<%8 $NE>Aw!"%Z!<%8$N=hM}MQ$N%a%C%;!<%8!"$5iK%W%m%;%C%5 4VDL?.MQ$N%a%C%;!<%8$,!"F10l@~>e$rF1;~$KJ#?tJ,lE $$$k!#$=$N$?$a!"#1DNMWAG%W%m%;%C%5K*$$$FAw?.!?< ?.5l$k%a%C%;!<%8$O!"I,MW$,$"lPF1;~$KJ#?t=hM}$5$l $k!#

%3%9%HKO!"%G%#%9%/XN%"%/%;%9%3%9%H!"%Z!<%8$NE> Aw%3%9%H$H$=$l0J30$NMW5a!?DL?.%a%C%;!<%8$N#3<oN`$,$ $k!#$7$+$7!"SSS–CORE GOFs<!5-21XN%"%/%;%9!"%j %b!<%H$J%a%b%j$X$N%"%/%;%9!"$=7F%/%i%9%?Fb%a%b%j$X $N%"%/%;%9$O3N=g$K%3%9%H$,+$+$k$H2>Dj$7$F$$$k!#FC $K%j%b!<%H$J%a%b%j%"%/%;%9$N5wN%$N0c$$$rH?1G9k$?$a $K!"DL?.$d%a%b%j%"%/%;%9$N%3%9%H$OE>Aw9k4V$KDL2a$9 $k%M%C%H%o!<%/$NCJ?t$KHfNc$9kbNH9k!#

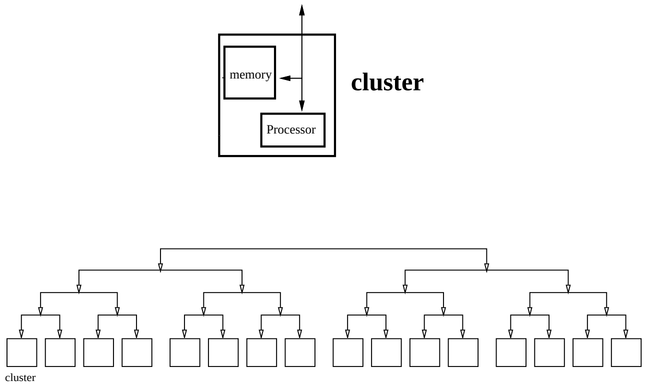
```
int
ALLOCATE(
  int reqPEs,
  NODE this_node
  PROCESS P)
{
  int # prep=0; /* total # PEs can be prepared.*/
  int # alloc=0; /* total # PEs allocated .*/
  int req[i]; /* # PEs to ask to child[i]. */

  if (this_node's free PEs < reqPEs) return 0;

  if (this_node is a leaf node)
    allocate this_node's PE to P;

  /* among children, in a fixed order, decicde
    how many PEs to ask to each child. */
  for each child[i] below which P occupy ANY page
    req[i] = MIN(reqPEs−# prep, his free PEs);
    # prep += req[i];
  for each child[i] below which P occupy NO pages
    req[i] = MIN(reqPEs−# prep, his free PEs);
    # prep += req[i];

  if (# prep < reqPEs) return 0;
  else
    for each child[i]
      alloc += ALLOCATE(req[i], child[i], P);

  return alloc;
}
```

?^ 4: %"%m%1!<%7%g%s!&%"%k%4%j%:%`

4.2 %a%b%j%b%G%k

%7%9%F%`A4BN$KJ,;66&M-%a%b%j$,MQ0U$5$l$F$$$k$b$N$H$9$k!#$3$&2>Dj$9$k$3$H$G!"%9%1%8%e!<%j%s%0$GMxMQ$9$k$?$a$K4IM}$5$l$k%Z!<%8$N>pJs$,%7%9%F%`A4BN$G0l4S$7$F4IM}$5lk3HKJ$k!#$=$NB>$NFCD'$O0J2<$Nh&KJ$k!#

