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Performance Evalution for Implementation of the Volume Rendering Method on Distributed-Memory Multiprocessors

Xiangping Wang

Abstract

Volume rendering is a direct visualization method of three dimensional space. It has been a very important method in the field of medical image generation. Nowadays, it is gradually regarded also as a powerful analysis tool for scientific computations. However,due to the numerous amounts of the volume data,generating such an image can be very computational expensive and good quality images with high ,it is dificult to realize high-speed image generation.

In this research, we propose volume rendering parallel algorithm based onray-casting and a high-speed volume rendering machin the *ReVolver*/C40.

The goals of this algorithm are high-speed image generation and visualization of translucent volume both with parallel and with perspective projections.

In order to achieve these goals,it is necessary for each processer to be able to calculate pixel values,thus each processer must have subvolume data.This paper adopts data distribution which used based on conflict free memory structure and a simplified voxel sampling method for volume data. So that we can simultaneously provide all voxels corresponding to a ray in arbitrary direction.

This parallel algorithm practice on master and slave computer which access differ from state.The master computer adopts macro-pipeline of the following stage: the initial state,the data distribution state,the Ray Casting state which generates rays,received pixel values from slave and the Shading stage which shades images.The slave computer adopts macro-pipeline which communicate with master and other slave computers,receives data concerning to the rays from the Ray Casting Stage and uses it to calculate voxel address and pixel values.

This paper the most important technique is Voxel-pipeline in processer for pixel calculation stage.Each processer contains the subvolume data and stores in its memory.Pixel-pipeline calculation stage calculates address of the voxel and memory access for voxel data,and pixel value calculation.In order to access to all voxel on any ray,we adopts a volume memory structure fitted for the pipelne.

This paper is implemented and executed on a Distributed-Memory Multiprocessors,the Fujitsu AP1000.

We aim effective parallel method of our algorithms,evaluated the amount and invocation times of communication ,improved a few parallel implementations method.These methods have been executed on AP1000 and implemented parformance of the parallel volume rendering.Hence,we ascertained thatthese parallel implemintations are quite effective way on a distributed-memory multiprocessors.

As a result,To make image for 64^3,256^3 volume data and screen size 256^2, 8 times and 12.5 times speedup is achieved with our algorithm using 64PE for 4PE,and A Sumed up the method that send amount of ray have obtained 8.5 times using 256 ray for 4 ray.In this reseach for 64^3 volume data and screen size 256^2 we also have obtained 4.1 times of speedup with 64PE for workstation .As a result we find out the method of effectiveness parallel algorithm.

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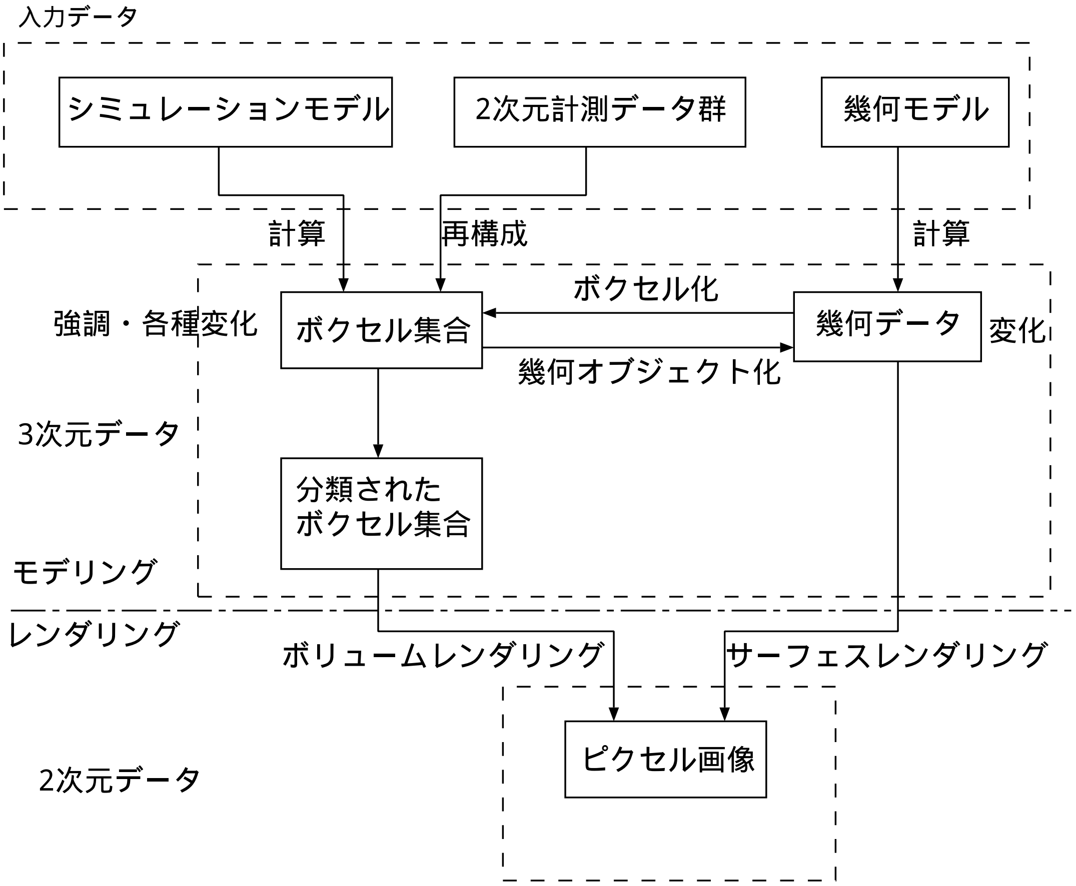

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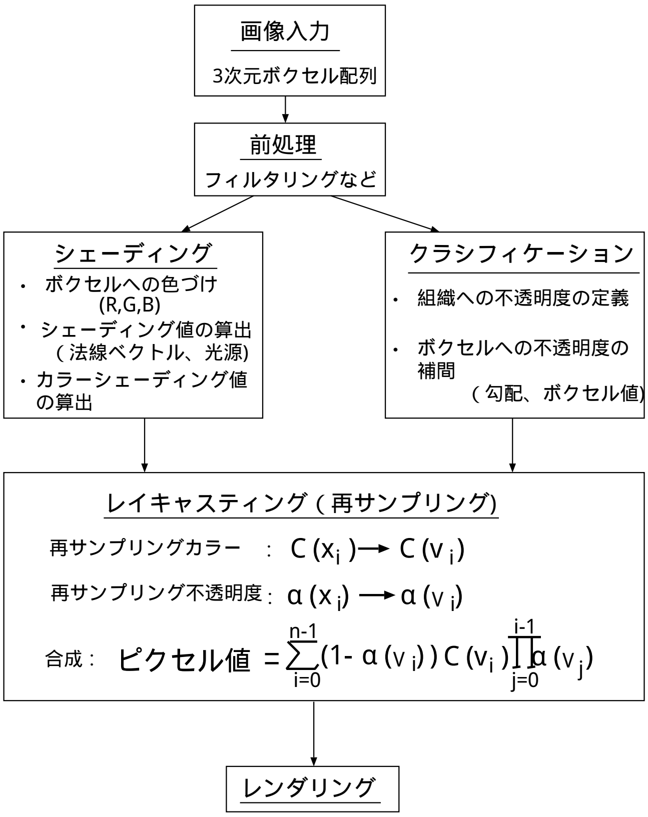

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1. 2hA|F~NO$H%b%G%j%s%0

   F~NO%G!<%?$+$i!"%a%b%j>e$K%\%/%;%k$N3<!85G[Ns$r9=@.$9$k!#%\%j%e!<

%`%l%s%@%j%s%0$K$*$$$F$O!"%\%/%;%k$N3<!85G[Ns$N9=@.$,3<!85J*BN$N%b%G%j%s%0$KAjEv$9$k!#%\%j%e!<%`!&G!<%?$N=hM}J}K!$K1~$8!"N%;6%b%G%k$HO"B3%b%G%k$N2<oN`$NI=8=J}K!$,$"$k!#

N%;6%b%G%k 3F%5%s%W%j%s%0E@$rCf?4$H7?C10IN)J}BN$r%\%/%;%k$H$7, %\%/%;%kFb$NG$0U$NE@$OCf?4$HF1$8CM$r;}$D!#

O"B3%b%G%k C10IN)J}BN$ND:E@$K%5%s%W%j%s%0E@$,B8:_$7!"C10IN)J}BN$NFbIt$NCM$O!"$=$NE@$r0O$`8D:E@$NCM$+$itri-linear Jd4VKh$j5a$ail$k!#

0J2<!"%5%s%W%j%s%0E@$x_i = (x_i, y_j, z_k)$ K*1k%\%/%;%k$N?'!"F)L@EY$JINCM$r $f(x_i)$ $HI=$9!#

2. A0=hM}

   bH$N%\%/%;%k%G!<%?$KBP$7!"%N%$%:=|5n!"2hA|6/D4JI$r2C$(k3HKhj!"0J9_$N%/%i%7%U%#%1!<%7%g%s$JIN=hM}$rMF0W$K9k!#

3. %/%i%7%U%#%1!<%7%g%s

   E57?E*$JAH?%$K0lDj$NITF)L@EY$\alpha_v$$rM?$(!"3FAH?%$KB0$9$k%\%/%;%kCM$K8GM-$JITF)L@EY$\alpha(x_i)$ $rJd4V=hM}$KhC$F5a$a$k!#$3$3$G!"J#?t$NO[$J$kAH?%$N6-3&K*1k%\%/%;%kCM$f(x_i)$ H=NCMKBP9kITF)L@EY$\alpha(x_i)$ $N4X?t$,M?$($il?>l9g!"8{G[CM$b9MN8$7$?G$0U$N%\%/%;%k$NITF)L@EY$\alpha(x_i)$ Of(x_i)$ NBg-5KhC$F7h$^kf(x_i)$ $N8{G[CM$N@dBPCM$H!"ITF)L@EY$NJd4VCMHN@Q$GM?$(il$k!#6qBNE*$J7W;;<0$O2<$N<0$G7W;;$9$k!#

$$\alpha(x_i) = |\mathrm{grad}\ f(x_i)| * \begin{cases} \dfrac{f(x_i)}{f_a}\alpha_a & (f(x_i) \le f_a) \\[2ex] \dfrac{(f(x_i) - f_a)\alpha_b + (f_b - f(x_i))\alpha_a}{f_b - f_a} & (f_a \le f(x_i) \le f_b) \\[2ex] \dfrac{(f(x_i) - f_b)\alpha_c + (f_c - f(x_i))\alpha_b}{f_c - f_b} & (f_b \le f(x_i) \le f_c) \\[2ex] \alpha_c & (f_c \le f(x_i)) \end{cases} \tag{2.1}$$

4. %7%'!<%G%#%s%0

   3F%\%/%;%kKD$$$F!"<~0O$N%\%/%;%k$NCM$+$i5aa?8{G[CM$rEv3:%\%/%;%k$K$*$1$kK!@~%Y%/%H%k$H$7!"%7%'!<%G%#%s%0CM$r5aak!#%+%i!<%7%'!<

%G%#%s%0$r9T$&KO!"FsDNJ}K!$,$"$k!#

(a) K!@~%Y%/%H%k $N(x_i)$ $H8w8;J}8~%Y%/%H%k L $NFb@QCM$+$i%7%'!<%G%#%s%0CM$r5aak!#K!@~%Y%/%H%k $N(x_i)$ $H3F%\%/%;%k$N%+%i!<%7%'!<%G%#%s%0CM $c(x_i)$ $O<!<0$G5a$^$k!#

$$N(x_i) = \mathrm{grad} f(x_i)/|\mathrm{grad} f(x_i)| \qquad (2.2)$$

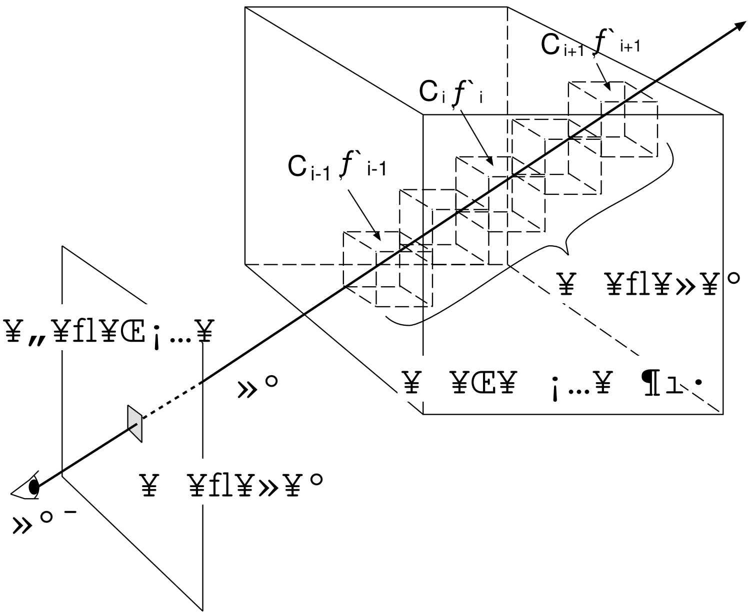
$$c(x_i) = h(N(x_i)\ !\&L) * c_k(x_i) \qquad (2.3)$$

$3$3$G!"$c_k(x_i)(k = R, G, B)$ $O3F%\%/%;%k$KM?$($??'>pJsG"$k!#h $O3H;6H?<M$Khk%7%'!<%G%#%s%04X?tG"$k!#

(b) ?'$NIU$$$?8w8;$GM?$($kJ}K!$G$"$k!#3l$O%\%/%;%k$rL5?'$NH?<MLL$H7FHi$(!"$=$N?'$O8w8;$N?'$H%7%'!<%G%#%s%0%b%G%kKhCF7hak!#

2.2.1 %l%$!&%-%c%9%F%#%s%0K!

%l%$!&%-%c%9%F%#%s%0K!$H$O!"%\%j%e!<%`%l%s%@%j%s%0$r9T$&:G$b4pK\E*$J%"%k%4%j%:%`$G$"$k!#



%;%k4H$K;kE@$H%T%/%;%kHr7k$V;k@~$K1hCF!";k@~$H8r:9$9$k%\%/%;%k$r ;kE@$K6a$$=g$K01Dj4V3V$G%5%s%W%j%s%0$7$J$,$i!"3F%\%/%;%k$N%+%i!<%7%'!< %G%#%s%0CM$c$!Jx_i) $HITF)L@EY$\alpha(x_i)$ $N@Q;;CM$,1 KJk^$G7+JV$7!"@Q$,7W;;$5 1k!#6qBNE*KO!"3F%\%/%;%k$KBP$7!"@a2.2 $K=R$Y$?3. $H4. $N=hM}$G3F%\%/ %;%kK"i+8aM?$($i1F$$$kITF)L@EY$\alpha(x_i)$ $H%+%i!<%7%'!<%G%#%s%0CM$c$!J x_i) HN>h;;1i;;Kh$j!"%\%/%;%k$rDL2a7?8w$,5a$^$k!#;k@~$,G$0U3Q$GF~<M 9k$?$a!"%\%/%;%k3J;RE@$NG[CV4 9$($,I,MW$KJk!#$3$1$O!"6aK5$N%\%/%;%k $KM?$(i1$?$c$!Jx_i) H\alpha(x_i)$ $rJd4Vl i;;$9k3HKhC$F:F%5%s%W%j%s%0$5$1 $??7$7$$ $c(v_i)$ H\alpha(v_i)$ $r5a$ak3HG$"$k !J$v_i$$O:F%5%s%W%j%s%0:BI8$r<($9!K# 9JoA!";k@~$K1h$CFJBs$@%\%/%;%k$K$D$$$F!"A0$+$i$-$?8w !J7'!K$H!"<+ i,H/9k!"0?$C8w8;$K>Hi5$1$FH?<M9k8wHr9g@.7F!"<!!9$H%\%/%;%k KEO7$F$$$-!":G8e$N%\%/%;%k$+$i=P$F$-$?8w(?'!K$,%1%s%@%j%s%02hA|$N%T %/%;%kCMHJ$k!#$f$($K%T%/%;%kCM$O!"0J2<$Nh&$K5a$ai1$k!#

$$\text{\%T\%/\%;\%kCM} = \sum_{i=0}^{N}(1-\alpha(v_i))c(v_i)\prod_{j=0}^{i-1}\alpha(v_j) \tag{2.4}$$

$3$3$G!"%\%/%;%kCM0!"1 O=1>1=$N%\%/%;%k$,F)L@$HITF)L@G"$k3H$r I=$9!#$c(v_i)$ $O!"%\%/%;%kCM$KBP1~9k?'!"$\alpha(v_i)$ $O!"%\%/%;%kCM$KBP1~9kF) L@EYG"$k!#

8=<B46$N9b$$3 <!851"1F2hA|$r@8@.$9k?$a!"%1%$!&%-%c%9%F%#%s%0K!r5 iK9bEY$J%1%$!&%H%1!<%7%s%0$H8F$P1kJ}K!$K3HD%$9k3HbG-$k!#

%1%$!&%H%1!<%7%s%0$H$O!"H?<M8w$HF)2a8w$r9MN8$7$?>19g!";kE@$+iN;k@~ !J1<!;k@~!K$H%\%/%;%kI=LL$,8r:9$9$k$HH?<M8w$d6~@^8w!J2<!;k@~!K$r@8@.$9 $k!#$3NI,MWJ8w$N@.J,$r5aak$?$a$K!"H?<M8w$HF)2a8wKD$$$F$"$k7-$$ CM$r1[$(k^$G!":F5"E*$J=hM}$,I,MW$G$"$k!#

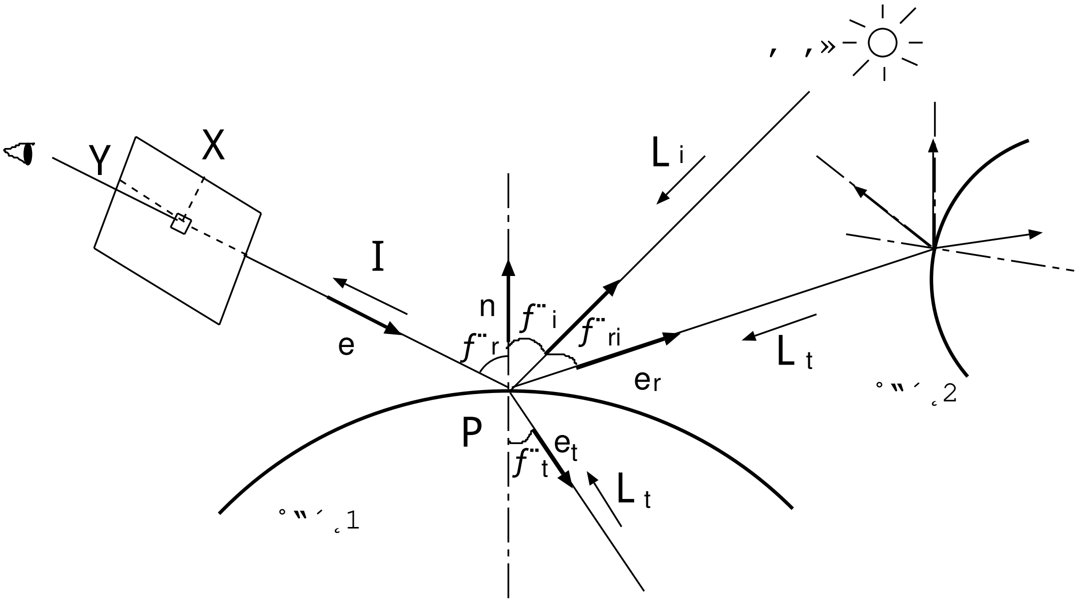
9YFN%T%/%;%k$N2D;kE@$KBP9k51EY7W;;$N%b%G%k$H7F<!$NWhitted $N J}<0$,M-L>G"$k[4]!#(?^2.4!K

$$I = I_a + k_d n * L_i + k_s L_r + k_t L_t \tag{2.5}$$

$?$@$7!"

