=$;NO@J8

J,;6%a%b%j7?JBNs7W;;5!$K$*$1$k
%\%j%e!<%`%l%s%@%j%s%0K!$N<BAu$H@-G=I>2A

;XF36541 IYEDbC<#65<x

5~ETBg3XBg3X1!9)3X8&5f2J
=$;N2]Dx>pJs9)3X@l96

2&fFhL

J?@.9G/27n14F|

J,; 6%a%b%j7?JBNs7W;;5!$K$*$1$k

%\%j%e!<%`%l%s%@%j%s%0K!$N<BAu$H@-G=I>2A

2&fFhL

FhMF9<35

6aG/3<!856u4V$rD>@\2<!852hA|$KEj1F$9$k$H$$&%\%j%e!<%`%l%s%@%j%s%0$N8&5f$,$5$+$s$H$J$j!"0eNE1g=uMQ$N2hA|@8@.$r$O$8$a$H$9$k3<!85J*BN$N?7$7$2D;k2=5;=Q$H$7$F=EMW$J0LCV$r@j$a$F$$$k!#0lJ}!"%9!<%Q%3%s%T%e!<%?$NH/C#$d%o!<%/%9%F!<%7%g%s$J$I$NG=NO$N8~>e$K$h$C$F2J3X5;=Q7W;;$N7k2L$N2r@O<jK!$H$7$F$b!"%\%j%e!<%`%l%s%@%j%s%0$OCmL\$5$l$k$h&$K$J$C$?!#$7$+$7!"%\%j%e!<%`%l%s%@%j%s%0$K$OKDBg$J5-21MFNL$H7W;;NL$rI,MW$H$9$k$?$a!"=hM};~4V$,$+$+$k$H$J$k!"9bB.$J2hA|@8@.$O:$Fq$G$"$C$?!#

$=$3$GK\8&5f$G$O!"=>MhDs0F$5$l$?%\%j%e!<%`!&l%$!&-%c%9%F%#%s05;=Q$H!"%\%j%e!<%`%l%s%@%j%s%0@lMQJBNs7W;;5!ReVolver/C40 $GDs0F$5$l$?J}K!$K4p$E$$$F!"%\%j%e!<%`%l%s%@%j%s%0$NJBNs=hM}$r9T$C$F$$k!#

K\8&5f$GDs0F$7$?JBNs%"%k%4%j%:%`$O9bB.$J2hA|@8@.$H$H$b$K!"H>F)L@$J%\%j%e!<%`$NI=<(($d1s6aK!$K$h$kEj1F$r4^$a$?2hA|@8@.$rL\I8$H$7$F$$$k!#

JBNs%"%k%4%j%:%`$G$O!"%^%9%?$H%9%l!<%V$N$=$l$>$l0[$J$k=hM}%9%F!<%8$r<B9T$9$k!#%^%9%?B&$N%9%F!<%8$O%9%l!<%V$N<B9T4D6-@_Dj!"=hM}$N=i4|2=!"%\%j%e!<%`!&G!<%?$r3F%W%m%;%C%5!ÐE)$KJ,3d$9$k%G!<%?J,;6%9%F!<%8!";kE@$+$i3F%T%/%;%k$X$N;k@~$r@8@.$9$k;k@~@8@.%9%F!<%8!"%9%l!<%V$+$i<u?.$7$?%T%/%;%kCM$r%7%'!<%G%#%s0=hM}$9$k%7%'!<%G%#%s0%9%F!<%89=@.$r:NMQ$7$F$$k!#%9%l!<%VB&$N%9%F!<%8$OB>$N%9%l!<%V$d^%9%?$HDL?.$7$J$,$i!";k@~@8@.%9%F!<%8$G@8@.$5$l$?;k@~$N%G!<%?$r85$K%5%s%W%j%s0$9$k%\%/%;%k$N%"%I%l%9$r7W;;$7!"FI$_=P$7$?%\%/%;%k$NCM$+$i%T%/%;%kCM$r7W;;$9$k%T%/%;%kCM7W;;%9%F!<%89=@.$r:NMQ$7$F$$k!#

K\8&5f$N:GBg$NFCD'$O!"$^$:!"3FPE $N%T%/%;%kCM7W;;%9%F!<%8$G$N%\%/%;%k %Q%$%W%i%$%s=hM}$G$"$k!#%\%/%;%k %Q%$%W%i%$%s=hM}$G$O!"3FPE $G$[$\F1$8Bg$-$5$K$J$k$h$&J,3d$7$?%5%V%\%j%e!<%`!&G!<%?$r;}$D!#%T%/%;%kCM7W;;$G$O!"%\%/%;%k$N%"%I%l%9$r7W;;$7!"%\%/%;%kCM$NFI$_=P$7$H%T%/%;%kCM7W;;$N=hM}$r#1$D$N%9%F!<%8$H$7!";k@~Kh$K%Q%$%W%i%$%sJ}<0$G=hM}$9$k!#3$N%\%/%;%k %Q%$%W%i%$%s=hM}$GG$0U$N;kE@JQ99$r9T$($k$h$&&$K$9$k$?$a!"%3%s%U