- $"$k%Z!<%8$,=i$a$F%G%#%9%/$+iFI^lk$H%[!<%`%Z!<%8$H$J$k!#%"%/%;%9$9$Y$-%Z!<%8$,%m!<%+%k$KB8:_$7$J$$;~$O!"$=$N%Z!<%8$N%[!<%`%Z!<%8$r;}$D%/%i%9%?$K%Z!<%8MW5a%a%C%;!<%8$rAw?.$7!"$=$N%Z!<%8$N%3%T!<$r<u1H$k!#%Z!<%8Kh$K%3%T!<%Z!<%8$,:n$il?=g$r5-O?$7!"%[!<%`%Z!<%8$,%a%b%j$+$i%j%W%l!<%9$5$l$k:]$K$O!" FIFO =g$K%3%T!<%Z!<%8$,?7$7$$%[!<%`%Z!<%8HJ$k!#



?^ 5: BP>]7W;;5!%7%9%F%`

- 3F%a%b%jFbGO%Z!<%8$N%j%W%l!<%9$O LRU $G9T$Jol$k!#$?$@$7%j%W%l!<%9$O%3%T!<%Z!<%8$+$i9T$Jol!"%[!<%`%Z!<%8$O%3%T!<%Z!<%8$KM%@h7F%a%b%j$K;D$5lk!#
- %Z!<%8$N%3%R!<%l%s%74IM}$OL5;k$7!"%j%b!<%H%"%/%;%9$NEY$K%3%T!<%Z!<%8$,@8@.5l%m!<%+%k%a%b%j$KE>Aw$5lk!#D^$j0lEY@8@.$5l?%Z!<%8$O%a%b%j!<$+$i%j%W%l!<%9$5lk$^$GB8:_9k!#
- Fs<!5-21XN%"%/%;%9!"%j%b!<%H$J%a%b%j$X$N%"%/%;%9!"$=7F%/%i%9%?Fb%a%b%jXN%"%/%;%9O3$N=g$K%3%9%H$,$+$+$k$H2>Dj$7$F$$$k!#<0$GI=$9$H

$$\%/\%i\%9\%?Fb \ll \%/\%i\%9\%?4V \ll Fs<!5-21$$

=>CF3F<o%3%9%H$Q%i%a!<%?$O!"3l$N2>Dj$K0cH?7J$$$CM$,M?$(il$k!#

4.3 %W%m%;%9$N<B9T%b%G%k

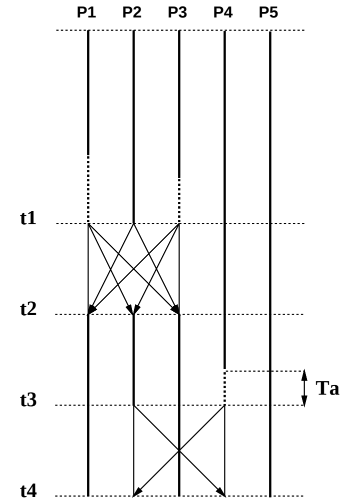
%7%_%e%l!<%7%g%s$N3+;O;~$KA4FN%W%m%;%9$,@8@.$5lk!#$^$?!"0lEY@8@.5l$?%W%m%;%9$O!"%9%1%8%e!<%j%s%0@)Ls$rJQ99$9k3HO$J$$!#9JoA!"%W%m%;%9$O8GDj$5l?JBNsEY$r;}$D!#$?$@$7M?$(il$?>r7o$rK~$?$7$?$H$-!"%W%m%;%9$O=*N;9k!#

$^$?!"%7%_%e%l!<%7%g%s$O%/%m%C%/$Y!<%9$K9T$Jok!#%W%m%;%9$KMQ0U$5l??6Iq$$$O0J2<NbNG$"$j!"%/%m%C%/Kh$K2DG=$J0lD,A*Br5l$k!#