I:51EY!"I_a:<~0O8w

n:LL$NK!@~%Y%/%H%k!"$k_d$:3H;6H?<MN(



?^2.4: Whitted $N5 1EY7W; ;%b%G%k

L_i:8w8 ;$+$i$NF~<M8w$N6/EY !%Y%/%H%k!K

k_s:@5H?<MN(!"k_t:F)2aN(

L_r:@5H?<M@.J,!"L_t:F)2a@.J,

G"$k!#; k@~$OD I@W7J$,$i5 1EY7W; ;$N2aDx$G!"D.$N=hM}$r9T$&!#

- 1F=hM} !'5 1EY7W; ;GO!"3F%5%s%W%j%s%0E@$G<!$Nh&$J=hM}$r9T$&!#8w8 ;$+iND>@\8w$,8=:_=hM}Cf$N%5%s%W%j%s%0E@KFO/$+H]$+$rH=Dj$9k?aK!"$=$N%5%s%W%j%s%0E@$+$i8w8 ;$K8~$+$&8=<B$H$O5UJ}8~$N2 <!; k@~$rH/$7!"$=$N; k@~H9YF$NJ*BN$H$N8rE@H=Dj$r<B9T9k!#
- H?<M=hM} !'8w8 ;$+$i$N8w$,J*BN$KC#$7$?E@$+$iH?<M8w$,H/@8$9$k>19g!"$=$NE@$r:F$S8w8 ;$H8+$J7F!"5UJ}8~$N2 <!; k@~$rH/@8$5$;!"$=$N2 <!; k@~H9YF$NJ*BN$H$N8rE@H=Dj$r9TCF; kE@$+$i0 1HV<jA0$N8rE@$r5a$a!"$=$N8rE@$N5 1EY7W; ;$r<B9T$9$k!#
- F)2a=hM} !'8w8 ;$+$i$N8w$,J*BN$KC#$7$?E@$+$iF)2a8w$,H/@8$9$k>19g$K!"$VD+C?J*BN$,F)2a8w$r5/$3$9>19gKO!"$=$NE@$+$i6~@^J}8~$K8~$1$F2 <!; k@~$r=P$7!">e$NE@$HF1$8h&$K8rE@H=Dj$r<B9T9k!#

Whitted $N5 1EY7W; ;<0$r:F5"E*KE,MQ9$1$P!"0 1DN%T%/%;%kKBP9$k7W; ;$G$"$CFb!"8w@~$NLZ9=B$$K=>CF; k@~$ND I@W$,I,MWHJ$k!#=>$C$F!"%1%$!&H%1!<%7%s%0K!$O9bI J<A$J2hA|$r@8@.$G$-$k$,!"KDBg$J7W; ;NL$,I,MW$G$"$k!#

2.2.2 %l%$!&-%c%9%F%#%s%0K!$N:GE,2=

0lK\$N;k@~$HJ*BN$N8r:9H=Dj$O!"J*BN?t×%9%/%j!<%s$N2hAG?t$KHfNc$7$?;~4V$,$+$+$k!#$3$N=hM};~4V$N:o8:N?$a!"=>Mh$h$j3F<o$N:GE,2=<jK!$,Ds0F$5lF$$$k!#

1. %T%/%;%kJBNs=hM}

   %l%$!&-%c%9%F%#%s%0K!$G$O!"%9%/%j!<%s$N3F%T%/%;%k$rDL2a$9$k;k@~Kh$KFHN)7F=hM}$r9T$($kE@$,Bg$-$JFCD'G"$j!"=EMW$JJBNs2=$NMWAG$G$"$k!#%9%/%j!<%s$NAv::@~$JIKBP1~7?NN0h$N2hAG72$rDL2a9k;k@~72$K%W%m%;%C%5$r3djIU1$F!"=hM}$NJBNs2=$r?^$k!#3NJBNs=hM}$O%W%m%;%C%5$,B?$/$JlP$=$l$@$13F%m!<%+%k%a%b%j$N%-%c%C%7%e$rB?$/:N$k3H$,$G$-$kNG!"DL?.$N%*!<%P!<%X%C%H$r:o8:G-k3HH$$$&MxE@$,$"$k!#

2. 3,AXE*%\%/%;%k=89g[3]

   ITF)L@EY$K4p$E$$$?%*%/%H%j!<$r9=B$$7$F3<!85%\%j%e!<%`6u4V$rJ,3d$9$k!#Bh2.2.1@a$G=R$Y$?%l%$!&-%c%9%F%#%s%0$K$h$k?'9g@.%"%k%4%j%:%`$+$iL@$i$+$Jh&$K!"ITF)L@EY$,0$N:F%5%s%W%j%s%0E@$O!"%T%/%;%k$N?'9g@.$KBP7FJK$b9W8%$7$J$$!#$=$3$G!"3<!85%\%j%e!<%`6u4V$rD>J}BN$KJ,3d$7!"$=$l$>$l$NJ,3d$5$l$?6u4V$r%;%k$H8F$V!#8 6y$N%\%/%;%k$NITF)L@EY$,$9$Y$F0$N%;%k$r"0"!"$=$l0J30$N%;%k$r"1!I$HJ,N`$9lP!"0$N%;%kFbIt$NG$0U$NE@GN:F%5%s%W%j%s%0$OL50UL#$G$"$k!#3N@-<A$KCmL\$7!"M?$($il?%\%/%;%k=89g$+$i%9%?!<%H7F!"NY@\$9$k8 8D$N%;%k$,0$NH-$K0$Noctant$H$7$F%^!<%8$9k3Hr%\%H%`%"%C%WE*$KH?I|$9lP!"%*%/%H%j!<$,9=@.$G$-$k!#%l%$!&-%c%9%F%#%s%0$N:]!"3N%*%/%H%j!<$rAv::$70$Noctant Fb$N:F%5%s%W%j%s%0$r9T$o$J$$$h$&$K9l$P!";~4V8zN($N8~>e$,4|BT$G$-$k!#

3. NN0h:FJ,3dKh$k%l%$!&-%c%9%F%#%s%0

   3AiO!"JkY/%l%$!&-%c%9%F%#%s%0$NK\?t$=$NbN$r:G>/2=$7h&H9$k<jK!$G$"$k!#$^$:!"%9%/%j!<%sA4BNrE,EvJ8D?t$N6k7A$N>.NN0h$KJ,3d$7!"$=$l$>$l$N>.NN0h$4HK!"0J2<$N<jB3$-$r9T$&!#

   Step 1 : >.NN0h$N4 6y$N%T%/%;%kKBP7F^$@%T%/%;%kCM$,7W;;5l$F$$$J$$>l9g%l%$!&-%c%9%F%#%s%0$r9T$&!#

   Step 2 :if(F@il$?#4$D$N%T%/%;%k?'$N0c$$$,4p=`CM$rl[$($k!K then go to *Step 3*;else go to *Step 4*;

Step 3 :>.NN0h$r4 EyJ,J,3d$9$k!<go to*Step 1*;

Step 4 :>.NN0hA4BN$rJd4V$9$k!#

2.3 %\%j%e!<%'%l%s%@%j%s%0$NJBNs=hM}

%\%j%e!<%'%l%s%@%j%s%0$OB?Bg$J1i;;=hM}G=NO$rI,MW$H5l!"IJ<A$N9b$$2hA|$r5a$ak?aK$O1i;;NL$OHs>o$KB?$/Jk!#=>Mh$+$i!"9bB.%l%s%@%j%s%0rO$+$k$?$a$K!"$5$^$6$^$JJBNs=hM}$,9T$olF$-$?!#h/MQ$$$ilkJBNs=hM}!"2hA|@8@.$N<jK!$KhjA0J}Ej1FK!$H8eJ}Ej1FK!$NFsDN%+%F%4%j!<$K<jK!$,J,1ilk!#JBNs=hM}$NJ}<0$H7F$O!"?^2.5$K<(9h$&$K;MDNJ}<0$,9M$(il$k[5][6]!#

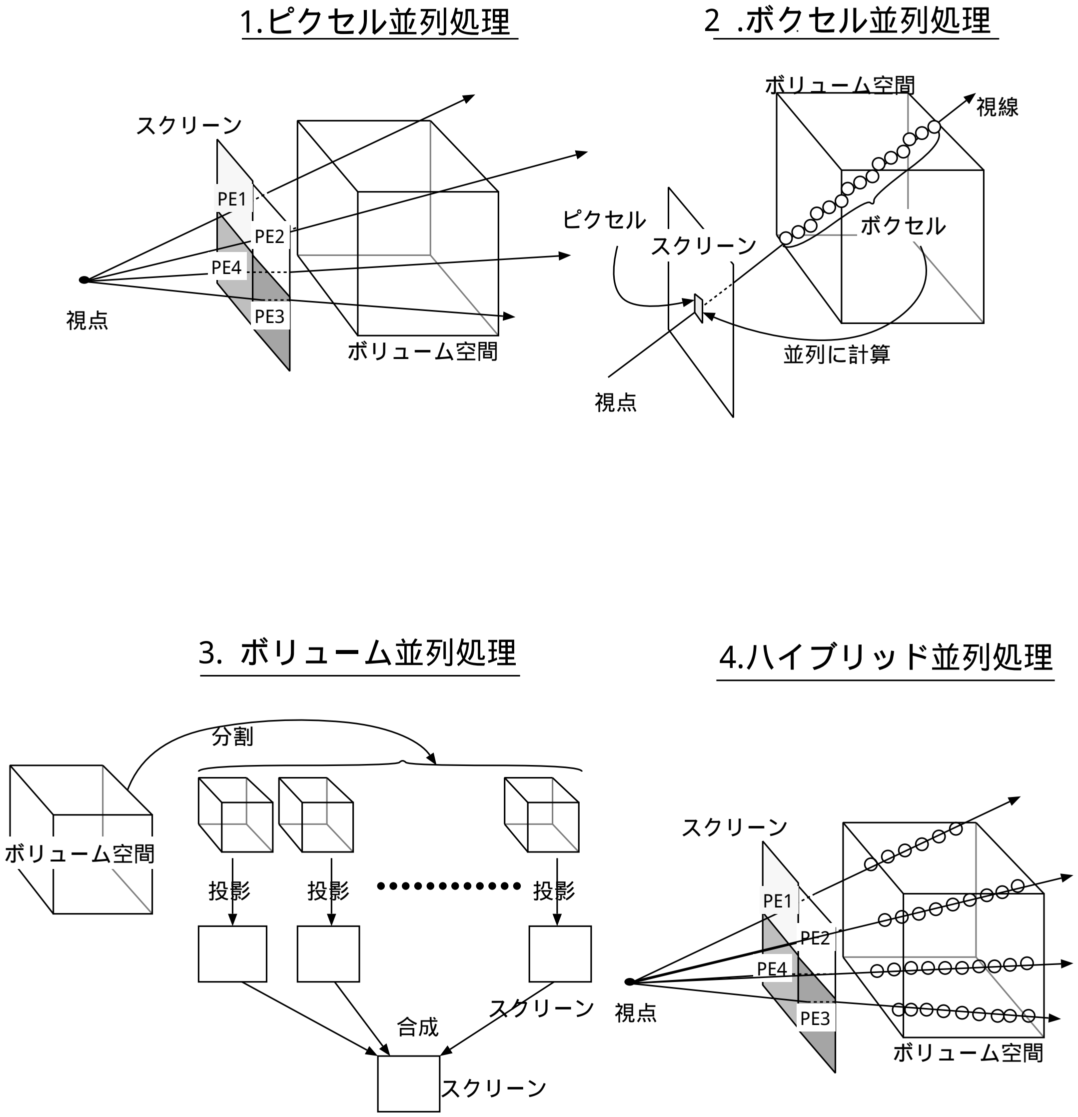
2.3.1 2hA|@8@.$N<jK!

1. A08~$-%^%C%T%s%0 !!&&*%V%8%'%/%H=gHb8FPl$k!#%\%j%e!<%'$r9=@.9k3F%\%/%;%k$r%9%/%j!<%s$KEj1F$7!"3F%\%/%;%k$,%9%/%j!<%s>e$N8D!9%T%/%;%k$KIl$@$11F6A$rM?$(k+$r7hDj$9k3HG!"3F%T%/%;%kCM$r5a$a$k%"%k%4%j%:%'$G$"$k!#
2. 8e8~$-%^%C%T%s%0 !!&&2hA|=g$H$b8F$Plk!#;kE@$+$i%9%/%j!<%s>e$N3F%T%/%;%k$rDL$k;k@~%Y%/%H%k$r@8@.$7!";k@~$,%\%/%;%k6u4V$rDL2a$7$?;~$K;k@~$H8r:9$9$k%5%s%W%kE@$N?'$*$h$SIIF)L@EY$NCM$r9g@.$9k3HKhC$F3F%T%/%;%kCM$r5aak%"%k%4%j%:%'G"$k!#

2.3.2 JBNs=hM}$NJ}<0

%W%m%;%C%5Bf?t P!"%T%/%;%k?t m^2 $H%\%/%;%k$NAm?t$r n^3 NH$-!"3FJBNs=hM}J}<0$NFCD'$O<!$Nh&KJ$k!#!J?^2.5!K

1. %T%/%;%kJBNs=hM}!!%9%/%j!<%s$N3F2hAGE@$4HK%W%m%;%C%5$r3d$jEvFk!#3F%W%m%;%C%5O=$N;k@~>e$N%\%/%;%kCM$r3<!852hA|%a%b%j$+$iC'<!E*$KFI$_=P$7!"N_@Q9k!#3<!852hA|%a%b%j$N%3%T!<$rA4FN%W%m%;%C%5$,M-$7F*lP!"=hM};~4V$O m^2n/P HJ$j!"%W%m%;%C%5Bf?t$KHfNc7?Hs>o$K9bB.$J=hM}$,2DG=$KJk!#7+$7!"$3lO%3%9%HE*$K8+9goJ$$!#3<!852hA|%a%b%j$r%P%s%/J,$1$7$?%7%9%F%'$d%-%&%C%7%e%a%b%j$rM-8zMxMQ7?%7%9%F%'$,;HMQ$5lk!#
2. %\%/%;%kJBNs=hM}!!K\8&5f$G<g$KMQ$$$?JBNs=hM}<jK!G"$k!#0l$D$N;k@~$KBP$7!"3<!852hA|%a%b%j$+$iF1;~$K;k@~>eN9YF$N%\%/%;%k!Am?t$On)rFI_=P$7!"N_@Q$9$k!#3<!852hA|%a%b%j$N9=B$$,=EMW$JLr3d$r2L$?$9!#


1.ピクセル並列処理

2 .ボクセル並列処理

3. ボリューム並列処理

4.ハイブリッド並列処理

?^2.5: %\%j%e!<%`%l%s%@%j%s%0$NJBNs=hM}J}<0 n 8D$N%\%/%;%kCM$O n/P 8D$KJ,3d$5$1! "3F%W%m%;%C%5$GItJ,N_@Q$5$1$k! #3F%W%m%;%C%5$r%j%s%09=B$$G7k9g$7! "$=1i$r%Q%$%W%i%$%sJ}<0$GN_@Q9k! #<B<AE*KO! "n/P ;~4V$G n 8D$N%\%/%;%kCM$NN_@Q$r9T$($k! #=>CF=hM}; ~4V$O m^2n/P HJ$k! #G$0U; kE@$G3 <!8 52hA |%a%b%j$+$i%\%/%;%k$rF I$_=P$ 72DG=! "%P%s%/%3%s%U%j%/%H%U%j! <$J%a%b%j9=B$$,3+H/$5$1$k! #

3. %\%j%e! <% 'JBNs=hM}! 3F%\%/%;%k$K01$D$:$D%W%m%;%C%5$r3d$jIU1k! #3F%\%/%;%k$+$i; kE@$K8~$+$&5U; k@~$H%9%/%j! <%sHN8r: 9$9$k2hAGE@K=$N%\%/%;%kCM$rN_@Q9k! #3F%W%m%;%C%5$G n^3/P 8D$N%\%/%;%k$rC4Ev9k! #5U; k@~>e$N $P^{1/3}$ 8D$N%W%m%;%C%5$G:G$b1 |$N%W%m%;%C%5$+$i7W; ;$7! "<!!9$K%G!<%?$rA0J}$N%W%m%;%C%5$K%Q%$%W%i%$%sE*$KEO7F$$$/J}<0rH$j! "$3$NJ?6QE>Aw; ~4V$r τ H9kH! "Am<B9T; ~4V$O $(n^3/P + P^{1/3})\tau$ HJ$k! #

4. %O%$%V%j%C%IJBNs=hM}! %T%/%;%kJBNs=hM}$H%\%/%;%kJBNs=hM}$rM;9g7?J}<0G"$k! #%T%/%;%kCM$N7W; ;$N9bB.2=$N$?$a$K! "F1; ~$KB??t$N%\%/%;%k$rF I$_=P$7%T%/%;%kCM7W; ;$rJBNs$K9T$&$3H,G-$k! #

2.4 =>Mh$NJBNs2=<jK!

%\%j%e! <% '%1%s%@%j%s%0$NJBNs=hM}$G$O! "9b$$%W%m%;%C%5$NMxMQEY$*hS:G>.$N%W%m%;%C%54VDL?.! "$h$$I i2Y%P%i%s%9JI$r9M$(J1$1$PJi$J$$! #=>Mh$NBeI=E*$JJBNs=hM}<jK!KO0J2<Nh$&$JbN$,$"$k! #

- %;%0%a%s%H2=$5$1$?%1%$!&-%c%9%F%#%s%0 [7]

  $3$1iNJ}K!GO! "%W%m%;%C%5OG$-$k$@$1N)J}BNNh$&$J%\%j%e! <% '!%G!<%?$N%5%V%V%m%C%/$rbD! #G$0U$K; k@~$N3QEY$rM?$($?; ~! "; k@~$,%\%j%e! <% '$NIN%5%V%V%m%C%/$rDL2a$9k+$r7hD j$9$k! #$3N?aK! "%5%V%V%m%C%/$NI=LL$r2hLL$KEj1F$7! "IN%T%/%;%k$,%5%V%V%m%C%/$N1FKJk,$rD4$Y$k! #; k@~$H8r: 9$N>pJs$r%P%C%U%!$KC_$(k3HKhC$F! "%1%s%@%j%s%0$,; O$^$kA0K9YF$N; k@~$r=8$a=*$k3H$,$G$-! "I i2Y%P%i%s%9$,H1$k! #<!$K%1%$%;%0%a%s%H$,%5%V%V%m%C%/KFO/4H$K?'$HIIF)L@EYCM$r7W; ;$7! "<!$N%W%m%;%C%5$XHAwk! #%W%m%;%C%5O=1>$1ItJ,E*$J; k@~NCMN=g=xIU$1$5$1$?9INs$r7W; ;$79g@.$5$1$F:G=*E*$J%T%/%;%kCMHJ$k! #

- %G!<%?J,; 6%1%$!&-%c%9%F%#%s%0 [8]

  %W%m%;%C%5$N%"%$%I%k>uBVrKI0$?$a! "binaray-swap 9g@.K!$H$$$&J}K!$,3+H/$5$1$?! #$3$1$O! "3F9g@.%9%F!<%8$G$=$1$>$12hLLrFsD$KJ,3d$7! "Fs

DN%W%m%;%C%5$,$=N&AN0lDKBP7F@UG$$rbD3HKh$j!"$9YF $N%W%m%;%C%5$,9YFN%9%F!<%8$G=hM}$K;22C9k$H$$$&bNG"$k!#$3 li$N=hM}<jK!$O!"%W%m%;%C%54V$G%\%j%e!<%`%G!<%?$r0\$9I,MW$,$J$/!"9b $$%W%m%;%C%5$NMxMQEY$HDL?.NL$N8:>/$,C#@.G-$k!#

- %?%9%/E,1~$NJBNs=hM}[9]

  3NJ}K!GO!"%9%-%c%s%i%$%sZ %P%C%U%!%"%k%4%j%:%`$rMQ$$$k!#$"$k;~ 9o$K;D$C$F$$$k7W;;NL$rF0E*$K%W%m%;%C%54V$KJ,3d$9$k!#$3$N=hM}<jK!$O!" 6&M-%a%b%j$rMQ$$$kBeoj$K!"%?%9%/$GI,MWHJ$k%G!<%?$r%3%T!<9k!# 3lKh$j!"I IMW$JDL?.$,$J$/$J$k!#%a%b%j$NI,MWNL$O:G>.$KJj!"%-%&C %7%eNCV-49$($r9T$&I,MW$,$J$$!#$^$?!"Ii2Y$K1~$8$F%?%9%/$,M}A[E*$K J,3d$5lk$H$$$&MxE@$,$"$k!#

- %$%s%?%i%/%F%#%V$J2hA|@8@.%7%9%F%`[10]

  3N%"%k%4%j%:%`$O;0$D$N%U%'!<%:$rbD!#$=$l$>$l!"%0%j%C%I$NJQ2=$N =hM}!"%S%e!<$NJQ2==hM}!"2hA|$N%l%s%@%j%s%0G"$k!#%^%9%?%W%m%;%C%5 $O%0%j%C%I!"%9%+%iCM!"%S%e!<!"E>Aw4X?t$N;XDj$N9 9?7$r9T$&$?$a!"%f!<%6 %$%s%?%U%'!<%9$HO"MmrH$k!#$^$?!"2hA|$N0 5=L$d%f!<%6%$%s%?%U%'!<%9 XN2hA|Aw?.$b9T$$!"JBNs%?%9%/Kb;22C9k!#%f!<%6KhCF?7$7$$%0 %j%C%I$,;XDj$5lk$H!"6&M-%a%b%j$K%U%!%$%k$+$i%G!<%?$,FI$_9~$^$l!"%; %k%U%'!<%9$N=i4|2=$,JBNs$K9Tol$k!#$=$N%?%9%/J,3d$O%U%'!<%9%0%k!< %WKhCF9Tol!"3liN%?%9%/$OF0E*$K@8@.5l$k!#

  3N%"%k%4%j%:%`$O!"JBNsMIMD 7?$G%"%/%;%9;~4V$N0[$J$k%m!<%+%k%a%b %j$H6&M-%a%b%j$r;}$D%"!<%-%F%/%A%cKBP7$F@_7W$5l?!#

3 Ds0F9kJBNs%"%k%4%j%:%`$N35MW

3.1 JBNs%"%k%4%j%:%`$N35MW

K\8&5fGO!"<!Nh$&$JFCD'$r;}$D%\%j%e!<%`%l%s%@%j%s%0$NJBNs%"%k%4%j %:%`$rDs0F$9$k!#

- %\%j%e!<%`A4BN$NMM;R$rGD0.$G$-$k$?$a!"%\%j%e!<%`$rH>F)L@$JJ*BN$H$7 $F07$(kh$&$K9k!#
- 1s6aK! !;JkE@$+$i$N;k@~$,J?9TGJ$$!K<jK!$r:NMQ$7!"Bg$-$J6u4V$rI=<(9k:]$K!"N)BN46$r:n$j=P$9$3H,G-$kh&K9$k!#