%j%/%H%U%j!<$J%a%b%j9=B$$K4p$E$/%G!<%?J,3dK!$rMxMQ$9$k$H!"%\%/%;%kCM$r JBNs$KF I$_=P$;$k$3$H$,J]>Z$G$-$k!#$^$?!"8zN($h$$JBNs2=<jK!$rL\I8$H$7!" %W%m%;%C%54V$N%G!<%?DL?.NL!"DL?.2s?t$HDL?.;~4V$N1#JC$J$I$r9M;!$7!"%W%m %;%C%54V$N%G!<%?E>AwJ}<0$K4X$9$k;k@~%G!<%?$N0l3gAw?.K!$H;k@~%G!<%?$N@h 9TAw?.K!$N:GE,2=<jK!$rDs0F$7$?!#

K\8&5f$G$O!"Ds0F$7$?JBNs%"%k%4%j%:%\$O:GE,2=<jK!$rMQ$$$FJ,;6%a%b%j7? JBNs7W;;5!AP1000>e$K<BAu$7!"JBNs%\%j%e!<%\%l%s%@%j%s%0$KM?$($k1F6A$r I>2A$7$?!#$3$N7k2L!"$3$l$i$N<jK!$,J,;6%a%b%j7?JBNs7W;;5!$G$N9bB.2=$KM- 8z$G$"$k$3$H$,<($5$l$?!#

$5$i$K!"AP1000 $X$N<BAu7k2L$+$i!"%\%j%e!<%\%5%$:$64^3,256^3$N%G!<%?$+$i 2hAG?t256^2$N2hA|$r@8@.$9$k$N$K!"64%W%m%;%C%5$G$O4%W%m%;%C%5$KBP$7!"Ls 8G\$H12.5G\$H9b$$JBNs@-$,F@$i$l$?!#$^$?!"64%W%m%;%C%59=@.$G!";k@~%G!< %?$r0l3gAw?.$7$?>l9g!"0l3g$KAw?.$9$k%G!<%??t$r256$H$9$k$H!"%G!<%??t4 $N>l9g$KBP$7$F!"=hM}B.EY$,8.5G\$H$J$C$?!#%\%j%e!<%\%5%$:128^3$N%G!<%?$+ $+$i2hAG?t256^2$N2hA|$r@8@.$9$k$N$K!"64%W%m%;%C%59=@.$G!";k@~%G!<%?$N@h 9TAw?.K!$K$h$k!"<B9T;~4V$N2~A1$,$[$\20%0J>eB.$5$rC#@.$9$k!#

$^$?!"%5%$:64^3$N%\%j%e!<%G!<%?$KBP$7!"2hAG?t256^2$N2hA|@8@.;~4V$r %o!<%/%9%F!<%7%g%s!Ültra SPARC 167MHz <g5-21128MB!K$G$NC\<!<B9T$H Hf3S$7$?7k2L!"64%W%m%;%C%5$G(SPARC 20Hz 64 <g5-2116MB )4.1G\$H$J$j!" K\J}<0$K$h$kJBNs%\%j%e!<%\%l%s%@%j%s%0$NM-8z@-$,<($5$l$?!#

# 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.

J,;6%a%b%j7?JBNs7W;;5!$K$*$1$k

%\%j%e!<%'%l%s%@%j%s%0K!$N<BAu$H@-G=I>2A

L\<!