- %a%b%jXN;2>HrI,MWH7J$$<B9T$G!"0lHL$N%l%8%9%?1i;;!"%a%b%jXN1F6ANJ$$$%-%c%C%7%eXN%"%/%;%9$,4^$^lk!#%7%_%e%l!<%?>eGO2?$bF0:n$r5/$3$5$J$$!#
- %a%b%j;2>H %j!<%I$H%i$$%H$N6hJL$O$J$$!#;2>H9k%"%I%l%9$O!"Fs$D$N%Q%i%a!<%? U !" V Kh$j7W;;$5lk!#3NN(U $G%W%m%;%9$4HKM?$($il?6u4VFb$+$i0lMM$K0l$D$N%"%I%l%9$,A*Pl$k!#;D$j$N $1-U$ $N3NN($G%W%m%;%9$N6u4V$N;MJ,E@$rJ?6Q$H9k!"J,;6

$, V $N#3$D$N@55,J,I[$N$&$A$N0l$D$K=>$,CF%"%I %l%9$r7W;;$9$k!#@55,J,I[$NA*Br$O#3$DNFbN0l$D $,0lMM$KA*Pl$k!#

F14| %W%m%;%9Kh$KF14|$r5/$3$94V3V$rM-8z<B9T%/%m%C%/ ?t$GM?$($k!#F14|$,5/$3k?SK!"<!$NF14|$X$N ;22C%W%m%;%C%5$r$=$N;~E@G=$N%W%m%;%9$,%9%1 %8%e!<%k5l$F$$$kMWAG%W%m%;%C%5NCf+$iMp?t$G A*sG$*$/!#MWAG%W%m%;%C%5O3NCM@$1M-8z<B9T $r7P83$9kEYKF14|BTAKJk!#F14|$K;22C$9$kMW AG%W%m%;%C%5A4$F$,F14|BT$AKJC?H3mG!"$3 li$NMWAG%W%m%;%C%5$O3F!9B>$NF14|BT$A%W%m%;%C %5KBP7$FF14|$rI=$9%a%C%;!<%8$rAw?.9k!#F14| $K;22C$9$k3FMWAG%W%m%;%C%5$O!"A4FNF14|;22C%W %m%;%C%5$+$i3N%a%C%;!<%8$r<u?.$7$?$H3m$G!" DL>o$N<B9TKLak3H$,$G$-$k!#3&9k3H$K hj!"F14|$HF14|$N4V$K%Z!<%8U%)!<%kH,5/3l $P!"%Z!<%8BT$Ar7$?J,$@$1F14|$N%?$$%_%s%0$ lk3HKJ$k!#?^6$K%7%_%e%l!<%7%g%sGNF14|$N Nc$r<(7?!#



DL>o$N<B9T .... F14|BT$A ——→ F14|DL?.

"($^$:#P#1!"#P#2!"#P#3$,F14|$r5/$3$7!"$D$$$G#P#2!"#P !!5/$3$7$F$$$k!#

"(#22sL\$NF14|$O#t#2$r%+%&%s%H%@%&%s$N3+;OE@$H$7!"Aa !!E~C#$7$?#P#4$O#T#a;~4V$@$1#P#2KhCFBT$?$5lF$$

?^6: %7%_%e%l!<%?>eGNF14|$N<B8=K!

3FMWAG%W%m%;%C%5$O!"%Z!<%8BT$Ab7$/$OF14|BTAGJ1 lP0J2<Nh$&$K7FF0:n$r7hDj$9$k!#

1. F14|$r5/$3$9%?$$%_%s%0$+D4$Y$k!#$=$&$G$"$l$PF1 4|$N=hM}r7!"$=$l0J30$N;~$K$O<!$N%9%F%C%W$K?J $`!#
2. %Q%i%a!<%?H7$F%W%m%;%9$K6&DL$KM?$(il$?!"1i ;; / %a%b%j;2>H $N5/$3$kIQEY$K=>CF!"3NN(E*K3 li$NFb0l$D$rA*Br$9$k!#