- %l%$!&-%c%9%F%#%s%05;=Q$Khj2hA|$r@8@.$9$k!#$3lO3F;k@~4HKD$$$$FFHN)$J=hM}$r9T$($kNG!"JBNs2==hM}$,2DG=$G$"$k
- ;kE@JQ99$r<+M3$K9T$($kh&K9$k!#$3lr<B8=9kKO!"G$0UJ}8~$+$iH/@8$9$k;k@~$r07$($kh&$K!"%G!<%?J,3d$NA*Br$r9M$(kI,MW,$"$k!#%"%k%4%j%:%`$G$O!"%\%j%e!<%`%G!<%?$rX!"Y!"Z <4$N3 :BI8<4$NJ}8~$X6Q0l$KJ,3d$9$k!"%G!<%?$N3 =E2= !%J3%s%U%j%/%H%U%j!<$J%a%b%j9=B$!K$H<g<4Ey4V3V%5%s%W%j%s%0K![5][6] $rA*Br$9$k!#$3lKhj!"%\%/%;%kCM$rJBNs2=$KFI$_=P$7$,2DG=$G$"$k!#

K\8&5fGO!"3liNJBNs2=J}?Kr=l>$l<B8=$9k3HKhC$F!"%\%j%e!<%`%l%s%@%j%s%0K!$NJBNs2=$rL\;X$9!#

3.2 4pK9$kC`<!%"%k%4%j%:%`

%\%j%e!<%`%l%s%@%j%s%0$r9T$&$?$a$K!"MM!9$J=hM}<jK!$,Ds0F$5$l$F$$$k!#$3$NCf$G$bLevoy[2] $K$h$jDs0F$5$l$?%\%j%e!<%`%l%$!&%-%c%9%F%#%s%05;=Q$Oh/MQ$$$ilk!#K\8&5f$O!"$3$NC`<!%l%$!&%-%c%9%F%#%s%05;=Q$K4p$E$-!"%\%j%e!<%`%l%s%@%j%s%0@lMQJBNs7W;;5!ReVolver/C40[5][6] Kh$jDs0F$5l?3=E2=%a%b%j$N9=@.K!$r%G!<%?J,3d$K1~MQ$7!"J,;6%a%b%j7?JBNs7W;;5!$GJBNs2=$r9T$&!#K\@a$G$O!"Ds0F$9$kJBNs%"%k%4%j%:%`$N4p$K$J$kC`<!%"%k%4%j%:%`$N<jK!$K$D$$$F@bL@9k!#

3.3 C`<!%"%k%4%j%:%`$N35MW

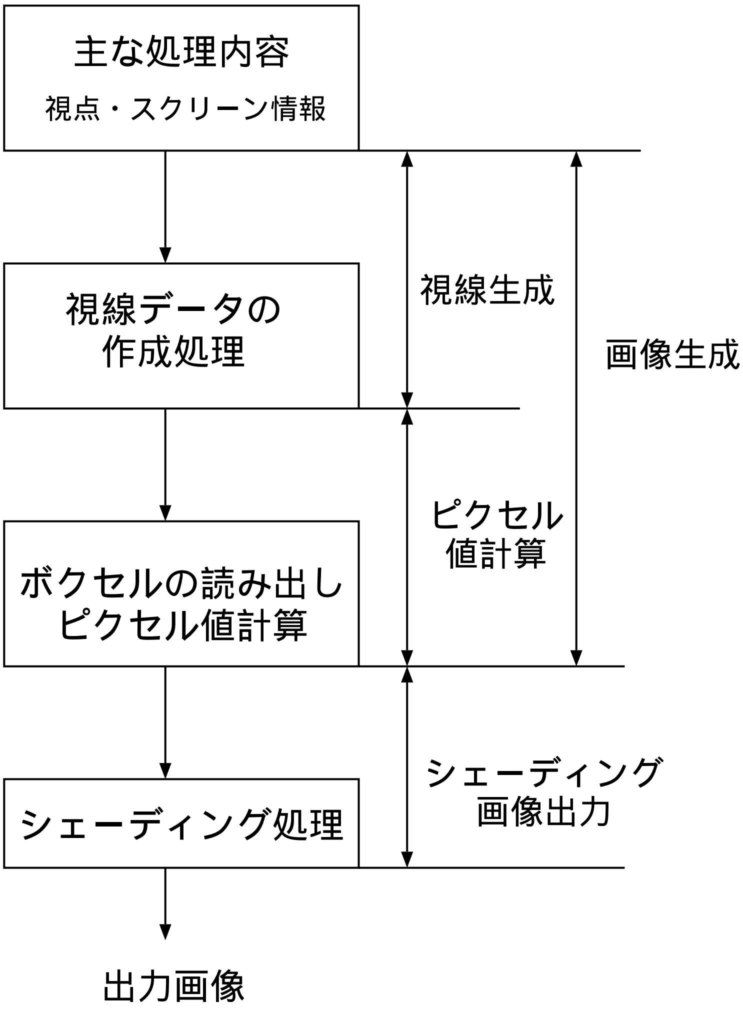
C`<!%"%k%4%j%:%`$N3F=hM}$H3N4V$rN.$l$k%G!<%?$r?^3.1$K<($9!#%"%k%4%j%:%`$O;MCJ3,$+$i9=@.$5lk!#

=i4|@_Dj ;kE@$d%9%/%j!<%s>pJs$JIr@_Dj9k!#

;k@~%G!<%?$N:n@.=hM} A0CJ3,$+iAwilF$/$k;kE@!&9%/%j!<%s$N>pJs$h$j!";kE@$+$i3F%T%/%;%k$rDL$k;k@~$N@8@.$r9T$&!#

%T%/%;%kCM7W;; A0CJ3,$+$i;k@~%G!<%?$K4p$E$-%\%/%;%kCM$rFI$_=P$7!"%l%$!&%-%c%9%F%#%s%0%"%k%4%j%:%`$rMQ$$$F%T%/%;%kCM$N7W;;$r9T$&!#

%7%'!<%G%#%s%0=hM} 7W;;5l$?%T%/%;%kCM$H;k@~%G!<%?$r<u$1<h$j!"depth gradient shading[11] J}K!Kh$j%7%'!<%G%#%s%0=hM}$r9T$&!#0J2<!"<g$J=hM}NCfK;k@~$N7W;;$H%T%/%;%kCM$N7W;;$*hS%7%'!<%G%#%s%0=hM}<jK!KD$$$F@bL@9k!#



?^3.1: C`<!%"%k%4%j%:%`

3.3.1 ;k@~$N7W;;

%l%$!&-%c%9%F%#%s%0=hM}J}K!$G$O!"$^$:;k@~$N@8@.$,I,MW$G$"$k!#;k@~$N@8@.$OD j5A5l$?;kE@!"%9%/%j!<%s$JIN%Q%i%a!<%?Kh$j7W;;$9k3H,G-$k!#6qBNE*$J7W;;J}K!$O<!$ND LjG$"$k[5]!#;HMQ5l$k3F<o%Q%i%a!<%?$rI=3.1$KD j5A$7!"$=$liN0LCV4X78$r?^3.2$K<($9!#

I=3.1Kh$j!"3F%Q%i%a!<%?$K$D$$$F@bL@9k!#

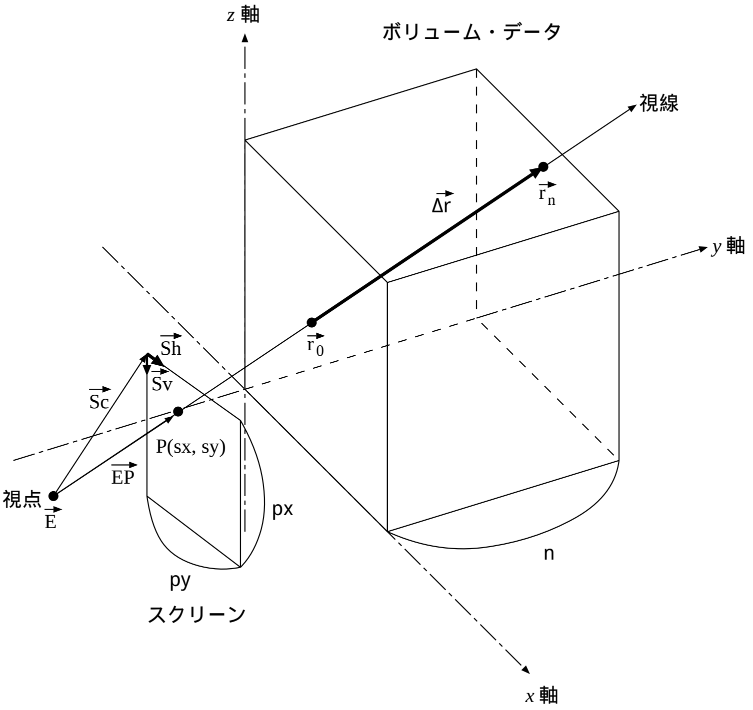
%\%j%e!<%`%G!<%?$O0lJU$K$N$ 8D$N%\%/%;%kCM$+$i$J$kN)J}BN$GI=$5$l$F$$$k$b$N$H$9$k!#$3$3$G, %\%j%e!<%`!&G!<%?$,N%;6%b%G%k$N>l9gKO, $v(x, y, z)$ $O, 6u4V:BI8$(x + 0.5, y + 0.5, z + 0.5)$ GN%G!<%?$NB0@-CM!J%\%/%;%kCM!K$G$"$kH9$k!#O"B3%b%G%k$N>l9gKO, $v(x, y, z)$ $O, 6u4V:BI8$(x, y, z)$ GN%G!<%?$NB0@-

I=3.1: %\%j%e!<%`!&1%s%@%j%s%0!&"%k%4%j%:%`\$N3F<o%Q%i%a!<%?

5-9f	0UL#	5-9f\$NFbMF
N	%\%j%e!<%`\$N0lJU\$NBg\$-\$5	—
Sn	%9%/%j!<%s\$N0lJU\$N%T%/%;%k2rA|EY	—
$v(x,y,z)$	(x,y,z) \$N%\%/%;%kCM	—
$m(x,y,z)$	%\%/%;%k(x,y,z) \$N%^%9%/!&U%i%0†	—
$c(v)$	%\%/%;%kCMv\$KBP1~\$9\$k%\%/%;%k\$N?′	(R, G, B)
$\alpha(v)$	%\%/%;%kCMv\$KBP1~\$9\$k%\%/%;%k\$NF)L@EY	—
px	%9%/%j!<%s\$Nx J}8~\$N%T%/%;%k?t	—
py	%9%/%j!<%s\$NyJ}8~\$N%T%/%;%k?t	—
$P(sx,sy)$	(sx,sy) \$N%T%/%;%kCM	(R, G, B, Vdis , FVC)†
$\vec{E}$	;kE@\$N0lCV%Y%/%H%k	(Ex,Ey,Ez)
$\vec{S}c$	;kE@\$+\$i%9%/%j!<%s\$N:8>eC<\$X\$N%Y%/%H%k	(Scx,Scy,Scz)
$\vec{S}h$	2hLL>e\$Nx J}8~1 %T%/%;%kJ,\$NJ}8~%Y%/%H%k	(Shx,Shy,Shz)
$\vec{S}v$	2hLL>e\$NyJ}8~1 %T%/%;%kJ,\$NJ}8~%Y%/%H%k	(Svx,Svy,Svz)
$\vec{P}$	2hLL>e\$G\$N%T%/%;%k:BI8	(sx,sy)
$\vec{EP}$	%T%/%;%kP =hM}Cf\$N;k@~\$NJ}8~%Y%/%H%k	(EPx,EPy,EPz)
$axis$	<g<4<1JL;R	00,01,10
$axisdir$	<g<4J}8~	1,-1
msk	%^%9%/:BI86-3&	—
$mskdir$	%^%9%/J}8~	$VALID,BEHIND,OUTER,END$
d_0	F~<ME@\$N5wN%	—
Δd	5wN%\$NA}J,	—
$\vec{r_0}$	;k@~\$H<g<4:BI8=0 J?LL\$H\$N8rE@	(r_0x,r_0y,r_0z)
$\vec{r_n}$	;k@~\$H<g<4:BI8=n J?LL\$H\$N8rE@	(r_nx,r_ny,r_nz)
$\vec{\Delta}r$	$\vec{r_n}-\vec{r_0}$	$(\Delta rx,\Delta ry,\Delta rz)$
$\vec{L_i}$	8w8;i \$NJ}8~%Y%/%H%k	(L_ix,L_iy,L_iz)
L_icolor	8w8;$_i$ \$N?′	(R, G, B)

† %^%9%/!&U%i%0\$,1 \$N;~, BP1~\$9\$k%\%/%;%kCM\$O0 \$H\$J\$j, F)L@%\%/%;%k\$H\$J\$k.

‡ FVC \$*\$h\$SVdis \$O, ;k@~\$H:G=i\$K8r:9\$9\$kF)L@\$G\$J\$\$%\%/%;%kCM\$H;kE@\$+\$i\$N5wN%\$G\$"\$k!#



?^3.2: ;k@~@8@.=hM}

CMG"kH9k!#3F%\%/%;%kCM$KBP1~$7$F,%^%9%/!&U%i%0 $m(x,y,z)$ $,Dj5A$5lk!#3N%U%i%0$O,BP1~$9$k%\%/%;%k$,M-8z$+L58z$+$r<($9%S%C%HG"$j!"1$N;~$OM-8z$HJk$,!"0 $N;~$OF)L@$J%\%/%;%k$HG'<1$9$k!#%\%/%;%k$N?' $c(v)$ $*$h$SF)L@EY $\alpha(v)$ $O!"F I$_=P7?%\%/%;%kCM v_i $r;H$C$FB0@-%F!<%V%k$r;2>H9k3HKh$j5a$ail$k!#$3$N%F!<%V%k;2>H$O!"0J2<$N2 DL$jN&$A$$$:l+$G9T$olk!#

- D>@\:%\%/%;%kCM$rD>@\%$%s%G%C%/%9H7$F!"B0@-%F!<%V%k$r;2>H9k!#K\8&5fGO3l$r;HMQ$9$k!#
- :9J,:NY@\%\%/%;%kCMHN:9J,$r%$%s%G%C%/%9H7$F!"B0@-%F!<%V%k$r;2>H9k!#

%9%/%j!<%s$O!"x J}8~$K px 8D!"y J}8~$K py 8D$N%T%/%;%k$r;}DbNH9k!#%9%/%j!<%s>e$N3F%T%/%;%k P KBP7$F!"%T%/%;%kCM $P(sx,sy)$ $,Dj5A$5lk!#$3$3$G%T%/%;%kCM$O(R, G, B, Vdis, FVC) $NMWAG$r;}$D!#R, G, B $O!"%T%/%;%k$N?'$N@V@.J,!"NP@.J,!"@D@.J,$G$"$j!"Vdis $O!"%T%/%;%k$rDL$k;k@~$H8r:9$9$k@hF,$NF)L@$G$J$$%\%/%;%k$H%9%/%j!<%s$N5wN%$rI=$9!#$3$3$G!"$3Nh$&$J%\%/%;%k$,B8:_$7$J$$>l9gKO!"CMDMAX $,BeF~$5lk!#$^$?!"FVC

$O!"$3$N%\%/%;%k$N%\%/%;%kCMG"$k!#6u4VFb$K;kE@$\vec{E}$$,Dj5A5l!"3NE@$+ $i%9%/%j!<%s$rDL7F%\%j%e!<%`$r4Q;!$9$k!#%9%/%j!<%s$NA4FN%T%/%;%k$N 6u4V:BI8$K$*$1$k0LCV$O!"6u4V:BI8K*1k;kE@$+$i%9%/%j!<%s:8>eC<XN%Y %/%H%k$\vec{S}c$!"x J}8~1 %T%/%;%kJ,$NJ}8~%Y%/%H%k$\vec{S}h$!"$y$J}8~1 %T%/%;%kJ,$NJ}8~ %Y%/%H%k$\vec{S}v$$KhC$FI=$5lk!#3liKhj!"$"$k%T%/%;%k$P(sx,sy)$ $r=hM} Cf$G$"$k;~!";k@~$NJ}8~%Y%/%H%k$\vec{E}P$$O<0

$$\vec{E}P = \vec{S}c + sx\vec{S}h + sy\vec{S}v \tag{3.1}$$

KhjH7W;;5l$k!#

$3$3$G!"I=3.1$K<(9h$&$K!"axis $O!"<g<4<1JL;R$G$"$j!"<g<4$,x <4!"y <4 $*$h$Sz <4$N;~$K!"$=l>$l00!"01!"10 NCMrHk!#$^$?!"axisdir $O!";k@~ $NJ}8~$,<g<4@5J}8~$*$h$SIiJ}8~$G$"$k3Hr=l>$l11 $*$h$S-1 NCMKhC $F<($9!#msk!"mskdir $O!"%\%j%e!<%`$N<g<4:BI8$,msk $G$"$kE@$r5/E@$H$7!" mskdir $N<($9J}8~$K$"$kA4$F$N%\%/%;%k$r%^%9%/$9$k$?$a$K;H$o$l$k!#$3$l$i $K$h$j!";kE@$,%\%j%e!<%`Fb$KB8:_9k;~$K!";kE@$N8eJ}$NA4%\%/%;%k$,%T%/ %;%kCM$K1F6A$rM?$($J$$$h$&$K, 3liN%\%/%;%k$rF)L@$K9k3H$,$G$-$k!#

;k@~@8@.$N%"%k%4%j%:%`$O!"0J2<Nh$&$KJk!#(?^3.3!K

1. ;k@~%Y%/%H%k$N;;=P:

   ;k@~%Y%/%H%k$r, $\vec{S}c$, $\vec{S}h$,$\vec{S}v$, $\vec{P}$$r;HCF5aak!#

2. <g<4$N7hDj:

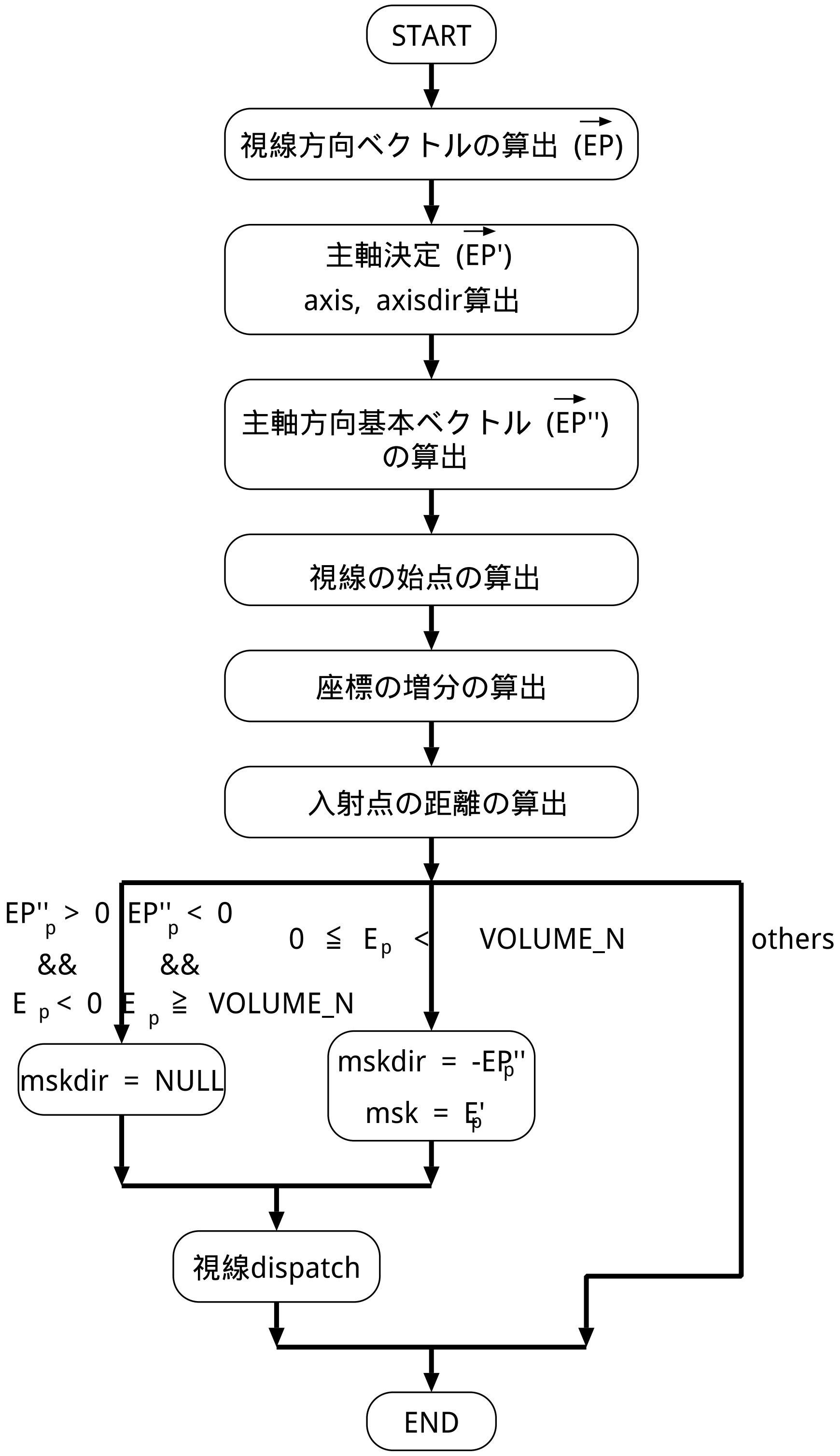
   <g<4HO!";;=P7?;k@~%Y%/%H%k$\vec{E}P$$N@.J,NCfG(EPx,EPy,EPz) $N @dBPCM$,:GBgNbN,<g<4$\vec{E}P'$$J$k:BI8J}8~$G$"$j!#<g<4J}8~$N@.J,$r!J $EP'_x, EP'_y, EP'_z)$ H7$F@_Dj$9$k!#