**1** $O$8$a$K **1**

**2** GX7J **2**

2.1 %\%j%e!<%'!&S%8%e&"%i%$%<!<%7%g%s$N35MW . . . . . 2

2.2 %\%j%e!<%'%l%s%@%j%s%0$N<B8=<jK! . . . . . 4

2.2.1 %l%$!&-%c%9%F%#%s%0K! . . . . . 6

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

2.3 %\%j%e!<%'%l%s%@%j%s%0$NJBNs=hM} . . . . . 10

2.3.1 2hA|@8@.$N<jK! . . . . . 10

2.3.2 JBNs=hM}$NU}<0 . . . . . 10

2.4 =>Mh$NJBNs2=<jK! . . . . . 12

**3** Ds0F$9$kJBNs%"%k%4%j%:%'$N35MW **13**

3.1 JBNs%"%k%4%j%:%'$N35MW. . . . . 13

3.2 4p$K$9$kC'<!%"%k%4%j%:%' . . . . . 14

3.3 C'<!%"%k%4%j%:%'$N35MW. . . . . 14

3.3.1 ;k@~$N7W;; . . . . . 15

3.3.2 %T%/%;%kCM$N7W;; . . . . . 20

3.3.3 %7%'!<%G%#%s%0=hM} . . . . . 21

3.4 %3%s%U%j%/%H%U%j!<$J%a%b%j9=@. . . . . 22

**4** JBNs%"%k%4%j%:%'$H<BAu **25**

4.1 JBNs%"%k%4%j%:%'$NL\I8 . . . . . 25

4.2 JBNs%"%k%4%j%:%' . . . . . 26

4.3 AP1000 $K$*$1$kJBNs2=<jK! . . . . . 30

4.3.1 AP1000 $N9=@.$*$h$SDL?.@-G=. . . . . 30

4.3.2 <BAu<jK! . . . . . 31

4.4 AP1000 $G$N:GE,2=<jK! . . . . . 32

4.4.1 1i;;$N%Q%$%W%i%$%s2=. . . . . 32

4.4.2 DL?.2s?t$NDc8: . . . . . 36

4.4.3 DL?.;~4V$N1#JC . . . . . 36

**5 J,;6%a%b%j7?JBNs7W;;5!$K$h$k@-G=I>2A 38**

5.1 <B9T7k2L . . . . . 38

5.1.1 <B9T;~4V$NI>2A . . . . . 39

5.1.2 Aw?.C10L$H$NI>2A . . . . . 41

5.1.3 @-G=M=B,%b%G%k . . . . . 44

5.1.4 ;k@~%G!<%?$N@h9TAw?.$N8z2L . . . . . 46

**6 $*$o$j$K 47**

**<UK- 48**

**;29MJ88% 48**

# 1 $O$8$a$K

8=:_$N2J3X5;=Q$K4XO"$7$?7W;;%b%G%k$K$*$1$k%*%V%8%'%/%H$d<+A38=>]$NB?$/$O!"6u4VE*$J3<!85$N%\%j%e!<%`!&G!<%?$H$7$FI=8=$5$l$k!#$3$&$$C$?%G!<%?$+$i2hA|%G!<%?$r@8@.$9$k%\%j%e!<%`!&%S%8%&"%i%$%<!<%7%g%s$,CmL\$5$l$F$$k!#

%\%j%e!<%`!&S%8%&"%i%$%<!<%7%g%s$K$h$j!"J*BN$NFbIt$rC5:w$7!"2r@O$9$k$3$H$,$G$-$k!#%\%j%e!<%`!&G!<%?$O!"%\%/%;%k$H8F$P$l$kItJ,6u4V$N=89g$H$7$FI=8=$5$l!"%\%j%e!<%`!&G!<%?$OIaDL!"N)J}BN$N%\%/%;%k$+$i$J$kEy4V3V3<!85%a%C%7%e9=B$$GI=8=$5$l$k!#

$7$+$7!"0eNEMQ$N0lO"$NCGAX1GA|$d2J3X5;=Q7W;;$J$I$+$i@8@.$7$?%\%j%e!<%`!&G!<%?$O!"FbIt$N3<!859=B$$rD>@\4Q;!$9$k$@$1$G$OM}2r$d2r@O$,Fq$7$$!#%\%j%e!<%`!&G!<%?$r;k3P$7!"J*BNFbIt$N>pJs$r?M4V$ND>46$KAJ$($k7A$GI=8=$9$k$?$a$K!"3F%\%/%;%k$rD>@\2hLL$KEj1F!"2hA|$r@8@.$9$k%\%j%e!<%`%l%s%@%j%s%0$H8F$P$l$k<jK!$,MQ$$i$l$k!#

%\%j%e!<%`%l%s%@%j%s%0$O2J3XJ,Ln$K$*$$F$O9-$$HO0O$GMxMQ$5$l$F$$k!#=>Mh$h$j!"0eNE1g=u$d2J3X7W;;$J$IBg$-$JJ,Ln$GMxMQ$5$l!":G6a$G$ONDE!Hs GK2u8!::!K$NJ,Ln$G$b;HMQ$5$l$k$J$I!"Hs>o$K=EMW$JLr3d$r2L$?$7$F$$k!#

0lJ}!"%\%j%e!<%`%l%s%@%j%s%0$K$OKDBg$J5-21MFNL$H7W;;NL$rI,MW$H$9$k$?$a!"%\%/%;%k?t$KHfNc$9$k=hM};~4V$H%3%9%H$,$+$+$j!"9bB.$J2hA|@8@.$,:$Fq$G$"$k!#$3$l$O%\%j%e!<%`%l%s%@%j%s%0$NLdBjE@$G$"$k!#

$3$NLdBj$r2r7h$9$k$?$a!"8=:_$^$G$K$5$^$6$^$J2D;k2=$NJBNs=hM}<jK!$,3+H/$5$l$F$$k!#FC$K!";k@~$K1h$C$F3<!85J*BN$r9=@.$9$k3F%\%/%;%k$rDI@W$9$k$3$H$K$h$jFbIt$N>pJs9=@.$rF1;~$K2D;k2=$9$k%l%$!&-%c%9%F%#%s05;=Q$,$h$/MxMQ$5$l$k!#K\8&5f$G$O!"<g$K$3$N=hM}J}K!$rMQ$$F!"J,;6%a%b%j7?JBNs7W;;5!$N4D6-$G=>Mh$N%\%j%e!<%`%l%s%@%j%s%0$NC'<!=hM}%"%k%4%j%:%'$K4p$E$/!"JBNs2=%"%k%4%j%:%'$rDs0F$9$k!#$^$?!"J,;6%a%b%j7?JBNs7W;;5!AP1000>e$G<BAu$H@-G=I>2A$r9T$&!#