@hEYNh$j9b$$%W%m%;%9$K3d$jEvFilF$$$?>l9g KO!";q8;4IM}LZ$N%k!<%H$N!<%I$+$i$?$I$j!"$J$k Y/B?$/<+J,$N%Z!<%8$,B8:_9kNN0h$K%9%1%8%e!< %j%s%0$9$k!#

algo3 3.4@a$G@bL@$7$?K\9F$GDs0F9k%9%1%8%e!<%j%s%0 K!!#

5 %7%_%e%l!<%7%g%s

5.1 <B83$7$?%9%1%8%e!<%j%s%0K!

#4DN%9%1%8%e!<%j%s%0K!$r<BAu$7!"$=$l$>$l%7%_%e %l!<%?$G<B9T$7Hf3S!&I>2A$r9T$JC?!#IN%9%1%8%e!<%j %s%0$N>l9g$b!"3.3@a$G@bL@$7$?M%@hEY$N7W;;K!$rMQ$$$F %W%m%;%9$NM%@hEY$N7W;;r7!"3F$?%$%`%9%i%$%9Kh$KM% @hEY$N9b$$%W%m%;%9$+$i$=$l$>$l$NJ}K!$K7?$,$C$F%9%1 %8%e!<%j%s%0$r;n$_$k!#

algo0 %i%s%@%`$J%9%1%8%e!<%j%s%0K!!#3F%W%m%;%9$KBP$7 $F@)Ls$G<($5$l$?I,MWBf?tJ,$NMWAG%W%m%;%C%5$r%i %s%@%`$KA*$S3djEvF$k!#J*M}%Z!<%8$N;HMQ>u67$H $OL54X78$K!"L$3dEv$JMWAG%W%m%;%C%5$,$"$k4V$O%9 %1%8%e!<%k$r;n$_$k!#

algo1 C<$+$i=g$K%W%m%;%C%5$r3djEvF$k%9%1%8%e!<%j%s %0K!!#3F%W%m%;%9KBP7$F@)Ls$G;XDj5l$?I,MWBf ?tJ,$NMWAG%W%m%;%C%5$r!"%7%9%F%`$NC<$+$i>o$KF1 $8=g=x$G3djEvF$k!#

algo2 algo3 $H4pK\E*$K$OF1$8J}K!!#$?$@$7!"%W%m%;%9$, hjB?$/%Z!<%8$r;}$DHO0O$N%W%m%;%C%5$,$9GKM%

5.2 %7%_%e%l!<%7%g%s!&%Q%i%a!<%?

;HMQ7?%Q%i%a!<%?$OI=2!"I=3$NDL$j!#I=3$N U!" V O=l>$l!"%W%m%;%9$,;2>H9k%"%I%l%9$r@8@.$9$k:]$N 0lMM%"%/%;%9$N3NN(!"$=$l0J30$N>l9g$KMxMQ$5lk@55,J, I[$NJ,;6$rI=$9!#$^$?!"F14|IQEY$OA4FN%W%m%;%9$GF1$8 CMK7$?!#Hf3SE*Bg$-$J;~J,3d$r%7%_%e%l!<%7%g%sG-$k h&$K!"%M%C%H%o!<%/>e$N%3%9%H%Q%i%a!<%?NCMr>.5a KH$j!"%7%_%e%l!<%7%g%s$G$N#1%/%m%C%/$O<B:]$N 10 $+ $i 20 %/%m%C%/DxEYG"kH2>Dj9k!#$=$N$?$a!"3F%W%m %;%9$N5/$3$9?6Iq$$$O%a%b%j$N;2>H$N$_$H7F%7%_%e%l!< %7%g%s$r9T$JC?!#