3. <g<4J}8~4pK\%Y%/%H%k$N;;=P:

   <g<4J}8~4pK\%Y%/%H%k$\vec{E}P''$$O<g<4:BI8$NA}J,$,± 1 HJ$k%Y%/%H%k$G$"$k!# 3l$O, $\vec{E}P'$$r$|EP'_p|$ $G3d$k3HKh$j5a$ail$k. <g<4J}8~$N@.J,$O;k E@$N:BI8$\vec{E}$$,JQokHJBY4 9$($k!#

4. ;k@~J}8~$N7hDj:

   ;k@~$NJ}8~$r<g<4J}8~%Y%/%H%k$N@5J}8~#1$NCM$HIiJ}8~—$1$ NCMGH=Dj$7 $F5a$a$k!#


START
視線方向ベクトルの算出 (EP)
主軸決定 (EP')
axis, axisdir算出
主軸方向基本ベクトル (EP'')
の算出
視線の始点の算出
座標の増分の算出
入射点の距離の算出
EP''p > 0
&&
E p < 0
EP''p < 0
&&
E p ≧ VOLUME_N
0 ≦ Ep < VOLUME_N
others
mskdir = NULL
mskdir = -EP''p
msk = E'p
視線dispatch
END

?^3.3: ;k@~@8@.%"%k%4%j%:%`

3.3.2 %T%/%;%kCM$N7W;;

%T%/%;%kCM$N7W;;$O!";k@~$r%\%/%;%k6u4V$KDL2a$78r:9$9$k%\%/%;%k$N%"%I%l%9$r;;=P!"%\%/%;%kCM$rFI$_=P$7!"<0 (2.4) $rMQ$$$F%T%/%;%kCM$N7W;;$r9T$&[2][13]!#

$$\begin{cases} C_k = C_{k-1} + (1-\alpha(v_k)) \cdot c(v_k) \cdot A_{k-1} \\ A_k = \alpha(v_k) \cdot A_{k-1} \end{cases} \quad (3.2)$$

$?$@$7!" $c(v_i), \alpha(v_i)$ O=l>$l%\%/%;%kCM v_i $r?'!"F)L@EY$KJQ49$7$?CMG"k3Hr<(7F$$$k!#%5%s%W%j%s%0$9$k%\%/%;%k?t$, N $N>l9g!"<0 (2.4) KhCF5aailk%T%/%;%kCM$O<0 (3.2) N C_N $HF1$lNCMHJk!#D^$j C_N $r5a$ak3HKhC$F!"%T%/%;%kCM$r5aak3H$,=PMh$k!#<0 (3.2) N C_k, A_{k-1} O $C_{k-1}, A_{k-1}, c(v_k), \alpha(v_k)$ $+$i5aak3H$,$G$-!" $c(v_k), \alpha(v_k)$ O v_k $rJQ49$7$?CM$G$"$k$+$i!"7k6I C_k, A_k O C_{k-1}, A_{k-1}, v_k $+$i5aak3H$,$G$-$k!#

H3m,;k@~$N<g<4@.J,$,@5$N;~$H!";k@~$N<g<4@.J,$,Ii$N;~$HGO!"=hM}$N9T$&J}8~$,5U$HJk!#hCFNc($P;k@~J}8~$,@5$N%T%/%;%kCM$N7W;;$r9T$C$F$$$k:GCf$K!";k@~J}8~$,Ii$N%T%/%;%kCM7W;;$r9T$*$&H9kH!"=hM}$N>WFM$,5/3j@-G=$,Dc2<$9$k!#

$=$3$G!"%Q%$%W%i%$%s$NC1J}8~2=N?$a!">o$K=hM}$NJ}8~$r@5H9k3Hr!"<!Nh$&$K7F<B8=7?!#<0 (2.4) $r<0 (3.3) $KJQ7A$9$k!#

$$C'_{k-1} = C'_k \cdot \alpha(v_{k-1}) + (1-\alpha(v_{k-1})) \cdot c(v_{k-1}) \quad (3.3)$$

hC$F!";k@~J}8~$,Ii$N>l9g$K i HV$N%\%/%;%k$K<0 (3.3) N C'_{N-i} $N7W;;$r9To;kH!"%\%j%e!<%`!&G!<%?$, $N^3 voxel$ H9kH!" $0, 1, \cdots, N$ HV$N%\%/%;%k$N=g$G=hM}$,9T$($k!#

0J>ehj!";k@~J}8~$,@5$N;~$O<0 (3.2) $r7W;;$7!";k@~J}8~$,Ii$N;~$O<0 (3.3) $r7W;;$9k3HG!">o$K=hM}$NJ}8~$rC1J}8~$H9k3H$,2DG=$G$"$k!#

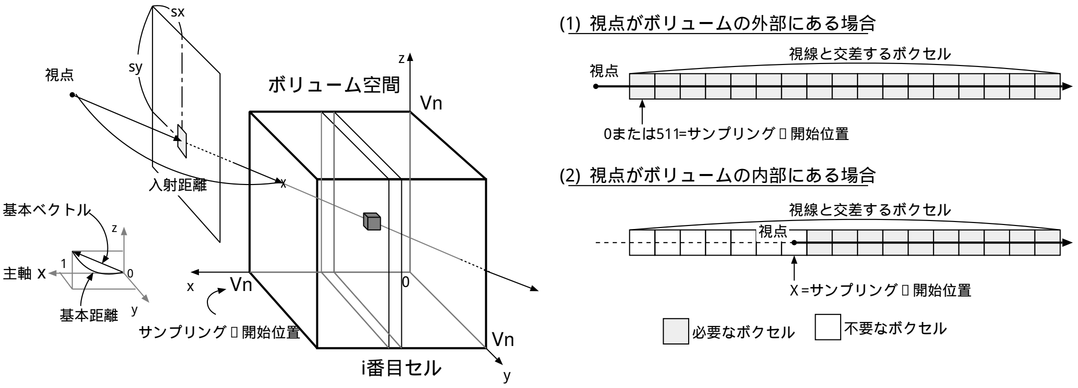
%T%/%;%kCM$N7W;;$OO0J2<$N<j=g$G9Tol$k!#

1. ;k@~@8@.%"%k%4%j%:%`Kh$j;k@~$r@8@.9k!#
2. <!$N<0$KhC$F!"i HVL\ $(1 \le i \le N)$ %5%s%W%j%s%0$9$k%\%/%;%k$N%"%I%l%9$r7W;;9k!#<0 3.4 F~<ME@:BI8$O?^ 3.4 $K<($9h&$K!"Nc$($P<g<4$, X <4$N>l9g!"J?LL $X = 0$ $H;k@~$H$N8rE@$N:BI8G"$k!#4pK\%Y%/%H%k$O;k@~%Y%/

%H%k$N<g<4@.J,$r#1H7$?;~$N;k@~%Y%/%H%kG"$k!#

F~<ME@ + 4pK\%Y%/%H%k × *i* (3.4)

3. %5%s%W%j%s%0E@$N%\%/%;%k!"%\%/%;%kCM$rFI$_=P$7!"%T%/%;%kCM$r7W;;$9$k!#
4. 7W;;7?%T%/%;%kCM$rMQ$$$?%7%'!<%G%#%s%0=hM}$r9T$&!#



?^3.4: ;k@~$H%\%j%e!<%`$N4X78

3.3.3 %7%'!<%G%#%s%0=hM}

%7%'!<%G%#%s%0=hM}GO!"8w8;>pJs$rMQ$$$F@8@.2hA|$N51EY$rJd@5$9$k3HKh$j!"2hA|$K8=<B46$r;}$?$;$k!#%\%j%e!<%`%l%s%@%j%s%0K!$K$*$$$F$O!"%\%j%e!<%`%G!<%?$,85$N%G!<%?$rN%;6:BI8$G$N%\%/%;%kCM$KhC$FI=$7$?$bNG$"$k$?$a!";k@~$HJ*BN$N8rE@K*1kJ*BN$NK!@~$r6a;wKhCF5aakI,MW$+$"$k!#

=>Mh!"depth gradient shading K!$,$h$/:NMQ$5lF$$$k!#3NJ}K!$O!"%\%j%e!<%`%G!<%?$r2hLL$KEj1F$7$?$H$-$K!"3F%T%/%;%kKh$K%T%/%;%kCM$HZ CM$r5-21$7F*$-!"3F;k@~$HJ*BN$N8rE@$K$*$1$kK!@~$O!";k@~rDLk%T%/%;%kK*1kZ CM$Hx!"y J}8~$KNY@\$9$k?t%T%/%;%k$NZ CM$H4X78$Khj6a;w9kJ}K!G"$k!#

%7%'!<%G%#%s%0ItJ,$N=hM}$O!"%T%/%;%kCM$N7W;;$+$i;k@~%G!<%?$H%T%/%;%kCMKh$j!"3F%T%/%;%k$N51EY$r5a$a$k!#6qBNE*$J=hM}$O0J2<$G@bL@9k!#

;k@~$N7W;;ItJ,$G:n@.5l$?F~<M5wN%!";k@~$H3F%\%/%;%k$N8rE@:BI8$*hS4pK\5wN%$rMQ$$$F!"<0(3.5) Kh$jdepth CM$r7W;;$7!"?<$5%P%C%U%!!Jdepth buffer!K$K3JG<$9$k!#

depth = F~<M5wN%!\8rE@ × 4pK\5wN% (3.5)

<!$K3F%T%/%;%k$N51EY$r5a$a$k!#6qBNE*$KO"$kP K*1kK!@~%Y%/%H%k$r5aak>l9g!"X $HY $NN>J}8~$K$D$$$F;HMQ9k%T%/%;%k$NHO0O$r7h$a!"<P@~6u4V$NN>C<%T%/%;%k$N?<$5CMD !xJ,y) $r<h$j=P$7!"<0(3.6)[15] Khj3NCMN:9$H:BI8$N:9$r;H$C$F8{G[$r6a;w9k!#

$$\begin{cases} \Delta Dx_+(i) & = & D(x+i,y) - D(x+i+1,y) \\ \Delta Dx_-(i) & = & D(x-i,y) - D(x-i-1,y) \end{cases} \tag{3.6}$$

5aail?CM$X_{min}, X_{max}, Y_{main}, Y_{max}$$K$$$F!"<0(3.7) Kh$j!"P K*1kK!@~%Y%/%H%kr\vec{v}_x = (P_x, 0, d_x)$ H\vec{v}_y = (0, P_y, d_x)$ $N30@Q!"$9JoA\vec{N}_p = \vec{v}_x \times \vec{v}_y = (-p_y$!&$d_x, -p_x$!&d_y, p_x !&$p_y)$ H9$k!#

$$\begin{cases} d_x & = & D(x+x_{max},y) - D(x+x_{min},y) \\ d_y & = & D(x,y+y_{max}) - D(x,y+y_{min}) \\ p_x & = & x_{max} - x_{min} + 1 \\ p_y & = & y_{max} - y_{min} + 1 \end{cases} \tag{3.7}$$

%7%'!<%G%#%s%0=hM}$r=*$($?%T%/%;%kCM$r%U%l!<%`%P%C%U%!$XAw=P$7!":G=*F@il$?2hA|$rCRT $X=PNO$9$k!#

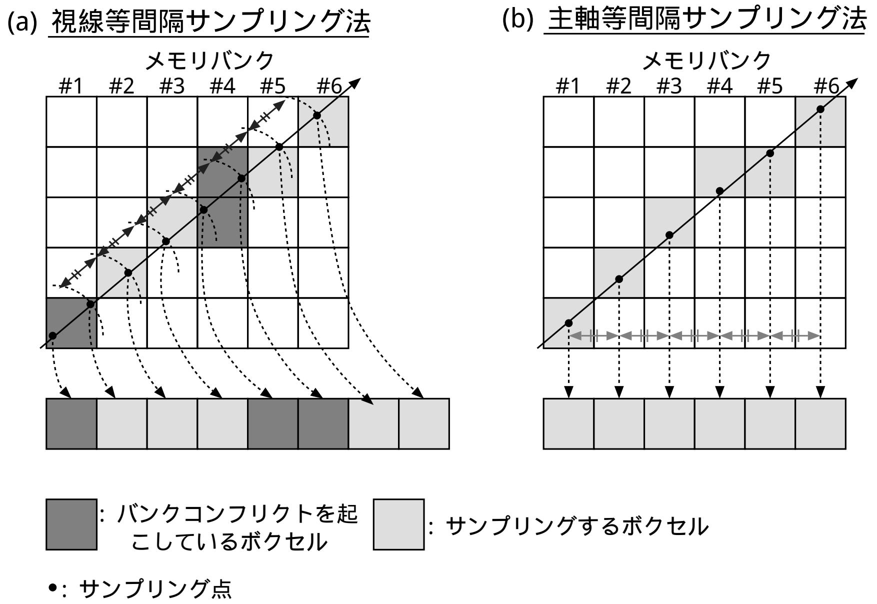
%\%j%e!<%`%l%s%@%j%s%0$O!";k@~@8@.=hM}!"%T%/%;%kCM=hM}$H%7%'!<%G%#%s%0=hM}$*hS2hA|$N=PNO=hM}$H$$$&9=@.rHk3HKhC$F!"FbIt=hM}$NFHN)@-$,9b$^$j!"JBNs7W;;5!$G<BAu9k3H$,2DG=$KJk!#3N7k2L9bB.2=$,F@$ilk3H$,M=A[$5lk!#

3.4 %3%s%U%j%/%H%U%j!<$J%a%b%j9=@.

K\8&5fK*1k#1DNL\I8$O;kE@JQ99$,G-!"G$0UJ}8~$KH/@8$9$k;k@~KBP7$F2hA|$r@8@.G-k3HG$"$k!#$=$N$?$a$K!"%G!<%?J,3dK!$NA*Br$,=EMW$G$"$k!#K\8&5fGO!"%\%j%e!<%`%l%s%@%j%s%0@lMQJBNs7W;;5!ReVolver/C40 $GDs0F$5$l$F$$$k%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.K!$K4p$E$/!"%G!<%?J,3dK!$r:NMQ$7$?!#0J2<!"$3$N%a%b%j$N9=@.$K$D$$$F@bL@$9$k!#=>Mh$N%\%j%e!<%`%l%s%@%j%s%0GO;k@~>e$N%\%/%;%kCM$N%5%s%W%j%s%0KOFsDNJ}<0$,$"$k[16][17]!#

- ;k@~Ey4V3V%\%/%;%k%5%s%W%j%s%0J}K!:;k@~J}8~$K1h$C$FEy4V3V$K%5%s%W%j%s%0$r9T$&h&K9$k!#

- <g<4Ey4V3V%5%s%W%j%s%0J}K!!';k@~%Y%/%H%k$N3 DN@.J,(x,y,z @.J,) $N@dBPCM$rHf3S$7!":GBgCM$N@.J,$N:BI8<4$r<g<4HDja!"3N<g<4J}8~KBP7$F;k@~>e$N%\%/%;%k$rEy4V3V%5%s%W%j%s%0$r9T$&$h$&$K9k!#



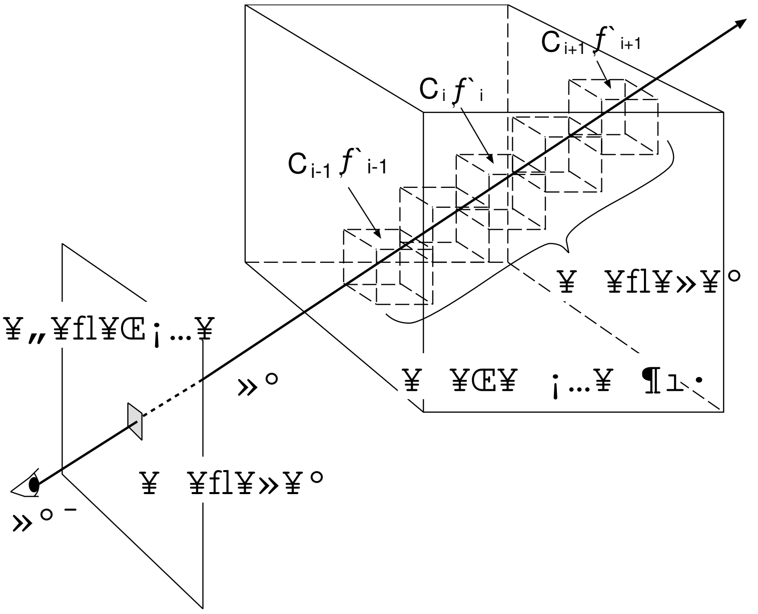
?^3.5: %5%s%W%j%s%0K!

;k@~Ey4V3V%5%s%W%j%s%0$O!"%\%/%;%kJBNs=hM};~$K!"%\%j%e!<%`%G!<%?$r%a%b%j%P%s%/$KJ,3d7F3JG<9k$H!"F10l;k@~>e$NJ#?t$N%\%/%;%k$,F10l%a%b%j%P%s%/$K3JG<$5lF$$$k>u67$,H/@8$9k3H,$"$j!"JBNs<B9T$N9bB.2=$N>c32KJ$k!#(?^3.5)

3lKBP7$F!"<g<4Ey4V3V%5%s%W%j%s%0J}K!$r:NMQ$7!"%P%s%/%3%s%U%j%/%HrKI0$?$a$K!"%P%s%/%3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$,Ds0F5l$?!#

6qBNE*KO!"?^3.6$K<($9h&$K!"%\%j%e!<%`6u4V$N1 JU$N%\%/%;%k?t$rN$H$7$F!"%\%j%e!<%`6u4V$rx,y,z <4$K?bD>$J N Kg $NJ?LL$K%9%i%$%9$rJ,3d$7!"3FJ?LL72$KBP$7!"J?LL$K1,2,···,N $HHV9f$r$D$1!"F1$8HV9f$r;}$DJ?LL$N%G!<%?r=$NHV9f$N%a%b%j%P%s%/$NBP1~$9$kNN0h$K3JG<9k!#Nc$($P!"%\%j%e!<%`Fb$N:BI8(p,q,r) $N%\%/%;%k$O!"%a%b%j%P%s%/p $NX NN0h!"%a%b%j%P%s%/q $NY NN0h!"%a%b%j%P%s%/r $NZ NN0h$N3 2U=j$K3JG<$5lk!#

3N9=@.Kh$j!"3FJ?LL72$NJ?LLO9YF0[JC$?%a%b%j%P%s%/$K3JG<5lkN$G!"<g<4Ey4V3V%5%s%W%j%s%0$r9T$&>l9g!"G$0UJ}8~$N;k@~$H8r:9$9$kA4%\



?^3.6: %\%j%e!<% `%G!<%?$N3JG<J}K!