K\9F$G$O0J2<!"Bh2>O$G8&5fGX7J$K$D$$F@bL@$7!"Bh3>O$GDs0F$9$kJBNs%"%k%4%j%:%'$N35MW$K$D$$F35@b$7!"B3$$FBh4>O$G$O!"AP1000$GJBNs%"%k%4%j%:%'$N<BAu$K$D$$F=R$Y$k!#$=$N8e!"Bh5>O$G$O!"@-G=I>2A$r9T$$!":G8e$KBh6>O$G!"$^$H$a$r9T$&!#

## 2 GX7J

### 2.1 %\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$N35MW

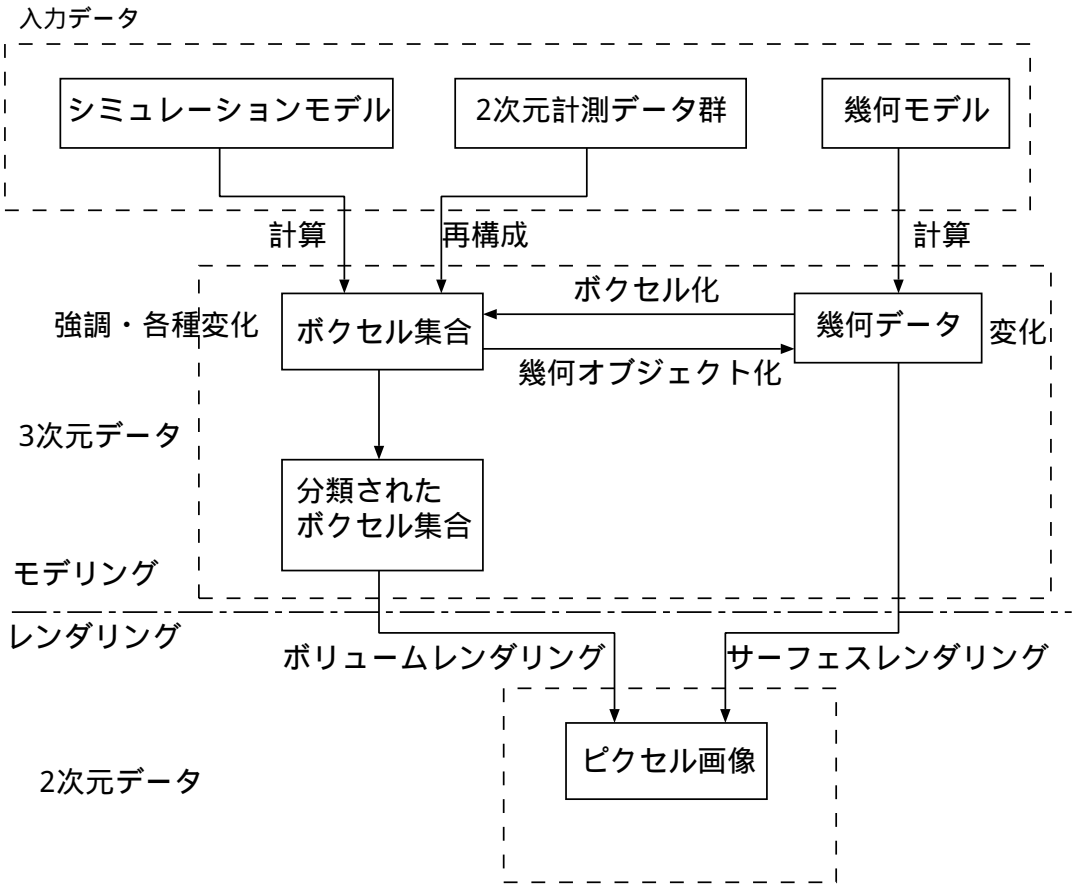
2J3X5;=Q7W;;$d0e3XJ,Ln$K$*$$$F!"=>Mh3<!85%*%V%8%'%/%H$N7A>u$rLL$d@~$NAH$_9g$o$;$H$7$F4v2?3XE*$KI=8=$9$kBe$o$j$K!"FbIt>pJs$r;}$G$?%\%j%e!<%`!&G!<%?$GI=8=$7!"$3$l$r%l%s%@%j%s%0$9$k?7$?$J2D;k2=$NBN7O$,%\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$G$"$k!#

%\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$NL\E*$O!"=>Mh$N%3%s%T%e!<%?%0%i%U%#%/%9$N<jK!$K$*$$$F$O8+$k$3$H$N$G$-$J$$%\%j%e!<%`J*BN$NFbIt$rC5:w$7!"2r@O$,:$Fq$G$"$G$?J#;($J9=B$$d?6Iq$$rM}2r$9$k$?$a$N;k3PE*$J<jK!$rDs6!$9$k$3$H$G$"$k!#?^2.1$K%\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$N=hM}$NN.$l$r<($9[1]!#%\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$N=hM}$O!"%b%G%j%s%0%9F!<%8$H%l%s%@%j%s%0%9F!<%8$KJ,$1$i$l$k!#A0H>$N%b%G%j%s%0$G$O%7%_%e&l!<%7%g%s%b%G%k!"2<!857WB,%G!<%?72!"4v2?%b%G%k$H$$&3<dN`$NF~NO%G!<%?$+$iI=<(MQ$N3<!85%G!<%?$r@8@.$9$k!#8eH>$N%l%s%@%j%s%0$G$=$l$i$r2<!85$N%T%/%;%k2hA|$K%^%C%T%s%0$9$k!#$=$l$>$l$N%9F!<%8$G$O0J2<$N$h$&$J=hM}$,9T$o$l$k!#