5.3 %7%_%e%l!<%7%g%s7k2L5Z$SI>2A

%7%_%e%l!<%7%g%s$K;HMQ$5lk%W%m%;%9$O%;%C%H A !JI= 5!K$H%;%C%H B !JI=6!K$N#2AH$G$"$k!#N>I=Cf$G!"6u4V%5 %$%:Ms$O3F%W%m%;%9$KM?$($il?%"%I%l%96u4V$N%Z!<%8?t $rI=$9!#6u4V%5%$%:$NAm?tMsKO%W%m%;%C%5Kh$NMW5a%W%m %;%C%5?t$H6u4V%5%$%:$N@Q$NAmOB$rI=<(7?!#%7%_%e%l!< %7%g%s$N3+;O;~$KA4FN%W%m%;%9$,@8@.$5$l!"%9%1%8%e!<

I= 2: 3F<o%3%9%H

9‘L\	CM
%G%#%9%/%"%/%;%9	10000 clk
%j%b!<%H%"%/%;%9	100 clk
DL?.	10 clk

I= 3: $=$NB>$N%Q%i%a!<%?

9‘L\	CM
%W%m%;%C%5?t	16 Bf
%7%9%F%‘$N7A>u	2 ?J 4 CJ
1 %a%b%j$N%Z!<%8?t	400 pages
1 %Z!<%8$N%5%$%:	4096 Byte
Am%a%b%jNL	25.6 Mbyte
1 quantum	100000 clk
U	0.1
V	0.01
F14│IQEY	1000 clk

%j%s%0$NBP>]$HJk!#3F%W%m%;%9$O 20 %?%$%‘%9%i%$%9$r
$NM-8z<B9T$r2a$4$9$H>CLG$5lk!#3F%9%1%8%e!<%j%s%0K!
$O!"A4$F$N%W%m%;%9$,=*N;9kNKMW7?%?%$%‘%9%i%$%9
?t$GI>2AHf3S$5lk!#

@-G=KD$$$F

?^ 4$,%;%C%H A!"%;%C%H B $N%7%_%e%l!<%7%g%s$N7k2L$G
$"$k!#%9%1%8%e!<%kK!4H$K!"=*N;$^GKMW7?%?%$%‘%9
%i%$%9?t$HM-8z<B9T;~4V!J%W%m%;%9$,%9%1%8%e!<%k$5lJ
$+$C$?%W%m%;%C%5$NJ,$r4^$‘!K$N@j$a$k3d9g$r<(7?!#

IAiN%7%_%e%l!<%7%g%sGb!" Algo3 $N>l9g$,:G$bAa
$/<B9T$,=*N;$7!" Algo0 $N>l9g$,:GbCY/<B9T$,=*N;$7$F
$$$k!#F1MM$KM-8z<B9TN($b Algo3 $,0lHVNI$/!" Algo0 $,
:G$b@-G=$,0-$/$JCF$$$k!#

$3$3$G!"#4$D$N%9%1%8%e!<%j%s%0K!$,INh&$K0c$&$+
9M$($F$_$k!# Algo0 $O%W%m%;%9$K3djEvF$kMWAG%W%m%;%C
%5$r%i%s%@%‘$KA*Br9k$?$a$K!"%W%m%;%9$N%Z!<%8$N=j:_
$OA4$/9MN8$5$l$J$$!#$^$?A*Pl$kMWAG%W%m%;%C%5F1;N$N
4VKO2?$b4X78$,$J$$$?aK!"$*8_$$$N5wN%$,Hs>o$K1s$/
Jk798~KJ$k!#$3lKBP7F Algo1 $O%W%m%;%9$N%Z!<%8
$N=j:_$r9MN8$7$J$$$E@GO Algo0 $HF1$8G"k,!"0lB3$N
$N%W%m%;%C%5$?Ar0lDN%W%m%;%9$K3d$jEvFk$?$a$K!"
Algo0 hj$OMWAG%W%m%;%C%5F1;N$N5wN%$,6a$$$/Jk!#
5i$K!"0JA0$K%W%m%;%9$,%9%1%8%e!<%k$5l?NHF1$8%W
0O$N%W%m%;%C%572$,3djEvFil$k2DG=@-$b$"$j!"$=$N%
$&$J;~KO%W%m%;%9O"$kDxEY<+J,$N%Z!<%8$r%m!<%+%k$K
;}CF$$$k3HKJ$k!#<B:]%;%C%H A $N Algo2 $H Algo1
$N:9$,$J$$$N$O!"%W%m%;%9$N?t$,>/$J$/$JC?;~$KF1$8%
$&$J>u67KBP7F[Hs$IF1$8%9%1%8%e!<%j%s%0$r9T$J$C
$F$$$?$?$aG"$k!# Algo2 $H Algo3 $O%9%1%8%e!<%j%s
%0$N:]$K;q8;4IM}LZ$N>pJs$rMxMQ7F!"JkY/%Z!<%8$N