%/%;%k$rF1;~$KFI$_=P$9$3$H$,$G$-$k!#

K\8&5fGO!"J,;6%a%b%j7?JBNs7W;;5!$N>e$GJBNs2=9k3H$,L\E*$G$"$k!#
%\%j%e!<% `%G!<%?$,>.$5$$>l9g$O!"%G!<%?$rJ,3d$;$:3FJ,;6%a%b%j$KF1$8%G!<
%?$r3JG<$9lP!";k@~Ey4V3V%\%/%;%k%5%s%W%j%s%0K!$r:NMQ$9kH!"%T%/%;%k
CM7W;;$NJBNs2=$,G-$k!#$7$+$7!"%\%j%e!<% `%G!<%?$,Bg$-$$>l9g$O!"%G!<%?
$rJ,3d$9kI,MW,$"$kNG!"F10l;k@~>e$NJ#?t$N%\%/%;%k$,F10l%W%m%;%C%5%a
%b%j$K3JG<$5lk>u67$,H/@8$9$k2DG=@-$,$"$k!#

$3$3$GK\8&5f$O!"%\%/%;%kJBNs=hM}Kh$k%T%/%;%kCM7W;;$N9bB.2=$,L\I8$G
$"$k!#3N<g<4Ey4V3V%5%s%W%j%s%0K!$r%G!<%?J,3d$K1~MQ9k3HKh$j!"G$
0U$N;k@~$K8r:9$9$kA4%\%/%;%k$rJBNs$KFI$_=P$72DG=G"$j!"8D!9$N%W%m%;%C
%5Cf$G%T%/%;%kKh$KFHN)=hM}9k3H$,$G$-$k!#<g<4Ey4V3V%5%s%W%j%s%0J}K!
Kh$k!"%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.$r:NMQ$9$k!#

$^$?!"<g<4Ey4V3V%5%s%W%j%s%0K!$O!"<4$HJ?9TGJ$$;k@~$,DL>o$N;k@~Ey4V
3V%5%s%W%j%s%0K!KHfYkH!"$=$N%5%s%W%j%s%04V3V$O:GBg$G$\sqrt{3}$$HJk$?$a!"
;k@~4H$K%T%/%;%kCM$NJd@5$,I,MW$HJk!#

4 JBNs%"%k%4%j%:%`$H<BAu

4.1 JBNs%"%k%4%j%:%`$NL\I8

K\>OGO!"$^$:!"%\%j%e!<%`%1%s%@%j%s%0$rJBNs2=$9$k:]$KL\I8$H$9$Y$-;v9`KD$$$F=RYk!#B3$$$F!"0lHLE*$J%a%b%jJ,;67?JBNs7W;;5!$rBP>]H7$?!"JBNs%"%k%4%j%:%`$rDs0F$7!"$5$i$K!"$=$N%"%k%4%j%:%`$N AP1000 XN<BAuKD$$$F=RYk!#

%\%j%e!<%`%1%s%@%j%s%0$O!"=hM}NL$,Hs>o$KBg$-$$$N$G!"$h$j9b$$JBNs@-$rF@$k$?$a$K!"Ii2Y$NJ,;6$HDL?.;~4V$N:o8:$,I,MW$H$J$k!#K\@a$G$O!"Ds0F$9$k%"%k%4%j%:%`$K4X$9$k4pK\E*$JL\I8KD$$$F=RYk!#

JBNs2=$NL\I8 3.1@a$K=RY?h&$K!"K\8&5f$G$O!"9bB.$K%\%j%e!<%`%1%s%@%j%s%0$r<B9T$9k?$a!"<!$Nh&$J4pK\L\I8$r@_Dj9k!#

K\<jK!GO!"%\%j%e!<%`$rH>F)L@$JJ*BN$H$7$FO7$$!"1s6aK!<jK!$H%3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$K4p$E$/%G!<%?J,3dK!$r:NMQ$9$k!#$^$?!"9bB.$J%\%j%e!<%`%1%s%@%j%s%0$r<B8=$9k?aK!"9bB.=hM}9kMWAG$r9M$(J1lPJi$J$$!#J,;6%a%b%j7?JBNs7W;;5!GO!"Ii2YJ,;6$,=hM}B.EY$KM?$($k1F6A$,6K$aFBg-$$!#$=$7$F!"%W%m%;%C%5$NMxMQN($r9b$a$k%W%m%0%i%`$r:n@.$9$k$?$a$K!"DL?.%1%$%F%s%7$rDc8:$9$k$N$,=EMW$G$"$k!#0lJ}C`<!%W%m%0%i%`$rJBNs2=$9$k>l9g$K$O!"I,$:$7$b$=$N%"%k%4%j%:%`$,JBNs%W%m%0%i%`$N$b$N$H$7$FE,@Z$H$O8B$i$J$$$?$a!"%"%k%4%j%:%`LL$G$N8+D>$7$,I,MW$HJk3Hb"$k!#

$3$1iNL\I8r=1>$1<B8=$9k3HKhC$F!"%\%j%e!<%`%1%s%@%j%s%0K!$rJBNs2=$9$k!#

JBNs2=$N4pK\<jK! %\%j%e!<%`%1%s%@%j%s%0$O!"%1%$!&%-%c%9%F%#%s%0K!$K$h$j!"3F;k@~$4$H$KFHN)$J=hM}$r9T$(!"JBNs=hM}$,2DG=$G$"$k!#Ii2Y$rJ,;6$9$k$?$a!"%\%j%e!<%`%G!<%?$r3F%W%m%;%C%5$KJ,3d$7!"3F%W%m%;%C%5$O!"$=$1$>$1$,=jM-$9$k%G!<%?$N1i;;$rC4Ev$9$k!#$^$?!";kE@JQ99$r9T$($kh&K9k?$a!"%3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$K4pE/%G!<%?J,3dK!$rMxMQ$9kH!"%\%/%;%kCM$rJBNs$KFI$_=P$72DG=G"$k!#

BP>]r9$kJBNs4D6- K\%"%k%4%j%:%`$O!"0J2<$NFCD'$r;}$D!#

- %a%b%jJ,;67?JBNs7W;;5!%7%9%F%`$rBP>]$H9k!#$3$1$O!"3F%W%m%;%C%5$N%a%b%j6u4V$,8_$$$KFHN)7?!"MIMD 7?$NJBNs7W;;5!$G$"$k!#

- 8D!9$N%W%m%;%C%54V$N%G!<%?$N<uEO$7$O%a%C%;!<%8$NAw<u?.KhCF<B8=5l$k!#
- Aw?.B&%W%m%;%C%5$+$iAwil$?%a%C%;!<%8$O!"%O!<%I%&%'%"$+OS%l%Y%k$G<u?.B&$N%P%C%U%!$KF~lk3H$,$G$-$k!#

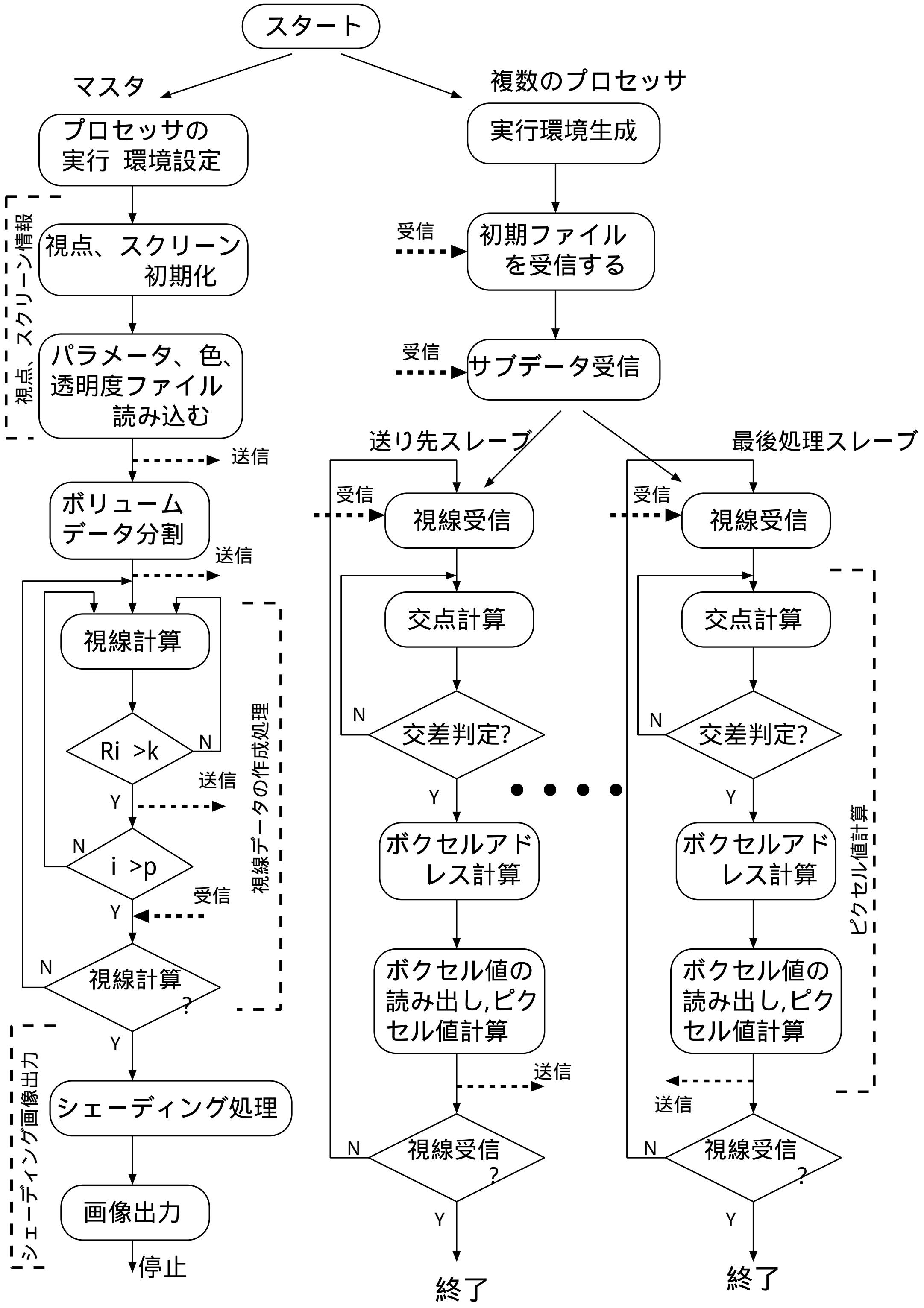
3Nh&$J%7%9%F%`$K$OAP1000$Nh&$JJBNs7W;;5!$@1GOJ$/!"$[$\F1Ey$N@-G=$r!CPU!"%G%#%9%/!"%a%b%j;q8;!K;}C?J#?t$N7W;;5!$,!"8_$$$K%M%C%H%o!<%/$G@\B3$5l?J,;64D6-$b4^$^lk!#

4.2 JBNs%"%k%4%j%:%`

K\8&5f$GDs0F$9$kJBNs%"%k%4%j%:%`$O!"#1Bf$N%^%9%?7W;;5!$HJ#?t$N%9%l!<%V7W;;5!$,F14|!JDL?.$rDL$8$F!"JBNs$K=hM}$r9T$&$b$N$G$"$k!#0J2<!"0lHIE*$J%a%b%jJ,;67?JBNs7W;;5!%7%9%F%`$rBP>]H7$?$3$N%"%k%4%j%:%`$N<B8=J}K!$K$D$$$F@bL@$9$k!#JBNs%"%k%4%j%:%`$N%U%m!<%A%c!<%H$r?^4.1$K<($9!#$3$3$G!"JQ?tRi!"pO=l>$l;k@~$N%G!<%??t!"%W%m%;%C%5Bf?t$r<($9!#

K\<jK!GO!"%^%9%?$H%9%l!<%V$G$=$l$>$l0[Jk%W%m%0%i%`$r<B9T$9$k!#%^%9%?MQ%W%m%0%i%`$O%9%l!<%V$N<B9T4D6-@_Dj!"=hM}$N=i4|2=!"%G!<%?$NJ,3d!";k@~$N@8@.$H%7%'!<%G%#%s%0=hM}$*$h$S2hA|$N=PNOJI$N=hM}$r9T$&!#%9%l!<%VMQ%W%m%0%i%`$OB>$N%9%l!<%V$d%^%9%?7W;;5!$HDL?.$7J,$i!"%T%/%;%kCM$rJBNs$K7W;;$9$k!#<g$J=hM}$NN.$l$r%^%9%?$H%9%l!<%V$NN>J}$KJ,1F@bL@9k!#%^%9%?7W;;5!B&$N=hM}!'

1. %9%l!<%V$N<B9T4D6-$r@_Dj9k!#
2. ;kE@!"%9%/%j!<%s>pJs$N@_Dj!"=hM}Cf$K07$&%Q%i%a!<%?%U%!%$%k!"%\%/%;%kCM!J'!"F)L@EY!K"B0@-%F!<%V%k%U%!%$%k$rFI$_9~$_!"A4%9%l!<%V$KAw?.$9$k!#
3. %\%j%e!<%`!&G!<%?$N%U%!%$%krFI_9~$_!"%G!<%?$NJ,3d$r9T$&!#J,3d5l$?%G!<%?$r8D!9$N%9%l!<%V$X=gHV$KAw?.$9$k!#
4. ;k@~%G!<%?$N:n@.=hM}$r9T$&!#%9%/%j!<%s%5%$%:Kh$k!"3.3.1@a$K=RY?;k@~@8@.J}K!$rMQ$$$F!"7+jJV7$F;k@~%G!<%?$r7W;;$7Aw$j@h$N%9%l!<%V$KEO$9!#$3$N=hM}$NCJ3,$G%Q%$%W%i%$%sJBNs=hM}$r9T$&!#$D$^$j!"$"$kNL$N;k@~%G!<%?$r@8@.7FAw?.7?8e!":G8e$N%9%l!<%V$+iAwil?%T%/%;%kCM$r<u?.$9$k!#$^$?!";k@~%G!<%?$rAw?.=*N;7?H-$K!"%9%l!<%V$+$i%T%/%;%kCM$r<}=8$9$k!#



?^4.1: JBNs%"%k%4%j%:%`$N%U%m!<%A%c!<%H

5. <}=8$5$l$?%T%/%;%kCM$r%P%C%U%!$K=q$-9~$_!"%7%'!<%G%#%s%0=hM}$r9T$&!#

6. 2hA|$r=PNO$9$k!#

%9%l!<%VB&$N=hM}:

1. %^%9%?B&$+$iAw?.5lF-$?;kE@$H%9%/%j!<%s>pJs!"%Q%i%a!<%?%U%!%$%k!"%\%/%;%kCM$*hSB0@-%F!<%V%k%U%!%$%k$r<u?.9k!#

2. J,3d5l$FAw?.$5l?$-$?%5%V%\%j%e!<%`!&G!<%?$N<+J,$NC4EvNN0h$r<u?.$7!"%a%b%j$K=q$-9~$`!#

3. %Q%$%W%i%$%sJ}<0$GJBNs$K%T%/%;%kCM$N7W;;$r<B9T9k!#(%Q%$%W%i%$%s<jK!$N6qBNE*$J=hM}$O4.4.1@a$G=RYk!K":G=i!"%^%9%?$+$i;XDj5l$?%9%l!<%V$OAwil$?;k@~$r<u?.9k!#%9%l!<%VO=l>lNC4EvNN0h$rDL2a$7$F$$$l$P!"8rE@H=Dj$Khj!"%T%/%;%kCM7W;;$r9T$&!#

4. %T%/%;%kCM$H;k@~$rNY@\%9%l!<%V$KAw?.$9$k!#Aw?.$5l?%9%l!<%V$O!"A0$NbN$r7W;;=*N;8e!"Aw?.$5l?;k@~%G!<%?$H%T%/%;%kCM$r<u?.9k!#

5. :G8e$N%9%l!<%V$O!"N_@Q7?%T%/%;%kCM$r%^%9%?$KAw?.9k!#

<!$K!"Ds0F$9$k%"%k%4%j%:%`$NFCD'$*$h$S6qBNE*$JJBNs2=<jK!KD$$$F=RYk!#

1. %G!<%?$NJ,;6

%\%j%e!<%`%l%s%@%j%s%0K!$O%a%b%jJ,;67?7W;;5!>e$G?^4.1$K<($9$h$&$KJBNs2==hM}$r9T$&!#$7$+$70lHL$K%\%j%e!<%`!&G!<%?$OHs>o$KBg$-$$$?$a!"3F%W%m%;%C%5$KBP7F%\%j%e!<%`%G!<%?$,J,;6$5lF$$$k3H$,A0Ds$HJk!#K\8&5fKD$$$F!"%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.$K4pE-%G!<%?J,3dK!$r:NMQ$9k?$a!"%G!<%?J,3d$O X !" Y !" Z <4$N;0J}8~$KEyJ,%9%i%$%9$GJ,3d$7!"3F%W%m%;%C%5(%W%m%;%C%5?t P H9$k)$N%a%b%j$K3d$jEvFk!#%T%/%;%kCM7W;;$r%Q%$%W%i%$%s2=$7d9$$$h$&$K!"%W%m%;%C%59=@.$r0l<!85$KHk!#D^$j3<!85%\%j%e!<%`%G!<%?!$ N^3 H9$k!K$r%^%9%?B&G=l>$l X !" Y !" Z <4$N;0$DJ}8~$K $\frac{N}{P} \times N \times N$!" $N \times \frac{N}{P} \times N$!" $N \times N \times \frac{N}{P}$ $NEy4V3V%9%i%$%9$KJ,3d$7!"8D!9$N%W%m%;%C%5$KAw$k!#$9YF$N%W%m%;%C%5$KBP7FIi2Y%P%i%s%9$r6Q0l$K5;kh$&$K3djEvFk3HH9k!#3NJ,3d$r:NMQ$9kH!";k@~$=$l$>$lNO3F%W%m%;%C%5$K1h$C$F3d$jEvFi$l!"FCDj%W%m%;%C%5$X$N;k@~$N=8CfEyr"$kDxEY8:>/$5$;$k8z2L$,4|BT$G$-$k!#%T%/%;%kCM7W;;$N%Q%$%W%i%$%s2=$Khj%^%9%?$+$i=gHVKAwilF$/$k;k@~>pJsEy$r8D!9$N%W%m%;%C%5$G=gHV$K=hM}$,$G$-$k!#

N^3 8D$N%G!<%?$K4X7FJ,3d$,;\$5l?;~!"3F%W%m%;%C%5$,=jM-$9$k%m!<%+

%k$J%G!<%?$\mathrm{LOCAL_CELL}(Vn_i)$ $O<!$N<0$GM?$(il$k!#

LOCAL_CELL(i HV%W%m%;%C%5$,;}$D%5%V%\%j%e!<%`%G!<%?)

$$\begin{aligned} &= (N_x \times N_y) \times (\frac{N_z}{P}) \\ &\quad + (N_x \times N_z) \times (\frac{N_y}{P}) \\ &\quad + (N_y \times N_z) \times (\frac{N_x}{P}) \\ &= \frac{3N^3}{P} \end{aligned}$$

2. 3F%W%m%;%C%5XN3djIU1

   %\%j%e!<%`!&G!<%?$rJ,;6$5$;$k:]!"%G!<%?$,Bg$-$$$N$G!"%U%!%$%k$+$i%^%9%?$KFI$_9~$`$H%a%b%jITB-$,5/3kLdBj$,$"$k!#$3$3$G!"%G!<%?$NJ,;6$,9Tol$k>l9g!"%^%9%?$O3 <4J}8~$K%\%j%e!<%`%G!<%?$rJ,3d$7!"9TNs$N%V%m%C%/9=B$$H$7$F%U%!%$%k$+$iFI$_=P$7!"3F%W%m%;%C%5$r=gHV$K3d$jIU$1$k!#J,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$r3F%W%m%;%C%5$KE>Aw$9$k>l9g!"%V%m%C%/%5%$%:NBg-5HDL?.2s?t$O!"DL?.;~4V$KB?Bg$J1F6A$r5Z$\$9!#Nc$($P!"0l3g7FE>Aw9k>l9g$KBP$7!"%5%V%\%j%e!<%`!&G!<%?$NE>Aw%V%m%C%/$N%5%$%:$,>.5/Jk$[$I!"%^%9%?NI,MWJ%a%b%j$O>/$J$/$Jk,!"DL?.2s?t$OA}2C$7!"B.EY$,Dc2<$9$k!#0J2<!"%G!<%?E>Aw$N4vD+$NJ}K!$K$D$$$F$r8!F$$9$k!#

   (a) JkY/DL?.2s?t$N8:$i$9$3Hr9M$($k$H!"J,3d$5l?%5%V%\%j%e!<%`!&G!<%?KD$$$F!"3 <4J}8~$N%G!<%?3 8D$r$^$HaF1 %V%m%C%/$GAw?.$9lP!"DL?.2s?t$O%W%m%;%C%5?t P KEy7$/Jk!#$?$@$7!"%^%9%?NI,MWJ%a%b%j$O $3 \times \frac{N}{P} \times N \times N$ G"$k!#

   (b) %\%j%e!<%`%G!<%?$,Bg$-$/!"(a) $,$G$-$J$$>l9g$O!"3 8D$N%G!<%?r=l>$lAw?.$9$k!#DL?.2s?t$O 3P $G!"%^%9%?$KI,MW$J%a%b%j$O $\frac{N}{P} \times N \times N$ G"$k!#

   (c) %\%j%e!<%`!&G!<%?$,$+$J$jBg$-$/!"(a)(b) $,$G$-$J$$>l9g$O!"3 <4J}8~$K$h$jJ,3d$5$l$?%G!<%?G[Ns $\frac{N}{P} \times N \times N$ $N%V%m%C%/$O%9%i%$%9$NI}$r:YJ,2=$7!"I}$,1 $H$7$F!"2 <!8 51 %U%l!<%`$H9M$($FAw?.$9lP!"DL?.2s?t$O 3N $G!"%^%9%?$NI,MW$J%a%b%j$O N^2 G"$k!#

   (d) %G!<%?$,Hs>o$KBg$-$/$F!">e$G=RY?J}K!Kh$kAw?.$,L5M}$N>l9g$O!"<!$NJ}K!$r9M$($k!#D^$j!"(c) $NJ}K!$K$D$$$F!"1 %U%l!<%`$N>e$N%G!<

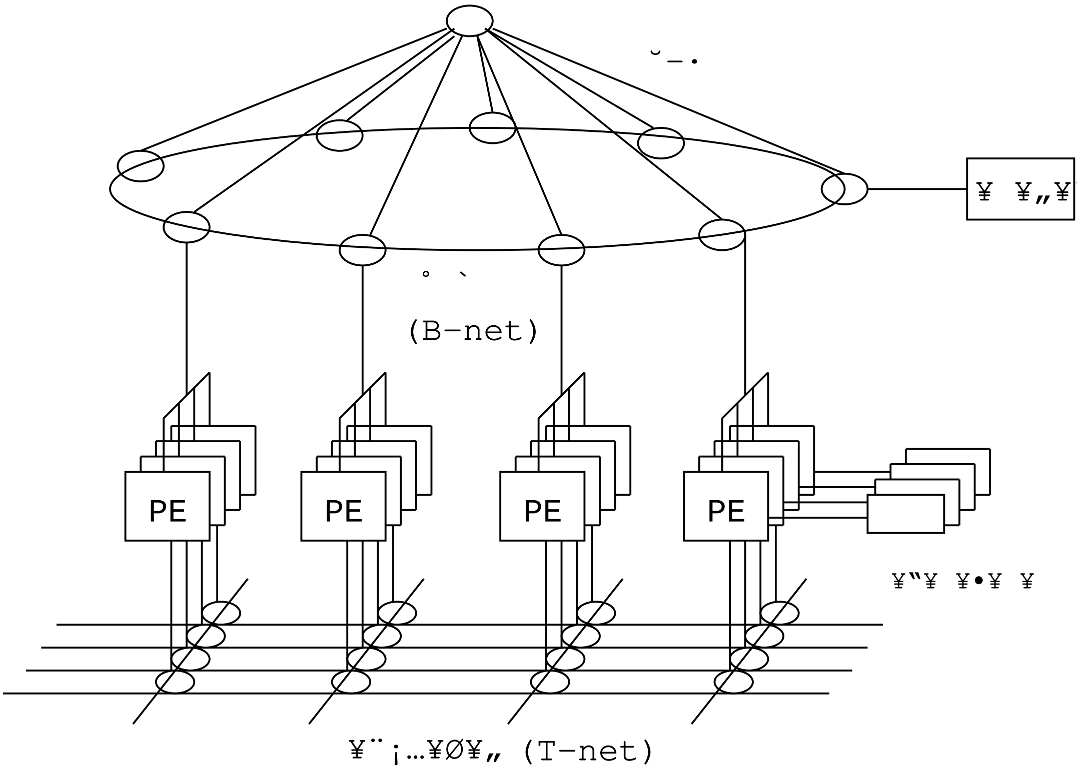
%?$r:FJ,3d$7!#DL?.2s?t$O3$N^2$$G!"%^%9%?NI,MWJ%a%b%j$ON G"$k!#N 8D$NMWAG$r;}$D1 <!85G[NsKh$K%G!<%?$rAw?.9k!#

4.3 **AP1000** K*1kJBNs2=<jK!