%\%/%;%k=89g$H4v2?%G!<%?$K$O$=$l$>$l!"%l%s%@%j%s%0$NA0=hM}$H$7$F!"2hA|=hM}$d4v2?%b%G%k$N=t5;K!$r6n;H$7$?:F5"JQ2=!6/D4!"4v2?JQ49$J$I!K$,I,MW$K1~$8$F;\$5$l$k!#%\%j%e!<%`!&S%8%e&"%i%$%<!<%7%g%s$N=hM}$NCf$GBg@Z$J$N$O!"N><T$N4V$N66EO$r9T$&L\E*$G!"4v2?%*%V%8%'%/%H=$H%\%/%;%k=$NAj8_JQ49$,CV$+$l$F$$$k$3$H$G$"$k!#

1. %b%G%j%s%0%9F!<%8:%b%G%j%s%0%9F!<%8$O!"F~NO%G!<%?$+$i%\%/%;%k=89g$H$J$k3<!85%G!<%?%;%C%H$KJQ49$9$k%9F!<%8$G$"$k!#%\%j%e!<%`!&G!<%?=!<%9$O!"%7%_%e&l!<%7%g%s!&G!<%?!"7WB,%G!<%?!"4v2?%G!<%?$N3<oN`$,9M$($i$l$k!#%\%j%e!<%`!&G!<%?$O!"5,B'E*$JEy4V3V3<!85D>8r3J;R$HHsEy4V3VIT5,B'$J3<!85%G!<%?$N$$:$l$+$KJ,N`$5$l$k!#?^2.1$N<($9$h$&$K!"3<!85%7%_%e&l!<%7%g%s$OD>@\?tCM7W;;$h$j%\%/%;%k=89g@8@.$9$k!#$^$?7WB,%G!<%?$O!"%9%-%c%J$d%;%s%5$N$h$&$J7WB,5!4o$rDL$8$F!"@lMQ$NJd4V<jK!$rMQ$$F!"%\%/%;%k=89g$K3<!85:F9=@.$5$l$k!#$5$i$K!"4v2?%G!<%?$G$O!"CAE4D6-$d0eMQCGAXAuCV$K$h$jIT5,B'$J%\%/%;%k=89g$H$7$F3<!85%\%j%e!<%`!&G!<%?$,@8@.$5$l$k!#

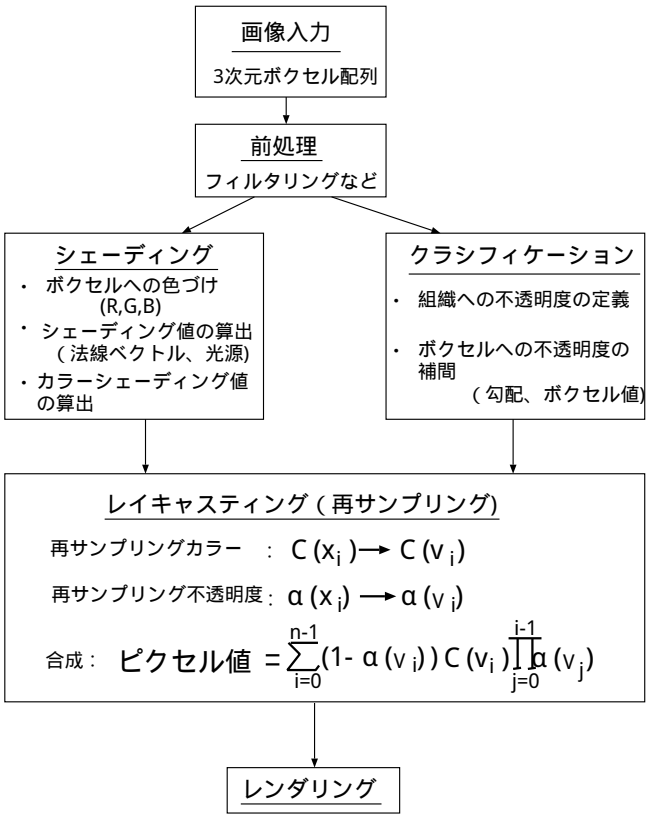
2. %l%s%@%j%s%0%9F!<%8&%l%s%@%j%s%0%9F!<%8$O!"%\%j%e!<%`!&G!<%?!3J<!