B?$/;}$DMWAG%W%m%;%C%5$r3d$jEvFh$&$H9k!#5i$K;
8;4IM}LZ$O%7%9%F%‘$NAj8_7k9gLV$HF1$89=B$$r7F$$$k$N
$G!"%H%]%m%8!<>e$N5wN%E*$K6a$$%W%m%;%C%5$?$A$rA*$s$
%W%m%;%9$K3d$jEvFk3H$,2DG=$G$"$k!#$?$@$7 Algo2 $N
>l9gKO$=$Nh&$J>l=j$K%9%1%8%e!<%kG-J+C?H-
KO%W%m%;%9$N%Z!<%8$NM-L5$K4X$oi:I,MW$JBf?t$r3d$j
EvFh$&$H9k$?$a!"%W%m%;%9$,<+J,$N%Z!<%8$r;}$D2DG=
@-$,Dc$/Jj!"$^$?%W%m%;%C%5F1;N$N5wN%$b Algo3 KHfY
$F1s$/Jk!#

3Nh&$K Algo3!" Algo2!" Algo1!" Algo0 $N=g$K!"
hjB?$/I,MW$J%Z!<%8$r;}$Dh&K+$D%W%m%;%C%5F1;N$
JkY/6a$/$Jkh$&$K%9%1%8%e!<%k9k2DG=@-$,9b$$!
H?BPK3$N5U=g$K!"hjB?$/$N%W%m%;%C%5$r3d$jEvFFM
P;$J$$%9%1%8%e!<%j%s%0$r9T$k3H$,$G$-$k!#

%7%_%e%l!<%7%g%s$N7k2L$r8+kH!" Algo3!" Algo2!"
Algo1!" Algo0 $N=g$K9b$$@-G=$r=P$7$F$$$k!#D^$j!"
%Z!<%8$N;HMQ>u675Z$S%W%m%;%9Kh$N@jM-<B%Z!<%8?t$r4IM
$7!"%9%1%8%e!<%j%s%0;~$K%W%m%;%9KO@jM-%Z!<%8$NB?$
%W%m%;%C%5$r3d$jEv$F!"%M%C%H%o!<%/$N%H%]%m%8!<$rH?1
7?;q8;4IM}LZ$rMxMQ$7Fh$j5wN%E*$K6a$$%W%m%;%C%5$
A*Br9k%9%1%8%e!<%j%s%0K!J}$,,9%7k2L$r=P7F$$$kH

I= 4: %7%_%e%l!<%7%g%s7k2L

algorithm	set A	set B
0	427 28.82	401 50.81
1	214 57.55	363 54.46
2	213 59.00	303 61.01
3	183 71.30	270 70.66