K\8&5fGO!"A05-$N%"%k%4%j%:%`$rJ,;6%a%b%j7?JBNs7W;;5!AP1000>e$K<BAu$7$?!#K\@a$G$O!"$^$:AP1000 $N9=B$$HFCD'E*$J5!G=$r35@b$7!"<!$KDs0F$9$k%"%k%4%j%:%`$N!"AP1000 $NJBNs<B9T4D6-$G$NJBNs2=<jK!$K$D$$$F=RYk!#

4.3.1 **AP1000** $N9=@.$*hSDL?.@-G=

K\8&5fGO!"16Bf$+$i1024Bf$^$G@\B32DG=$NJ,;6%a%b%j7?JBNs7W;;5!AP1000[12]>e$K<BAu$r9TC?!#AP1000 $O3<oN`$N%M%C%H%o!<%/T-net, B-net,S-net $r;}$D!"8r49J}<0$O%o!<RS%[!<%kJ}<0$G$"$j!"%G%C%I%m%C%/$NKI;_$,G-$k!#$^$?!"9bB.DL?.$r9T$&$?$a!"3F%W%m%;%C%5$K$O%a%C%;!<%8%3%s%H%m!<%i!MSC!K$,MQ0U$5lF$$$k!#AP1000 $N9=B$$r?^4.2$K<($9!#



?^4.2: AP1000 $N9=B$

- T-net:3F%W%m%;%C%54V$N#1BP#1DL?.$K;HMQ9k$O2<!85%H!<%i%9LV$G$"$k!#

- B-net:#1BPB?DL?.$KMQ$$$k%V%m!<%I%-%c%9%H%M%C%H%o!<%/G"$k!#
- S-net:%P%j%"F14 |MQ$N%H%j!<LV$G$"$k!#

AP1000 $N%"%W%j%1!<%7%g%s$O!"C 8@8l$rMQ$$$F:n@.9k!#DL?.$dF14 |$JIN JBNs=hM}$r9T$&>l9g!"%M%C%H%o!<%/9=@.$r0U<1$7$?5-=R$,G-kh$&$K!"MM!9 $J%i%$%V%i%j$,MQ0U$5lF$$$k!#AP1000 GO!"<B9T%W%m%0%i%`$O%^%9%? !0J 2<!"%[%9%H$H8F$V!K7W;;5!MQ$HJ#?t$N%W%m%;%C%5 !0J2<!"%;%k$H8F$V!KMQ$N2 <oN`$,I,MW$G$"$k!#$=$l$>$l$NLr3d$O<!NDLjG"$k!#

- %[%9%H%W%m%0%i%`$O%;%k$N<B9T4D6-$N@_Dj!"%;%k$G<B9T5l$k%?%9%/$N@8 @.!"%;%kXN%a%C%;!<%8Aw?.!"%;%k$+$i$N%a%C%;!<%8<u?.!"%;%k$N>uBV4F ;kJI$r9T$&!#
- %;%k%W%m%0%i%`$O3F%;%k>e$GJBNs<B9T5l!"L\E*H9$k7W;;$rJBNs$K=hM} 9k!#

4.3.2 <BAu<jK!

K\@aGO!"Ds0F9kJBNs2=%"%k%4%j%:%`$rAP1000 $G<BAu$9$kJ}K!$K$D$$$F =RYk!#?^4.1$N%W%m!<%A%c!<%H$G$O!"%^%9%?$,%[%9%H!"3F%9%l!<%V$,%;%k$P_i$KBP1~$9$k!#i !iJ=0,1, !!&&a) $O%;%k$NHV9fG"$k!#

6qBNE*$J<BAu<j=g$O0J2<$G@bL@$9$k!#

%[%9%HB&$N=hM} !'

1. %;%k$N<B9T4D6-$r@_Dj9k!#%Q%$%W%i%$%sJ}<0$rMQ$$$k$?$a$K!"%;%k$NO@ M}9=@.$O1 <!85$H$7!"A4$F$N%;%k$N=i4 |2=$r9T$&!#
2. ;kE@!"%9%/%j!<%s>pJs$N@_Dj!"=hM}Cf$K07$&%Q%i%a!<%?%U%!%$%kParafile() !"%\%/%;%kCM!J'Colorfile()!"F)L@EYTransfile()!K$NB0@-%F!<%V%k%U%! %$%krFI_9~$_!"A4%;%k$K%V%m!<%I%-%c%9%H9k!#
3. %\%j%e!<%`'!&G!<%?%U%!%$%kVolumefile() $+$i!"%G!<%?$NJ,;6$r9T$&!#J, ;6$5$l$?%G!<%?$r8D!9$N%;%k$X=gHV$KAw?.$9$k!#K\<BAu$G!"MQ$$$?%\%j%e!< %`'!&G!<%?%5%$%:$,Bg$-$$>l9g$O!"4.2@a$G=RY?(c) $NJ}K!$r:NMQ7?!# $^$?!"E>AwNLKBP7DL?.B.EY$N1F6A$r5.1@a$G(c) $H !dJ) $NN>J}J}<0$K$D$$ FB,Dj7$?!#
4. %9%/%j!<%s%5%$%:$NBg$-$5Kh$jfor %k!<%W$G;k@~$H<g<4$r7W;;9k!#$3 3G8zN(Nh$$JBNs2=r9k?$a!"4v$D$+$N2~NIJ}K!$rMQ$$$F<BAu$r9T$&!#
    - ;k@~%G!<%?$O%[%9%H$+$i%;%k$N0 HV$XAw?.$7!"3F%;%kGN%Q%$%W%i%$ %sJ}<0$G<B9T$9$k!#;k@~%G!<%?$H%T%/%;%kCM$NDL?.2s?t$r8:i9$?$a

$K!";k@~%G!<%?$H%T%/%;%kCM$r?^4.5$Nh&$K1 8D$N9=B$BNmes_pixel $K3JG<$9$k!#!KT\O@$G!"3N9=BBNrMQ$$$FAw?.9k3H$rJ?9TAw?.K!$H8F$V!K

- $^$?!"8zN(h/JBNs2=9k$?$a!"3N9=BBNrk 8D$N9=B$BNG[NsH9$k!#
- 5i$K!"DL?.;~4V$r1#JC9k$?$a!";k@~%G!<%?$H%T%/%;%kCM$,8_$$$K 0MB8$7$J$$$N$G!">e5-$Nmes_pixel 9=BBNKBP$7!";k@~%G!<%?$H%T%/%;%kCMr=l>lN9=BBNH9k!#!4J.4.3@a$G6qBNE*$K=RYk!K

3liN<BAuJ}K!KD$$$F$O4.4@a$G>\$7$/=R$Y$k!#% [%9%H$G;k@~%G!<%?$r @8@.$7$?8e!"0 HV$N%;%k$KAw?.$9$k!"n(%;%k$NBf?t!K2s;k@~%G!<%?$rAw?.$7$?8e!"% [%9%H$Gn !<#1HVL\$N%;%k$+$iAwil$?%T%/%;%kCM$r<u?.9k!#$^$?!"%Q%$%W%i%$%sJ}<0Kh$j;k@~%G!<%?$rAw?.=*N;H-$K!":G8e0l2s$N%k!<%W$G%;%k$NCf$K;D$C$?%T%/%;%kCM$r<}=8$9$k!#

5. <}=8$5$l$?%T%/%;%kCM$r%P%C%U%!$K=q$-9~$_!"%7%'!<%G%#%s%0=hM}$r9T$&!#
6. 2hA|$r=PNO$9$k!#

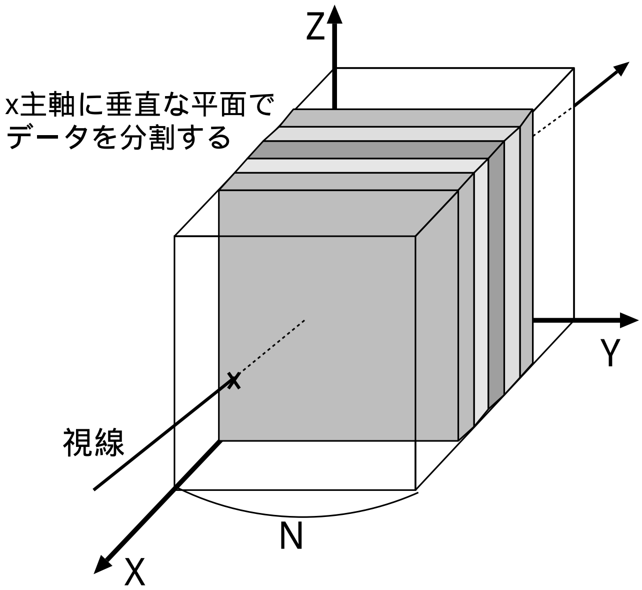
%;%kB&$N=hM}: 6qBNE*$J<j=g$O4.2@a$G=RY?h&$K!"8D!9$N%;%k$O%Q%$%W%i%$%sJ}<0$GJBNs$K%T%/%;%kCM$N7W;;$r<B9T$9$k!#

AP1000 $G<BAu$7$?%G!<%?$NJ,3d!NJc$K!"X <g<4$N>l9g!K$r?^(4.3) $K<($9!#AP1000 $N%;%k9=@.Bf?t$O2<!85%H!<%i%9$N>e$G!"X $HY N>J}8~$NBf?t;XDj$,$G$-$k!#K\<BAuGO!"%Q%$%W%i%$%s2=7d$9$$$?$a!"%W%m%;%C%59=B$!$X_{cell}$$H9k!K$,C10lJ}8~$KHk!#3F%;%k$N%a%b%j$K3JG<5l$?%5%V%\%j%e!<%`!&G!<%?$O$=$l$>$l X!"Y!"Z <4$H$7$F;0$DJ}8~$+$iJ,3d$5$l$?%V%m%C%/%G!<%?$G$"$k!#Ii2YJ,;6$r6Q0l$K$9$k$?$a!"%V%m%C%/%G!<%?$N8|$5$O%\%j%e!<%`!&G!<%?$N0lJU$ND9$53d$k%;%kBf?tKh$j7h$a$k!#

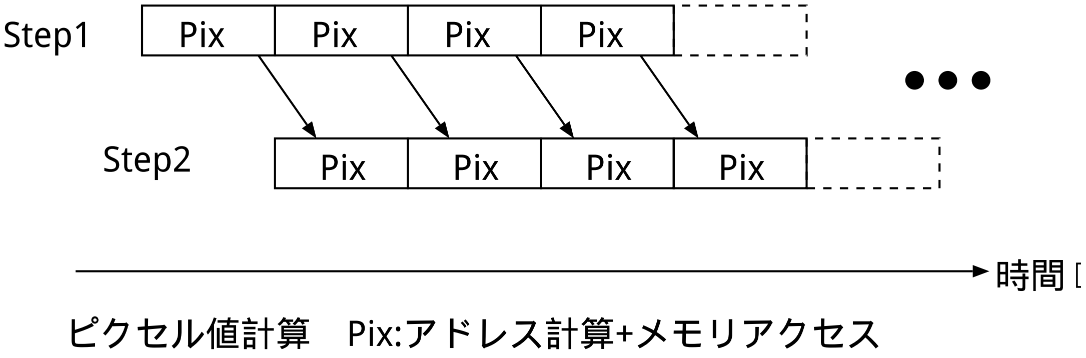
4.4 **AP1000** GN:GE,2=<jK!

4.4.1 1i;;$N%Q%$%W%i%$%s2=

Bh4.3.2@a$K=R$Y$?$h$&$K!"%\%j%e!<%`%G!<%?O9YF$N%W%m%;%C%5$KJ,;6$5$l$k!#%l%$!&%-%c%9%F%#%s%05;K!Kh$k%\%/%;%kJBNs=hM}$O;k@~$K1h$C$F;kE@$K6a$$=g$K%\%/%;%k6u4V$rC5:w$7!"8D!9$N%W%m%;%C%5$OC4EvHO0O$N;k@~$H8r:9$9$k%\%/%;%kCM$rFI$_=P$7!"%T%/%;%kCM$r7W;;$7!"$=$NCM$r<!$N%W%m%;%C%5$XEO$9!#?^4.4$K<($9h&$K%G!<%?E>Aw$H%T%/%;%kCM$N7W;;$O%Q%$%W%i%$%s2=$,2DG=$G$"$j!"3F%W%m%;%C%5$OEv3:%T%/%;%kCM7W;;$9$k;~4V$K<!$N%G!<%?$,E~Ce$9



?^4.3: <g<4Kh$k%G!<%?$NJ,3d



?^4.4: %T%/%;%kCM$N%Q%$%W%i%$%s2=

lP!"%P%C%U%!%j%s%0r9k3HKhj!"%G!<%?E>Aw;~4V$N0lItJ,$r1#JC9k
3H$,$G$-$k!#K\8&5fGO!"%\%j%e!<%`%l%s%@%j%s%0$N%\%/%;%kJBNs=hM}$K4p
$E$$$F%Q%$%W%i%$%sJ}<0$r9T$&!#A0=R7?h&$K%[%9%HB&$O<B9T=hM}$NA4BN$N
>uBV$r4F;k$9$k!#;k@~%G!<%?$r@8@.7F%;%k$HDL?.$7J,$i!"%T%/%;%kCM$r=g
HV$K<}=8$9$k!#$3$3$G!"4.3.2@a$G=R$Ykh$&$K!";k@~%G!<%?$H%T%/%;%kCM$O0l
DN9=B$BN mes_pixel H7$F3JG<9k!#6qBNE*$J%T%/%;%kCM7W;;$N%Q%$%W%i%$
%s$O0J2<$N<j=g$G9T$olk!#!J?^4.6!K

1. $^$:!"%[%9%HGO!"%9%/%j!<%s%5%$%:$K$h$jfor %k!<%W$G;k@~@8@.ItJ,$r
9T$&!#@8@.$5l?;k@~%G!<%?$O0 HV$N%W%m%;%C%5$KAw?.$9$k!#

```
struct mes_pixel{
  vector_t ray;        /* ;k@~$N%Y%/%H%k  */
  vector_t relative;   /* ;k@~%Y%/%H%k$ND9$5 */
  char     axis;       /* <g<4       */
  int      axisdir;    /* <g<4$NJ}8~ */
  pixel_t  ret;        /* %T%/%;%kCM */
  float    alpha;      /* F)L@EYCM   */
  float    contrib;    /* ?'!"F)L@EYJQ49$7$?CM  */
}
```

?^4.5: ;k@~%G!<%?$H%T%/%;%kCM$N9=B$BN

2. 8D!9$N%W%m%;%C%5$O9Y$F<u?.BT$A>uBVKJ$k!#$O8a$K!"0 HV$N%W%m%;%C%5$,!"%[%9%H$+$iAw?.$5l?;k@~%G!<%?$r<u$1<hCF%P%C%U%!$KF~$l$k!#
3. %W%m%;%C%5$OC4Ev$9$kHO0O$N;k@~$H8r:9$9$k%\%/%;%k$N8r:9E@$r7W;;$9$k!#3.3.2@a$GM?$($?<0 3.4$N;k@~%G!<%?$HF~<M5wN%Kh$j5a$a$k!#Nc$($P!"<g<4$,X<4$N>l9g!"J?LL $X = 0$ $H;k@~$H$N8rE@$N:BI8G"$k!#;k@~$Hi HVL\%W%m%;%C%5$N%\%/%;%k8rE@:BI8$O $x_i = i$,$y_i = y_0 + i\Delta y$,$z_i = z_0 + i\Delta z$ $r5a$a!" $\Delta y = \frac{y_n - y_0}{N}_y$, $\Delta z = \frac{z_n - z_0}{N}_z$ Kh$k7W;;$r9k!#$3$3$G!"$N_x, N_y, N_z$ $OC4EvHO0O$N%5%V%\%j%e!<%`%G!<%?$Nx!"y!"z J}8~$NI}G"$k!#$x_i, y_i, z_i$ $O;k@~$Hi HVL\%W%m%;%C%5$N%\%/%;%k8rE@:BI8$G$"$k !i$=0,1,$!!&&a)!#
4. 7W;;7?8r:9E@$,!"3.3.2@a$GM?$($?<0 3.4Kh$j%\%/%;%k$N%"%I%l%9 !0L CV!K$r7W;;$9k3H,G-$k!#Nc$($P!"<g<4X H7$F!"%\%j%e!<%`$NCf?4:BI8$O V(0,0,0) $H$7!";k@~$Oi HVL\%W%m%;%C%5$H8r:9$7$?%W%m%;%C%5$NHV9f$, $cid = (Vn/2 + x)/(N_x)$ $r5a$a!"$3$NHV9f$H<+J,$r;}$DHV9f$,0lCW$9$k>l9g!"%a%b%j$N%"%I%l%9 $cid = (Vn/2 + x)mod(N_x)$ $rC5$7!"$3$N%a%b%j$N%"%I%l%9$r%"%/%;%9$7$F!"%\%/%;%kCM$rFI$_=P$9!#$3$3$G!"%\%/%;%k:BI8$,%\%j%e!<%`30G"$kH-!"$^$?$O!"%\%/%;%k$,%^%9%/5l$F$$$kH-KO!"%\%/%;%kCM$r#0$H7F07$&!#
5. 4.$G7W;;$7$?%\%/%;%k%"%I%l%9$Khj!"%\%/%;%kCMrFI_=P$9!#<0 2.4$Khj%T%/%;%kCM7W;;$r9T$&!#0 HV$N%W%m%;%C%5$O%T%/%;%kCM7W;;9kA0$K%T%/%;%kCM$N=i4|2=$r9T$&!#

```
cell_main(){
  typedef struct mes_pixelray,axis,axisdir,mask,color,alpha,contrib;
  pixel_stage(){
    while(1){
      if(cell_cid==0){            /*<+J,$,%;%k#0$@$G$?$i*/
        %[%9%H$+$imes_pixel $r<u?.$9$k;
        mes_pixel $r0 HV%;%k$K=q$-9~$_;
        Pixel_count();                      /* %T%/%;%k7W;; */
        mes_pixel $ri+1 %;%k$KAw?.$9$k;
       }
      if(cell_cid==n-1){
        i-1 %;%k$+$imes_pixel $r<u?.$9$k;
        mes_pixel $ri HV%;%k$K=q$-9~$_!(
        Pisel_count();
        mes_pixel $r%[%9%H$KAw?.$9$k;
       }
      if(cell_cid==i){
        l_arecv(i-1 %;%k$+$imes_pixel $r<u?.$9$k!K;
        mes_pixel $ri HV%;%k$K=q$-9~$_;
        Pisel_count();
        mes_pixel $ri+1 %;%k$XAw?.;
      }
    Pixel_count(){
      InOutpoint();                         /* 8rE@7W;; */
      for(i=MX*cell_cid; i<MX*(cell_cid+1);i++){
        adress_count();                     /* %"%I%l%97W;; */
        read_voxel();                       /* FI$_=P$7     */
        pixel_count();                      /* %T%/%;%kCM7W;;*/
       }
     }
   }
 }
```

?^4.6: %T%/%;%kCM7W;;$N%Q%$%W%i%$%s2=

6. 0 HV$N%W%m%;%C%5$O<+J,$NC4Ev$9$kHO0O$N%T%/%;%kCM$r7W;;=*N;8e!"<!$N%W%m%;%C%5$K;k@~%G!<%?$H%T%/%;%kCMrEO9!# HV$N%W%m%;%C%5$O<u?.>uBVKJC?H-!"%a%C%;!<%8$r<u$1<h$j!"%P%C%U%!$K=q$-9~$`!#=hM}%9%F%C%W3.4.5. $r7+$jJV$9!#

7. :G8e$N%W%m%;%C%5$ON_@Q7?%T%/%;%kCM$r%[%9%H$KE>Aw9k!#

4.4.2 DL?.2s?t$NDc8:

%a%C%;!<%88r497?JBNs7W;;5!GODL?.=hM}2s?t$r8:$i$9$3H,=EMWG"$k!#C;$$%a%C%;!<%8r?$/$5$sDL?.$9kH!"=hM}%3%9%H$,Hs>o$KBg$-$/Jk!#$3$3$G!"Aw?.%G!<%? !J,3d$5l?%5%V%\%j%e!<%`%G!<%?!";k@~%G!<%?!"%T%/%;%kCMJI!K$r!"$JkY$/$^Ha$F#1$D$ND9$$%a%C%;!<%8H7$FAw?.$9lP!"DL?.=hM}$N2s?t$r8:i9$3$H$,$G$-$k!#8zN(Nh$$DL?.=hM}$r<B8=$9k?aK!"K\8&5fGO!"0J2<Nh$&$K:GE,2=$r9T$&!#

1. %5%V%\%j%e!<%`%G!<%?$NAw?.