?^2.1: %\%j%e!<%`%S%8%e&"%i%$%<!<%7%g&s$N=hM}%U%m!<

8 5%G!<%?!K$+$i2hA| !2J<!8 5%G!<%?!K$r@8@.$9$k%9%F!<%8$G$"$k!#%\%j%e!<%`!&G!<%?$+$i2hA|$r@8@.$9$kJ}K!$H$7$F!"D>@\@8@.K!$H!"4V@\@8@.K!$N2<dN`$,$"$k!#D>@\@8@.K!$O!"%\%j%e!<%`!&G!<%?$r9=@.$9$k3F%\%/%;%k$rD>@\2hLL$KEj1F$9$k$3$H$K$h$j2hA|$r@8@.$9$kJ}K!$G$"$j!"%\%j%e!<%`2hA|$N%S%e!<%$%s%0$H%7%'!<%G%#%s%0$NFs$D$N%W%m%;%9$+$i9=@.$5$l$k!#$3$A$i$N%"%W%m!<%A$O%\%j%e!<%`%l%s%@%j%s%0$H8F$P$l$k!#4V@\@8@.K!$O!"%\%j%e!<%`!&G!<%?$r2<!85$N%W%j%_%F%#%V$KJQ49$7!"<!$K%5!<%U%#%9%l%s%@%j%s%0K!$J$I5lMh$N4v2?%l%s%@%j%s%05;K!$rMQ$$$F!"2<!85%9%/%j!<%s>e$KMn$H$9J}K!$G$"$k!#5!<%U%#%9%l%s%@%j%s%0K!$G$O!"J*BN$OI=LL$r%]%j%4%s!"2<!6JLL!"<+M36JLL$G6a;w$5$l$FM?$($i$l$k!"Cf?H$K4X$9$k>pJs$r$b$?$J$$%b%G%k$G$"$j!"2hA|$OEyCMLL2=!"1#$lLL>C5n!"%7%'!<%G%#%s%0$N3FCJ3,$r7P$F9=@.$5$l$k!#

K\8&5f$G$O%\%j%e!<%`%l%s%@%j%s%0K!$rMQ$$k$3$H$H$9$k!#07$&%\%j%e!<%`!&




?^2.2: %\%j%e!<% '%l%s%@%j%s%0$N=hM}<j=g

%G!<%?$ON)J}BN$N%\%/%;%k=89g$+$i$J$kEy4V3V3 <!85D>8r3J;R9=B$$H$9$k!#

## 2.2 %\%j%e!<% '%l%s%@%j%s%0$N<B8=<jK!

%\%j%e!<% '%l%s%@%j%s%0$H$O!"3 <!856u4V$KDj5A$5$l$?3 <!85J*BN$K$D$$F!"G$0U$N;kE@$+$i$N;k@~DI@W!@l%$!&-%c%9%H!K$r9T$$!"AH?%4V$N6-3&LL$N$_$J$i$:FbIt$N>pJs9=B$$bF)$+$7F2D;k2=$9$kJ}K!$G$"$k!#?^2.2$K$*$$F!"%\%j%e!<%'%l%s%@%j%s%0$N0lHLE*$J=hM}<j=g$r<(9[2]!#%\%j%e!<%'%l%s%@%j%s%0$N<g$JFCD'$O!"%/%i%7%U%#1!<%7%g%s!(classification)=hM}$K$*$$F3FAH?%KBP$9$kITF)L@EY$r!"%7%'!<%G%#%s%0=hM}$K$*$$F$"$i+$8$aM?$($i$l$F$$k?'>pJs$+$i%+%i!<%7%'!<%G%#%s%0CM$r$=$l$>$l5a$a!"$3$l$r%l%$!&-%c%9%F%#%s%0$K$h$j9g@.$7$F%l%s%@%j%s%02hA|$r9=@.$9$k$3$H$G$"$k!#

0J2<$K3F=hM}2aDx$K$D$$F@bL@$9$k!#

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$N2<dN‘$NI=8=J}K!$,$"$k!#
N%;6%b%G%k 3F%5%s%W%j%s%0E@$rCf?4$H$7$?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:_$7!"C10IN)J}BN$NFb
It$NCM$O!"$=$NE@$r0O$‘8D:E@$NCM$+$i tri-linear Jd4V$K$h$j5a$a$i$l$k!#
0J2<!"%5%s%W%j%s%0E@$x_i = (x_i, y_j, z_k)$K$*$1$k%\%/%;%k$N?’!"F)L@EY$J$I
$NCM$r f(x_i)$HI=$9!#

2. A0=hM}
   $b$H$N%\%/%;%k%G!<%?$KBP$7!"%N%$%:=|5n!"2hA|6/D4$J$I$r2C$($k$3$H$K
   $h$j!"0J9_$N%/%i%7%U%#%1!<%7%g%s$J$I$N=hM}$rMF0W$K$9$k!#
3. %/%i%7%U%#%1!<%7%g%s
   E57?E*$JAH?%$K0lDj$NITF)L@EY$\alpha_v$rM?$(!"3FAH?%$KB0$9$k%\%/%;%kCM$K8G
   M-$JITF)L@EY$\alpha(x_i)$rJd4V=hM}$K$h$C$F5a$a$k!#$3$3$G!"J#?t$N0[$J$kAH
   ?%$N6-3&$K$*$1$k%\%/%;%kCM $f(x_i)$H$=$NCM$KBP$9$kITF)L@EY$\alpha(x_i)$N4X?t
   $,M?$($i$l$?>19g!"8{G[CM$b9MN8$7$?G$0U$N%\%/%;%k$NITF)L@EY$\alpha(x_i)$O
   $f(x_i)$NBg$-$5$K$h$C$F7h$^$k$f(x_i)$N8{G[CM$N@dBPCM$H!"ITF)L@EY$NJd4V
   CM$H$N@Q$GM?$($i$l$k!#6qBNE*$J7W;<0$O2<$N<0$G7W;$9$k!#