#1CJL\!’=*N;;~4V!J%?%$%‘%9%i%$%9?t!K
#2CJL\!’M-8z<B9TN(

6 $^$H$a

$N#U#M#A7?JBNs7W;;5!$d%o!<%/%9%F!<%7%g%s%/%i%9%?
a$K!"HFMQJBNs OS $r9=C[$9k?aN%+!<%M%k%l%Y%k!&%9%1
%8%e!<%j%s%0KD$$$F8!F$$7$?!#J#?t$NJBNs%"%W%j%1!<
%7%g%s$N8z2LE*$J<B9T$rK8$2$:$K%^%k%A%f!<%6!?%^%k%A
=%9%V4D6-$rDs6!$9k?aK!"%7%9%F%‘$N%M%C%H%o!<%/$N
F1$8=B$$r7?;q8;4IM}LZ$rF3F~$7!";q8;$NMxMQ>u67$r9N
7?%9%1%8%e!<%j%s%0K!$rDs0F$7$?!#$5iK%7%_%e%l!<
%7%g%sKh$j!"%Z!<%8$N;HMQ>u675Z$S%W%m%;%9Kh$N@jM-<
<B%Z!<%8?t$r4IM}$7!"%9%1%8%e!<%j%s%0;~$K%W%m%;%9$K$O@
jM-%Z!<%8$NB?$$%W%m%;%C%5$r3d$jEv$F!"%M%C%H%o!<%/$N%
%H%]%m%8!<$rH?1G$7$?;q8;4IM}LZ$rMxMQ7Fhj5wN%E*$K6a

I= 5: %W%m%;%99=@. − %;%C%H A

%W%m%;%9	MW5a%W%m%;%C%5?t	6u4V%5%$%: [pages]
0	4	300
1	4	50
2	4	300
3	4	50
4	8	300
5	8	300
6	8	50
7	8	50
8	16	100
9	16	50
10	16	50
Am?t	96	11600

I= 6: %W%m%;%99=@. − %;%C%H B

%W%m%;%9	MW5a%W%m%;%C%5?t	6u4V%5%$%: [pages]
0	3	150
1	3	150
2	3	100
3	3	100
4	3	50
5	6	200
6	6	200
7	6	200
8	6	200
9	6	200
10	6	200
11	13	50
12	13	50
13	13	50
14	16	50
Am?t	106	11600

$$%W%m%;%C%5$rA*Br$9$k%9%1%8%e!<%j%s%0J}K!$,9%7k2L$r=P$9$3$H$r<($7$?!#

:#8e$O!"%W%m%;%9$N%^%$%0%l%$%7%g%s$d!"$h$jB?$/$N%9%1%8%e!<%j%s%0@)Ls$r07$&%9%1%8%e!<%kK!$N8&5f!?3+H/5Z$S!"<B5!$X$N<BAu$,2]BjHJ$k!#

7 <U<-

K\8&5f$O>pJs=hM}?66=;v6H2q!J#I#P#A!K$,<B;\$7$F$$$kFHAOE*>pJs5;=Q0i@.;v6H$N0l4D$H7F9TJC$?!#

;29MJ88%

[1] Thomas E. Anderson, Brian N. Bershad, Edward D.Lazowska, , and Henry M. Levy. Scheduler activations: Effective kernel support for the user-level management of parallelism. *Proceedings of the Thirteenth ACM Symposium on Operating Systems Principles*, 25(5):95–109, October 1991.

[2] >>K\>0 8EAq?J0l, J?LZ7I. HFMQD6JBNs%*%Z%l!<%F%#%s%0%7%9%F%`#S#S#S!]#C#O#R#E. F|K\%=%U%H%&%'%"2J3X2qBh *11* 2sBg2qO@J8=8, pages 13–16, October 1994.

[3] >>K\>0. %^%k%A%W%m%;%C%5>e$NF14|5!9=$H%W%m%;%C%5%9%1%8%e!<%j%s%0$K4X$9$k9M;!. 7W;;5!%"!<%-%F%/%A%c8&5f2qJs9p *No.79-1*, pages 1–8, November 1989.

[4] >>K\>0. :YN3EYJBNs<B9T;Y1g%^%k%A%W%m%;%C%5$N8!F$. #C#P#S#Y *89-37*, pages 37–42, August 1989.