   J,3d5l$?%5%V%\%j%e!<%`%G!<%?$O8D!9$N%W%m%;%C%5$K3djIU1J1lPJi$J$$!#%[%9%H$GJ,3d$5l?%G!<%?$r3F%W%m%;%C%5$KE>Aw9k>l9g$O!"Aw?.%G!<%?$NBg$-$5Kh$j!"DL?.;~4V$,1F6A$rM?$($k!#

   4.2@a$G=R$Y$?$h$&$K!"K\8&5fGO!"J,3d5l$?%5%V%\%j%e!<%`!&G!<%?$NE>Aw$O(c) J}K!$r:NMQ$7!"MQ$$$?F s=E$Nfor %k!<%W9=J8$+$i<B8=$7$?!#;0=E$Nfor 9=J8$+$i9=@.5l$?(d) J}K!$HHf3S9k$H !<JBAu7k2L$O5.1$K<($9)DL?.=hM}$N2s?t$,8:>/9k3H$,$o$+$k!#

2. ;k@~%G!<%?r^Ha$FAw?.$9$k

   4.3.2@a$K=R$Ykh$&$K!"%[%9%H$G;k@~$r@8@.9k!#@8@.5l$?;k@~%G!<%?$O%Q%$%W%i%$%s$G%W%m%;%C%5$KAw?.9k!#;k@~%G!<%?NBg-5Khj!"JBNs2==hM}8z2L$,Bg$-$/1F6A$5lk!#$3$3$G!"for 9=J8$G$"$kDxEY$N;k@~%G!<%?$r7W;;$7=8$a$F%W%m%;%C%5$KAw?.9k:GE,2=$r<B8=$7$?!#

4.4.3 DL?.;~4V$N1#JC

4.3.2@a$d4.4.1@a$G=RY?h&$K!"%T%/%;%kCM7W;;$N%Q%$%W%i%$%s=hM}$O%[%9%H$G$N;k@~@8@.$H!"%;%k$G%\%/%;%kCM$HA0CJ$N%;%k$+$iE>Aw$7F-$?%T%/%;%kCM$NCf4V7k2L$+$i%T%/%;%kCM$rN_@Q$9$k=hM}$H7FJ,1ilk!#

$^$?!";k@~%G!<%?r^Ha$FAw?.$9k3HG:GE,2=9kJ}K!$r9M;!$9kH!"%\%j%e!<%`%G!<%?$N=hM}$K$OB?$/$N7W;;$rI,MW$H$7!"#1;k@~4H$N=hM}$O%a%b%jXN%"%/%;%9$KHf3SE*;~4V$rMW$7!"$^$?!"$3$N=hM}$r9Tol$k>l9g$N#12hLL

$r@8@.$9kNKMW9$k; ~4V$T$ $O

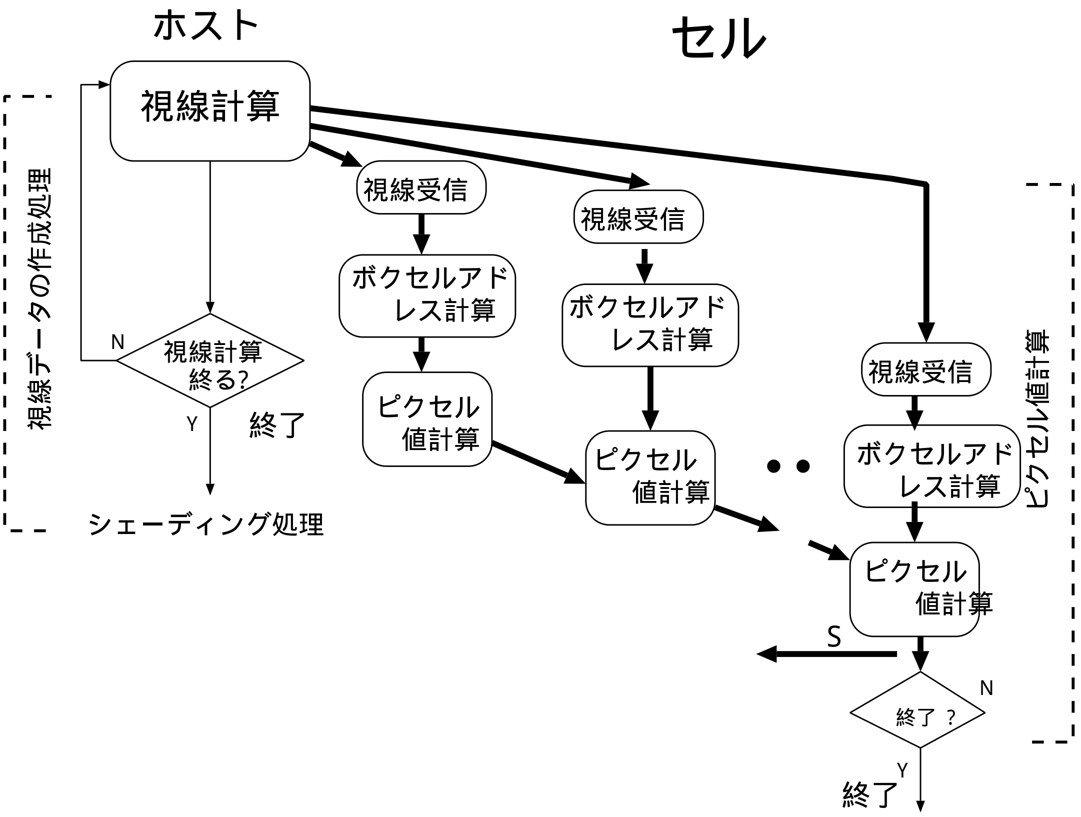
$$T = (T\_hcom + T\_comm + T\_run + T\_wait) * m^2nP \tag{4.1}$$

$GI=$5lk! #$3$3$G! "$T\_hcom$ $O% [%9%H$+$i; k@~%G! <%?$r%;%k$KE>Aw! "$"$k$$ $O%;%k$+$i7W; ;7k2L$r% [%9%H$K< }=8$9kNK+$+$kDL?.; ~4VG"$k! #$T\_comm$ $O%;%k$H%;%k$"$?jN; k@~%G! <%?$*$h$S%T%/%;%kCM$NCf4V7k2L$rE>Aw$K$+$+$k ; ~4V$G$"$k! #T_run $O3F%;%k$G%T%/%;%kCM7W; ;9k=hM}; ~4VG"$k! #$T\_wait$ $O 3F%;%k$N%a%C%;! <%8rBTA; ~4VG"$k! #$^$?! "%9%/%j! <%s$N2hAG?trm^2$! "%\ %j%e! <% `%G! <%?$rn^3! "%;%k$NBf?t$rP H9$k! #l ; k@~$4HK=hM}$r9T$&$HDL?. ; ~4V$,$+$Jj+$+$kNG! "DL?.; ~4V$NI #JC$,G-J/Jk! #$=$N$?$aDL?.BT$A ; ~4V$,B?$/$J$j! "=hM}; ~4V$NA}2C$r>7$-! "JBNs=hM}Kh$kB.EY8~>e$rK8$2$k7k 2LHJ$k! #$=3G! "3l$r2~A1$9k?$a! "DL?.; ~4V$N:o8:$*$h$SDL?.; ~4V$NI # JC$r9T$$! "9bB.2=rO$+$k=hM}$N%"%k%4%j%:% `$rDs0F9k! #

$^$:! "DL?.; ~4V$NI #JC$9k3Hr9M$($k! #%\%j%e! <% `%l%s%@%j%s%0$N%"%k%4 %j%:% `K*$$$F! "<02.4$K<($9h&$K! "%\%/%;%kCM$N%"%I%l%97W; ;$H%T%/%;%kCM 7W; ;$OD>@\4X78J/! "F I$_=P$9%\%/%;%kCM$N%"%I%l%97W; ;$K$O! "%T%/%;%kCM7W ; ;%9%F! <%8$G5a$ail$k! #%T%/%;%kCM$NCf4V7k2LOI,MWJ$/! "; k@~%G! <%?$N$_ $+$i7W; ;9k3H$,$G$-$k! #3N3H$rMxMQ$7$F! "?^4.7$K<(9h$&$K! "% [%9%H $Ok K\; k@~$N@8@.r^Ha$F7W; ;$7! "%P%C%U% !$K3JG<$9$k! #< !$K%V%m%C%/7A$G K K\$N; k@~%G! <%?$r0 HV%;%k$N%P%C%U% !$KE>Aw$9kNGOJ/! "A4%;%k$XAw?. 9kDL?.4X?t**cbroad()** $G; k@~%G! <%?$NAw?.$r9T$&! #K\O@J8GO! "3NJ}K!$r @h9TAw?.K!$H8F$V! #$3$N@h9TAw?.K!$Khj! "3F%;%k$O; k@~%G! <%?$r<u?.7?8e! " %\%/%;%kCM$,<B:]$KI,MWHJ$k0JA0$K! "< !$KF I$_=P$9%\%/%;%k$N3JG<5l$F$$ $k%a%b%j%"%I%l%9$r7W; ;$7! "$=NCMrJ]; }7F$*$/! #$=$7$F! "A0$N%;%k$+$iAw ?.$-$?%a%C%;! <%8$,$"C?$i! "$=$N%T%/%;%kCM$NCf4V7k2L$r<u?.$7! "%l%8%9%? $+$i%\%/%;%kCM$rF I$_=P$7! "%T%/%;%kCM$N7W; ;$H<u?.$7$?Cf4V7k2L$+$i?7$?$J %T%/%;%kCM$r7W; ;9k! #3lKh$j! "%\%/%;%k%"%I%l%9$N7W; ;$H! "A0CJ$N%;%k GN%T%/%;%k7W; ;$HDL?.; ~4V$r%*! <%P! <%i%C%W9k3H$,$G$-$k! #

K K\$N; k@~%G! <%?$N0l3gAw?.$H@h9TAw?.K!$NJ;MQ=hM}$r9T$&>l9g! "#12hLL$N @8@.KMW9$k; ~4V$T$ $O

$$T = \frac{1}{k}(T\_hcom + T\_comm + T\_run + T\_wait) * m^2nP \tag{4.2}$$



?^4.7: @h9TAw?.%"%k%4%j%:%`$N%U%m!<%A%c!<%H

HJ$k!#%T%/%;%kCM7W;;$N%Q%$%W%i%$%s2=<B9TbG$-$k!#=hM}$N9bB.2=$,O+lk!#

5 J,;6%a%b%j7?JBNs7W;;5!Kh$k@-G=I>2A

5.1 <B9T7k2L

K\@aGO!"K\8&5f$GDs0F$7$?%\%j%e!<%`%l%s%@%j%s%0K!$NJBNs=hM}%"%k%4%j%:%`$N<BAu7k2L$H@-G=I>2A$r9T$&!#%\%j%e!<%`%G!<%?$O$64^3, 128^3, 256^3$H$7!"%9%/%j!<%s$NBg$-$5r256^2H9$k!#

JBNs@-G=I>2A$O0J2<$G<(7?9`L\$N@-G=XN1F6A$r9M$($F!"<B9T$r9T$&!#

- %\%j%e!<%`%G!<%?%5%$%:$HMQ$$$?%;%kBf?tXN1F6A!#
- J,3d5l$?%5%V%\%j%e!<%`!&G!<%?$r%;%k$KAw?.$9$k:]!"%G!<%?$NBg$-$5Kh$j!"DL?.;~4V$N1F6A!#
- %[%9%H$G@8@.$7$?;k@~%G!<%?$r%;%k$KAw?.$9$k:]!"n K\$N;k@~%G!<%?$r0l=o$KAw?.9k3HKh$k8z2L!#

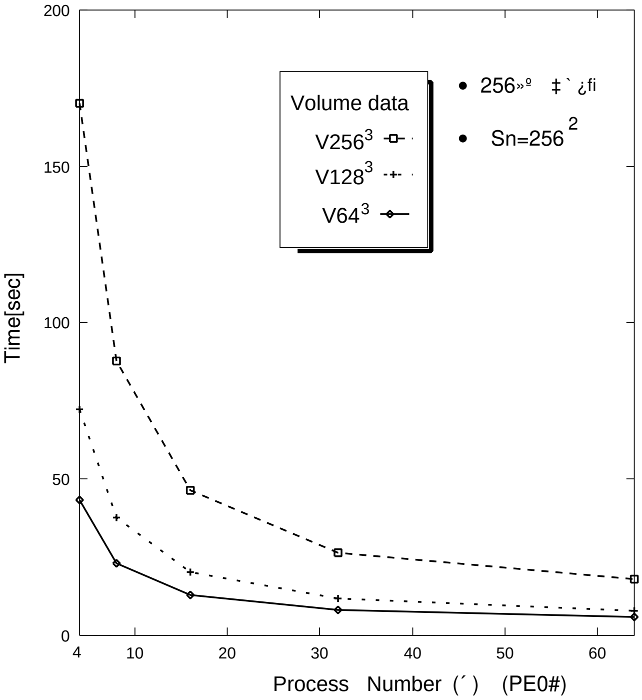
- DL?.; ~4V$r1 #JC$9k?$a! "; k@~%G! <%?$r@h9TAw?.9k8z2L! #

I=5.1: AP-1000 K*1k%\%j%e! <% ' ! &1%s%@%j%s%0$NI>2A%Q%i%a! <%?

%Q%i%a! <%?	%Q%i%a! <%?$NCM
%;%kBf?t	4 ! "8 ! "16 ! "32 ! "64 Bf
; k@~	4 ! "16 ! "32 ! "64 ! "128 ! "256 K\
%\%j%e! <% 'NBg-$5! ?%T%/%;%k$NBg$-$5	$64^3/64^2$,$64^3/128^2$,$64^3/256^2$
	$128^3/64^2$,$128^3/128^2$,$128^3/256^2$
	$256^3/64^2$,$256^3/128^2$,$256^3/256^2$

5.1.1 <B9T; ~4V$NI>2A

3N@aGO! "%\%j%e! <% '%G! <%?%5%$%:$H%;%kBf?t$NJQ4 9$K$D$$$F! "K\<BAu$N JBNs=hM}8z2L$r9M; !9k! #I=5.2GO! "%\%j%e! <% '%G! <%?$O$64^3, 128^3, 256^3$$rMQ $$$F! "%9%/%j! <%s%5%$%:$O$256^2$$H7F! "%;%kB&$G; k@~%G! <%?$r256 K\$^Ha$K <u?.$7! "<B9T$r10 2s9T$C$?(L=10) $N<B8 37k2L$G$"$k! #$?$@$7! "@-G=I>2A$N$? $a! "< ($7$?; ~4V$OAP1000 $N>e$G%H%1! <%9$r9T$C$?; ~4V$G$"$k! #0 [Jk%5%$%: $N%\%j%e! <% ' ! &G! <%?$KBP9kJBNs=hM}$N8z2L$r?^5.1$K< ($9! #



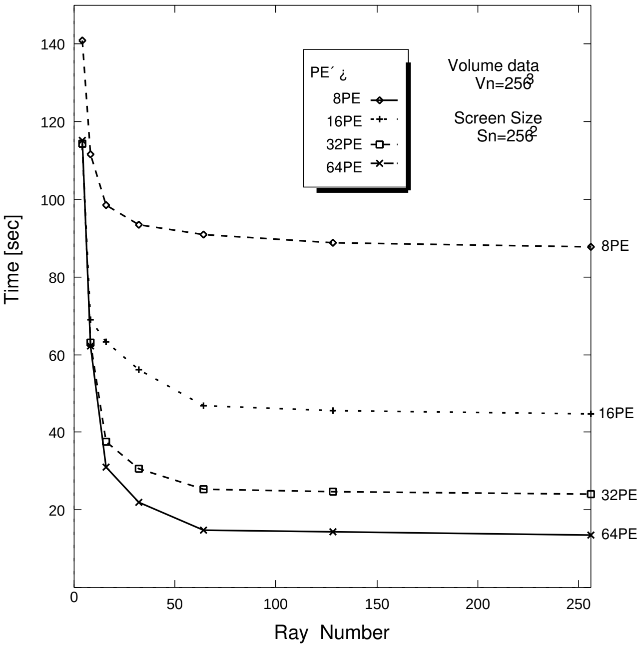
?^5.1: JBNs=hM}8z2L

I=5.2: AP1000 K*1k%\%j%e!<%'!&1%s%@%j%s%0$N=hM}; ~4V(L=10)

%\%j%e!<%'/	PE(Bf)	<B9T; ~4V[sec]	%?%9%/; ~4V[sec](%)	DL?.; ~4V[sec](%)	%7%9%F% `=hM}; ~4V[sec](%)
64^3 !?256^2	4	432.2	406.9(94.15)	9.5(2.20)	15.7(3.65)
	8	232.3	209.6(90.22)	9.7(4.19)	12.9(5.59)
	16	131.5	113.0(85.95)	9.5(7.25)	8.93(6.8)
	32	83.7	65.7(78.55)	9.7(11.61)	8.2(9.84)
	64	59.2	41.6(70.29)	9.7(16.44)	7.84(13.26)
128^3 !?256^2	4	726.0	694.9(95.72)	9.2(1.71)	21.84(3.01)
	8	378.8	356.8(94.18)	9.3(3.39)	12.7(3.36)
	16	206.2	186.5(90.44)	9.1(4.41)	10.6(5.15)
	32	119.1	101.1(84.91)	9.3(7.81)	8.6 (7.28)
	64	80.7	58.0(71.87)	9.6(11.86)	13.1(16.26)
256^3 !?256^2	4	1711.4	1631.8(95.35)	16.42(0.96)	63.1(3.69)
	8	883.8	813.8(92.07)	12.8(1.45)	57.25(6.48)
	16	468.0	412.5(88.14)	10.9(2.35)	44.4(9.51)
	32	260.3	214.1(82.25)	10.1(3.9)	36.0(13.85)
	64	155.7	115.2(73.98)	9.6(6.15)	30.9(19.87)

I=5.3: JBNs=hM}8z2L$NHf3S

PE	$64^3/256^2$		$128^3/256^2$		$256^3/256^2$	
[Bf]	<B9T; ~4V[sec]	B.EY8~>e	<B9T; ~4V[sec]	B.EY8~>e	<B9T; ~4V[sec]	B.EY8~>e
64	53.4	8.04	72.2	9.94	135.3	12.52
32	77.9	5.51	113.1	6.34	240.1	7.05
16	127.8	3.36	200.5	3.58	450.0	3.76
8	229.4	1.87	372.6	1.92	865.5	1.96
4	429.5	1.0	717.0	1.0	1693.4	1.0



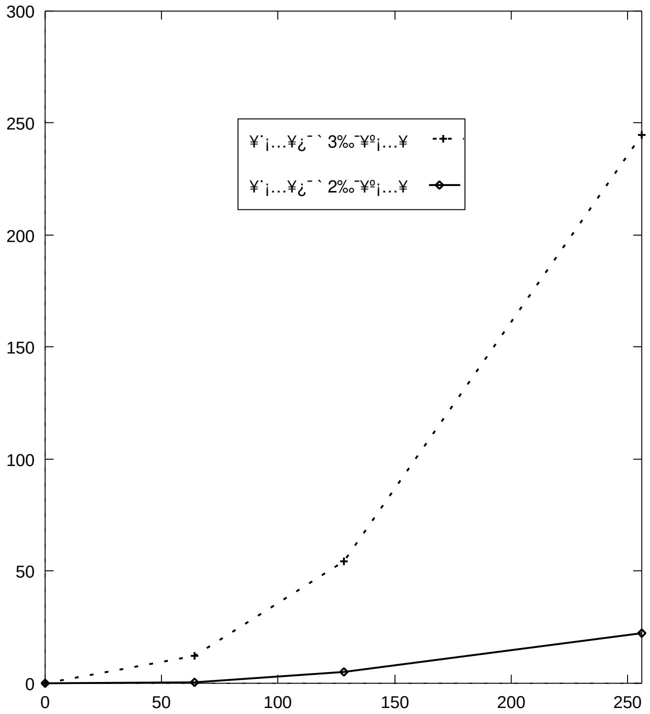
?^5.2: ;k@~%G!<%?$N013gAw?.8z2L

- 3F%\%j%e!<%`%G!<%?$O%G!<%?%5%$%:$r01Dj$H7F!"%W%m%;%C%5Bf?t$rJQ2=$5$;$?>19g!"<B9T;~4VK[$\@~7A@-$,F@il$?!#$D$^$j!"%;%k$NBf?t$r8:i9;~!"3F%W%m%;%C%5$NIi2Y=hM}NL$,B?$/!"%?%9%/=hM};~4V$NHfN($,9b$/!"<B9T;~4V$,CY$/Jk!#H3m,%;%k$NBf?t$rA}d9$H!"Ii2YJ,;6$N7Z8:Kh$j!"$h$$Bf?t8z2L$rC#@.$9k3H,o+$k!#
- $^$?!"DL?.;~4V$rD4$YkH!"I=5.2$K<($9h&$K!"$3lO%\%j%e!<%`%G!<%?NBg-5H4X78J/!"DL?.NL$O%9%/%j!<%s$N%5%$%:$G7h$^$kNG!"%W%m%;%C%5Bf?t$,A}2C$7Fb!"%;%kKh$NDL?.NL$,$[$\01DjG"k3H,o+$k!#

5.1.2 Aw?.C10LHNI>2A

- $^$:!"%[%9%H$GJ,3d$5l?%5%V%\%j%e!<%`!&G!<%?$r%;%k$KAw?.$9$k:]!"4.2@a$G=R$Y$?$h$&$K!"!cJ!KJ}K!$N1 %U%l!<%`$G%G!<%?$rAw?.9k$H !dJ!KJ}K!$N1 <!85G[NsKh$K%G!<%?$rAw?.9k!#3F%\%j%e!<%`!&G!<%?%5%$%:$NB,Dj7?7k2L$r?^5.3$K<($9!#