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

4. %7%’!<%G%#%s%0
   3F%\%/%;%k$K$D$$$F!"<~0O$N%\%/%;%k$NCM$+$i5a$a$?8{G[CM$rEv3:%\%/%;
   %k$K$*$1$kK!@~%Y%/%H%k$H$7!"%7%’!<%G%#%s%0CM$r5a$a$k!#%+%i!<%7%’!<

%G%#%s%0$r9T$&$K$O!"Fs$D$NJ}K!$,$"$k!#

(a) K!@~%Y%/%H%k$N(x_i)$H8w8;J}8~%Y%/%H%kL$NFb@QCM$+$i%7%'!<%G%#%s%0CM$r5a$a$k!#K!@~%Y%/%H%k$N(x_i)$H3F%\%/%;%k$N%+%i!<%7%'!<%G%#%s%0CM$c(x_i)$O<!<0$G5a$^$k!#

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

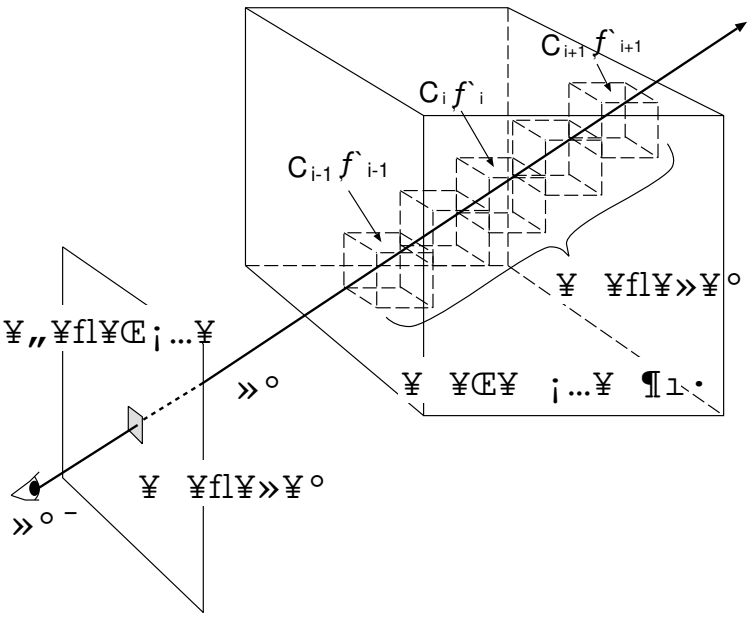
$$c(x_i) = h(N(x_i)\ !\&) * c_k(x_i) \tag{2.3}$$

$3$3$G!"$c_k(x_i)(k = R, G, B)$O3F%\%/%;%k$KM?$($??'>pJs$G$"$k!#h$O3H;6H?<M$K$h$k%7%'!<%G%#%s%04X?t$G$"$k!#

(b) ?'$NIU$$?8w8;$GM?$($kJ}K!$G$"$k!#$3$l$O%\%/%;%k$rL5?'$NH?<ML$H$7F$H$i$(!"$=$N?'$O8w8;$N?'$H%7%'!<%G%#%s%0%b%G%k$K$h$C$F7h$a$k!#

### 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!#



%;%k$4$H$K;kE@$H%T%/%;%k$H$r7k$V;k@~$K1h$C$F!";k@~$H8r:9$9$k%\%/%;%k$r
;kE@$K6a$$=g$K0lDj4V3V$G%5%s%W%j%s%0$7$J$,$i!"3F%\%/%;%k$N%+%i!<%7%'!<
%G%#%s%0CM$c$!$J_i$)$HITF)L@EY$\alpha(x_i)$$N@Q;;CM$,1$K$J$k$^$G7+JV$7!"@Q$,7W;;$5
$l$k!#6qBNE*$K$O!"3F%\%/%;%k$KBP$7!"@a2.2$K=R$Y$?3.$H4.$N=hM}$G3F%\%/
%;%k$K$"$i$+$8$aM?$($i$l$F$$$kITF)L@EY$\alpha(x_i)$$H%+%i!<%7%'!<%G%#%s%0CM$c$!J
$x_i$)$H$N>h;;1i;;$K$h$j!"%\%/%;%k$rDL2a$7$?8w$,5a$^$k!#;k@~$,G$0U3Q$GF~<M
$9$k$?$a!"%\%/%;%k3J;RE@$NG[CV49$($,I,MW$K$J$k!#$3$l$O!"6aK5$N%\%/%;%k
$KM?$($i$l$?$c$!$J_i$)$H$\alpha(x_i)$$rJd4V1i;;$9$k$3$H$K$h$C$F:F%5%s%W%j%s%0$5$l
$??7$7$$$c(v_i)$$H$\alpha(v_i)$$r5a$a$k$3$H$G$"$k$!$J_i$O:F%5%s%W%j%s%0:BI8$r<($9!K#
$9$J$o$A!";k@~$K1h$C$FJB$s$@%\%/%;%k$K$D$$$F!"A0$+$i$-$?8w$!$J'!K$H!"<+
$i$,H/$9$k!"0?$O8w8;$K>H$i$5$l$FH?<M$9$k8w$H$r9g@.$7$F!"<!!9$H%\%/%;%k
$KEO$7$F$$$-!":G8e$N%\%/%;%k$+$i=P$F$-$?8w(?'!K$,%l%s%@%j%s%02hA|$N%T
%/%;%kCM$H$J$k!#$f$($K%T%/%;%kCM$O!"0J2<$N$h$&$K5a$a$i$l$k!#