  7k2L$r9M;!$9kH!"013gE>Aw1 %U%l!<%`$N%G!<%?$N$[$&$,DL?.2s?t$r8:i9!"1 <!85G[NsKh$K%G!<%?Aw?.J}K!$h$j10 G\B.$5$,F@$il?!#
- Aw?.C10L(;k@~%G!<%?!KNBg-5Khj=hM}B.EY$N1F6A$rD4Yk$?$a$K!"%\%j%e!<%`%G!<%?$r 256^3 !"%9%/%j!<%s%5%$%:$O 256^2 $H$7!"Aw?.C10L$rJQ2=$5



?^5.3: %5%V%\%j%e!<% '%G!<%?$NAw?.8z2L

$;$F<B9T$r10 2s9T$G$?8e$N<B9T;~4VrB,Dj7$?!#7k2L$rI=5.4$K<($9!#Aw?.C10L$N8z2L$r?^5.2$K<($9!#

I=5.4: 256^3%\%j%e!<%'!&1%s%@%j%s%0$N=hM};~4V(L=10)

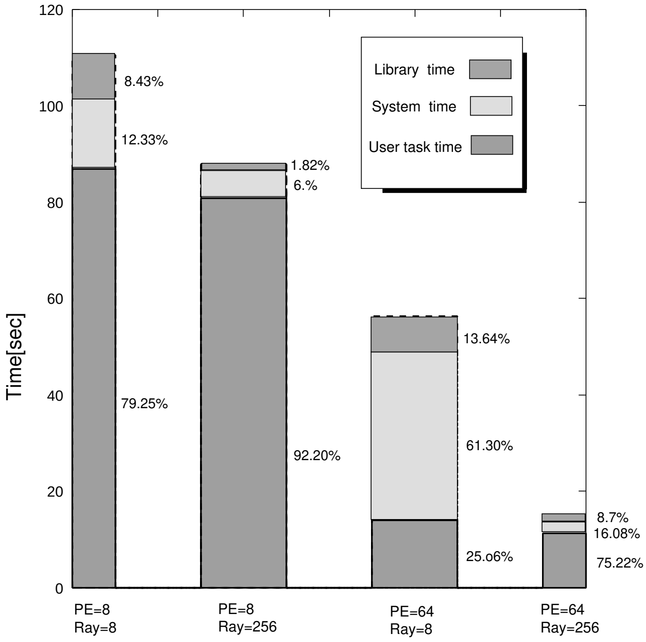
;k@~?t	<B9T;~4V[sec]				
	4 Bf	8 Bf	16 Bf	32 Bf	64 Bf
4	250.5	140.9	113.6	114.3	115.2
8	204.7	111.6	68.9	63.0	62.3
16	184.1	98.6	63.2	37.6	31.1
32	178.7	93.5	56.2	30.6	21.9
64	177.2	90.9	46.8	25.3	14.7
128	174.0	88.9	45.5	24.7	14.3
256	170.0	87.8	44.8	23.9	13.5

3N7k2L$r9M;!$9kH!"E>Aw%G!<%?NL$,>/$J$/$JkHDL?.2s?t$,A}2C$7!"=hM};~4VO+JjCY$/$J$k!#JBNs2=$N8z2L$,8+$ilJ$$!#7+$7!"E>Aw%G!<%?NL$r

A}d9$H!"=hM};~4V$,@~7AE*$KB.$/Jk!#$^$?!"E>AwNL!;Jk@~%G!<%?R!a256!K$H%;%k$NBf?t!$P = 64)$NN>J}$,A}2C$9kH!"=hM}$,$5iK9bB.2=KJ$j!"JBNs2=$N8z2L$,8+$ilk!#

0J2<!"<B9T;~4V$KM?$($F$$$k1F6A$rI>2A$9k?aK!"AP1000 $NDL?.%i%$%V%i%j$N<B9T;~4V!"=hM}%7%9%F%`$N<B9T;~4V!"$*$h$SDL?.0J30$N1i;;$N<B9T;~4V$,Am<B9T;~4V$K@j$a$k3d9g$rB,Dj$7$?!#AP1000 $NDL?.%i%$%V%i%j;~4V$O<B:]$N%a%C%;!<%8Aw<u?.$r9T$&;~4V$G$"$k!#=hM}%7%9%F%`$N<B9T;~4V$O%G!<%?$N%Q%C%-%s%0!?%"%s%Q%C%-%s%0$*$h$SAw?.%P%C%U%!$N%U%i%C%7%e$r9T$C$F$$$k;~4VG"$k!#

MQ$$$k%\%j%e!<%`!&G!<%?$O$256^3$H%9%/%j!<%s$N%5%$%:$O256^2G$"$k!#%;%kBf?t$N8z2LI>2A$K$D$$$F$O8 Bf$H64 Bf$r0?7$&!#0l3g7FAw?.9k;k@~%G!<%??tO=l>$l8 K\$H256 K\$G$"$k!#0J2<!"=hM};~4V$HDL?.;~4V$N3d9g$O?^5.4$G!"<B9T;~4V$NFbLu$OI=5.5N=l>lr<($9!#



?^5.4: =hM};~4V$HDL?.;~4V$N3d9g

1. %;%kBf?t$,>.$5$$>l9g!"0l3gAw?.9k;k@~%G!<%??t$,>/$J$$$H!"%[%9%HB&$O%;%k$X$NAw?.;~4V!Ths!K"%;%k$+$i<u?.;~4V!Thr!K$H%;%kB&$O!"%[%9%H$+$i!Tcor)0?$OB>$N%;%k$+iN<u?.;~4V!Tcnr)!"%[%9%H$X0?$OB>%;%k

I=5.5: <B9T;~4V$NFbLu

PE´ ¿		PE=8´				PE=64´			
` ¿fi¸		ray=8		ray=256		ray=8		ray=256	
	¥Ø¥⁄¥ ¥Ø¥Œ	† ¿	…´„ » ·	† ¿	…´„ » ·	† ¿	…´„ » ·	† ¿	…´„ » ·
ホスト	L_asend(Ths)	81920	157.9 (14.6%)	2560	12.8 (1.49%)	81920	165.3 (30.24%)	2560	12.8 (9.38%)
	Crecv(Thr)	81920	87.2 (8.06%)	2560	3.5 (0.41%)	81920	94.6 (17.31%)	2560	3.4 (2.51%)
	Readmsg (Trm)	81920	86.3 (7.98%)	2560	18.2(2.11%)	81920	66.3 (17.61%)	2560	18.0 (13.22%)
	Count(Thc)	—	750.5(69.36%)	—	828.3(96%)	—	190.5(34.84%)	—	102.05(74.88%)
	Total(Th)	245762	1082.0 (100%)	7682	862.8(100%)	245762	546.7(100%)	7682	136.3(100%)
セル	H_recv(Tcor)	37	0.05 (0.00%)	37	0.05(0.01%)	9	0.00(0.00%)	9	0.00(0.00%)
	Readmsg (Tcom)	81957	16.6 (1.51%)	2597	8.3 (0.95%)	81929	15.8 (2.81%)	2569	7.4(4.91%)
	Crecv(Tcns)	81921	61.4 (5.60%)	2561	3.5 (0.40%)	81921	46.9 (8.35%)	2561	1.3(0.88%)
	L_asend (Tcns)	81920	14.4 (1.31%)	2560	4.1 (0.46%)	81920	13.9 (2.49%)	2560	4.0(2.67%)
	Count(Tcnc)	—	1004.5(91.57%)	—	861.7(98.18%)	—	484.8(86.36%)	—	138.3(91.54%)
	Total(Tc)	245835	1096.9(100%)	7755	877.6(100%)	245779	76.6 (13.64%)	7699	151.0(100%)

4V$NAw?.;~4V!JTcns)$JIbA}Bg$7!"DL?.2s?t$,B?$$!#$^$?!"%\%j%e!<%`%G!<%?$,Bg$-$$>l9g!"Bf?t$N8z2L$,8+il$J$$$H!"%;%kB&$O7W;;;~4V$,D9$/$J$k!#

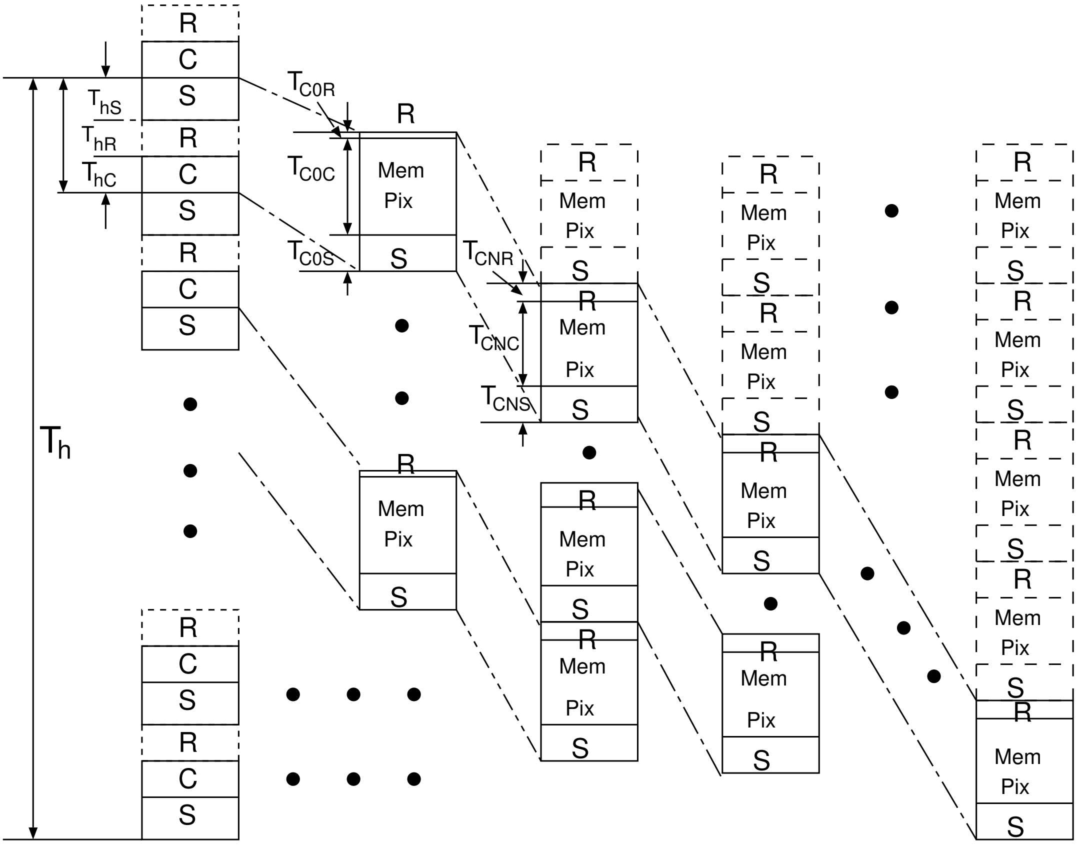
2. %;%kBf?t$,JQ$oi:!"0l3gAw?.9k;k@~%G!<%?$rA}$d9H!"%[%9%H$H%;%k$NN>J}$GDL?.%i%$%V%i%j;~4V$,==J,$K8:i9!"7+$b!"Bf?t$,>/$J$$$H!"%;%kB&$N=hM};~4V$H%[%9%HB&NBTA;~4V$N%P%i%s%9$,0-$/!"7k6I=hM}B.EY$,$"$^$jB.$/JiJ+C?!#

3. %;%kBf?t$HE>AwNL$,5U$K!"Bf?t$,A}d7!"E>AwNL$,>/$J$$>l9g$O!"#1%;%kEv$?jN7W;;NL$,8:>/$7$F!"Bf?t8z2L$,8+il$k!#$7$+$b!"E>AwNL$,A}2C$7$J$$$H!"%[%9%HB&$NDL?.2s?t$rA}d9!"%;%kNBTA;~4V$,Am=hM}<B9T;~4V$N3d9g$NB?$/$r@j$a$k!#

4. 0lJ}!"%;%k$NBf?t$HE>AwNL$rN>J}A}$d9H!"1%;%kEv$?$j$N1i;;NL$,6KaF8:>/$7!"DL?.%i%$%V%i%j;~4V$bAw?.NL$,>/$J$$>l9gN\frac{1}{30}$$KDc2<$7!"JBNs2=$N8zN($,$h$$$H$$$($k!#$3$N>l9g$N%[%9%H$H%;%k$N$=$l$>$l$NDL?.%i%$%V%i%j<B9T;~4V$r?^5.5$K<($9!#

5.1.3 @-G=M=B,%b%G%k

8zN($O@-G=$r7hDjE1$k3FMW0x$NAj8_:nMQ$K0MB8$9kNLG$"$j!"8zN($=$NbN$rD>@\%b%G%k2=$9k3HO:FqG$"$k$,!"<B9T;~4V$K4p$E$$$F@-G=M=B,%b%G



?^5.5: DL?.%i%$%V%i%j$N<B9T; ~4V

%k$r9M$ (kH! "3FMW0x4H$KJ,3d$7$F9M$ (i1kN$GM}2r$7d9$$! #K\8&5fDs 0F7?JBNs%"%k%4%j%:% `$OJBNs7W; ;5!>e$G<B9T$7$?7k2L$+$i! "%"! <%-%F%/%A%c $K1~$8$F! "E,@Z$J%\%j%e! <% `! &G! <%?%5%$%:! "%W%m%;%C%5?t$rA*Br9kKh$j! " @-G=M=B,%b%G%k$rF@k3H,2DG=HJ$k! #K\@a$G$O! "$3$1$K$D$$$F=RYk! #

?^5.5Kh$j! "AP1000 $G<B9T$7$FF@$i1?7k2L$+$i! "% [%9%H$N; k@~%G! <%?$r %;%k$N0 HV$KAwkH$-! "DL?.; ~4V$,Hs>o$K> .$5$/$G! "L5; k9k3H$,2DG=$G$" $k! #$3$3$G! "%Q%$%W%i%$%sJ}K!$G8D!9$N%W%m%;%C%5$O3FCJ3,$G$N1i; ;; ~4V! "DL ?.; ~4V$Khk! "0J2<$NJBNs<B9T; ~4V$N?dB,<0$r8+@Q$bk3H,G-$k! #3F%W%m %;%C%5$NJBNs7W; ;; ~4VT_cO! "

$$T_h = T_{ho} + P_i - 1(T_p + T_{com}) + (T_{ho} \times L) + T_hr \qquad (5.1)$$

$H8+@Q$b1k! #$?$@$7! "$P_i$$O%W%m%;%C%5Bf?tG"$k! #L $O%9%/%j! <%s$N%5%$%:$Sn^2$ $H; k@~%G! <%?$NAw?.NL!R!KOL = \frac{Sn^2}{R}$$rDL?.2s?tKJ$k! #$T_{ho} = Ths + Thr + Thc$ G"$k! #$T_p$$O%W%m%;%C%5GN1i; ;; ~4VG"$k! #$T_{comm} = Tcnr + Tcns$ $O%W%m%;%C

I=5.6: @h9TAw?.$HJ?9TAw?.$NHf3S(s)

%\%j%e!<%'/%T%/%;%k	PE(Bf)	@h9TAw?. [sec]	J?9TAw?. [sec]	<B9T;~4V $N2~A1[%]
64^3œ,A!?256^2	4	47.58	47.64	0.13
	8	25.63	25.83	0.77
	16	13.95	14.12	1.20
	32	8.82	9.12	3.28
	64	5.82	6.16	5.42
128^3œ,A!?256^2	4	91.65	91.92	0.30
	8	47.59	47.81	0.46
	16	25.20	25.56	1.41
	32	13.90	14.44	3.74
	64	8.64	9.02	4.21
256^3œ,A!?256^2	4	the limit of memory	-	-
	8	87.92	88.18	0.29
	16	46.08	45.8	1.57
	32	24.19	24.74	2.22
	64	13.63	14.09	3.26

%5$NDL?.;~4V$G$"$k!#

5.1.4 ;k@~%G!<%?$N@h9TAw?.$N8z2L

4.4.3@a$G=R$Y$?$h$&$K!"K\8&5f$GDL?.;~4V$r1#JC9k$?$a$K!"%"%k%4%j%:%`$r<B8=$9$k$H$-$K!";k@~%G!<%?$NAw?.J}K!$r2<dN`$r9M$($?!#I=5.6$O!"@h9TAw?.K!$HJ?9TAw?.K!N=l>lN%\%j%e!<%`!&G!<%?%5%$%:$KBP$9$k!"<B9T;~4V$NHf3S$G$"$k!#I=$N7k2L$+$i9M;!$9$k$H!"@h9TAw?.K!$[$&$,9b$$8z2L$,F@$i$l$?$H$$$($k!#%G!<%?%5%$%:$,>.$5$$>l9g$G$b!"@h9TAw?.K!$OJ?9TAw?.K!$h$j2%0J>e<B9T;~4V$,C;$$!#%\%j%e!<%`%5%$%:$,$128^3$$NH-$K!"$[$\20%$N2~A1$rC#@.$G$-$?!#DL?.1#JC$,4|BT$5lk@h9TAw?.K!$N%"%k%4%j%:%`$N<B8=$,$G$-$k!#

6 $*$ojK

K\8&5fGO!"%a%b%jJ,;67?JBNs7W;;5!$rBP>]$H9k%\%j%e!<%`%l%s%@%j%s%0$NJBNs%"%k%4%j%:%`$rDs0F$7$?!#

K\%"%k%4%j%:%`$O!"=>Mh$NC`<!%"%k%4%j%:%`$r4p$K!"%W%m%;%C%54V$N%Q%$%W%i%$%s$K$h$k%\%/%;%kJBNs=hM}$r9T$&!#$^$?!"%\%j%e!<%`%l%s%@%j%s%0@lMQJBNs7W;;5!ReVolver/C40 $GDs0F$5l?%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.K!$r%G!<%?J,3d$K;HMQ$7$F$$$k!#3lKh$j!"%G!<%?$N:FJ,3d$r9T$&3HJ/G$0UJ}8~$+iN;k@~$r=hM}$9k3H,G-!";kE@JQ99$r9T$C$?>l9g$K$b9bB.$J2hA|@8@.$,2DG=$G$"$k!#

K\%"%k%4%j%:%`$rJBNs7W;;5!AP1000>e$K<BAu$7!"@-G=I>2A$r9T$C$?!#K\<BAu$G$O!"E,EY$JN3EY$G%\%j%e!<%`%G!<%?$d;k@~$rE>Aw$7!";k@~$N@hAwjKhkDL?.$N1#JC$r?^kJIN:GE,2=Kh$j!"9b$$@-G=$,F@$il?!#

AP1000 GN@-G=I>2A$N7k2L!"

- %5%$%:$64^3$,$256^3$$N%\%j%e!<%`%G!<%?$+$i2hAG?t$256^2$$N2hA|$r@8@.$9kN$K!"64 %W%m%;%C%5$G$O4 %W%m%;%C%5$KBP$7!"$=l>$lLs8 G\$H12.5 G\$H!"9b$$JBNs@-$,F@$il?!#
- %\%j%e!<%`!&G!<%?$,Bg$-$$>l9g$O!"J,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$r1 %U%l!<%`$GAw?.9k$[$&$,DL?.2s?t$r8:i9!"1 <!85G[NsKh$K%G!<%?Aw?.J}K!$h$j10 G\B.$5$,F@$il?!#
- 0l3gAw?.9k;k@~%G!<%??t$O64 %W%m%;%C%5$G;k@~%G!<%??t$,256 $O4 $KBP$7!"=hM}B.EY$,8.5 G\$HJC$?!#
- $^$?!"@h9TAw?.K!$O0l3gAw?.K!$h$jAw?.$9$k%a%C%;!<%8$ND9$5$,C;$/$N$G!"DL?.;~4V$KBP7F!"@h9TAw?.K!$O0l3gAw?.K!$hj"$kDxEYDL?.;~4V$,8:i9$3$H$,$o$+$k!#
- 5i$K!"%5%$%:$64^3$$N%\%j%e!<%`%G!<%?$KBP$7!"2hAG?t$256^2$$N2hA|@8@.;~4V$r%o!<%/%9%F!<%7%g%s!Ultra SPARC 167MHz <g5-21128MB!K$G$NC`<!<B9T$HHf3S$7$?7k2L!"64 %W%m%;%C%5$G4.1 G\$HJj!"K\J}<0Kh$kJBNs%\%j%e!<%`%l%s%@%j%s%0$NM-8z@-$,<(5l$?!#

<UK-

K\8&5f$N5!2q$rM?$($F2<5j!"E,@Z$J8f;XF3$r;roC$?IYEDbC<#65<x$K?<?S$J<U0U$rI=7^$9!#

?t!9$NM-MQ$J8f0U8+$r$$$?$@$$$?CfEg9@=u65<x!"?tB?$/$N8fAjCL$K1~$8$F$$$?$@$$$??9bC0lO:=u65<x!"8^Eg@5M5=u<jJiSK=yMx;a$K?<$/46<UCW7^$9!#

%W%m%0%i%`$N<B9T$K$"$?$j!"JBNs7W;;5!AP1000 $N<B9T4D6-$r8fDs6!$$$?$@$-$^$7$?!3Jt!KIY;NDL8&5f=j$K46<U$N0U$rI=7^$9!#

$^$?!"?t!9$N=u8@$r$$$?$@$$$?:#Hx8xFs;a!"2.LnM'N4;a$HM-1W$J8f0U8+$r$$$?$@$$$?BgLnOBI';a!"7&ED>;;K;a$K46<UCW$7$^$9!#

5i$K!"F|:"8fF$O@$$$?$@$$$?IYED8&5f<<$N=t;a$K46<UCW7^$9!#

;29MJ88%

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