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

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

8=<B46$N9b$$3<!851"1F2hA|$r@8@.$9$k$?$a!"%l%$!&-%c%9%F%#%s%0K!$r$5
$i$K9bEY$J%l%$!&H%l!<%7%s%0$H8F$P$l$kJ}K!$K3HD%$9$k$3$H$b$G$-$k!#

%l%$!&H%l!<%7%s%0$H$O!"H?<M8w$HF)2a8w$r9MN8$7$?>l9g!";kE@$+$i$N;k@~
!$J<!;k@~!K$H%\%/%;%kI=LL$,8r:9$9$k$HH?<M8w$d6~@^8w!$J<!;k@~!K$r@8@.$9
$k!#$3$NI,MW$J8w$N@.J,$r5a$a$k$?$a$K!"H?<M8w$HF)2a8w$K$D$$$F$"$k$7$-$$
CM$r1[$($k$^$G!":F5"E*$J=hM}$,I,MW$G$"$k!#

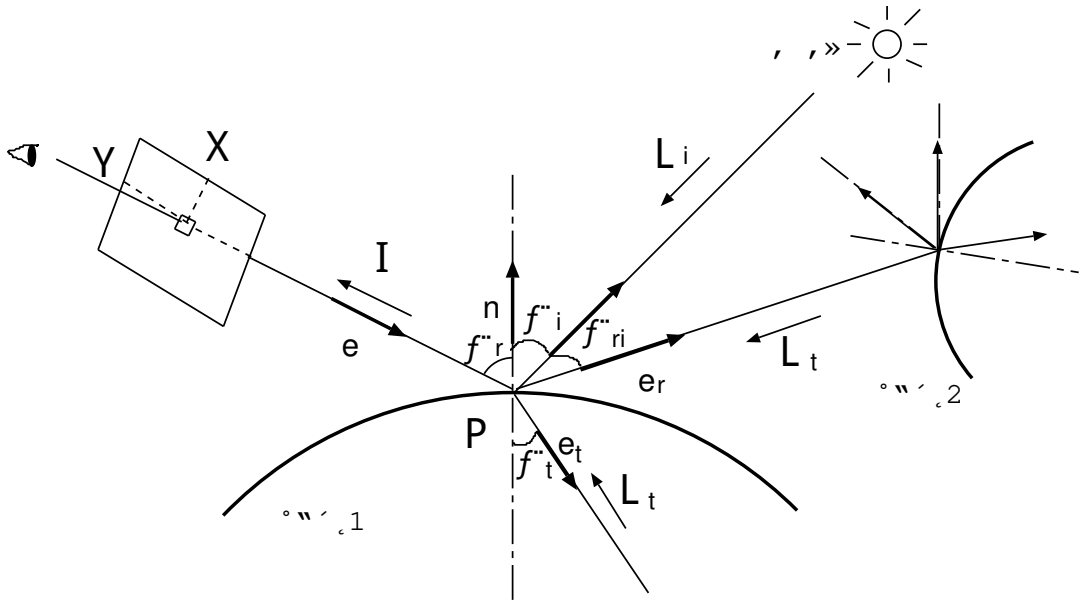
$9$Y$F$N%T%/%;%k$N2D;kE@$KBP$9$k51EY7W;;$N%b%G%k$H$7$F<!$NWhitted$N
J}<0$,M-L>$G$"$k[4]!#(?^2.4!K

$$I=I_a+k_dn*L_i+k_sL_r+k_tL_t \tag{2.5}$$

$?$@$7!"

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

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




?^2.4: Whitted $N51EY7W;;%b%G%k

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

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

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

$G$"$k!#;k@~$CDI@W$7$J$,$i51EY7W;;$N2aDx$G!"$D$.$N=hM}$r9T$&!#

- 1F=hM}!'51EY7W;;$G$O!"3F%5%s%W%j%s%0E@$G<!$N$h$&$J=hM}$r9T$&!#8w8;$+$i$ND>@\8w$,8=:_=hM}Cf$N%5%s%W%j%s%0E@$KFO$/$+H]$+$rH=Dj$9$k$?$a$K!"$=$N%5%s%W%j%s%0E@$+$i8w8;$K8~$+$&8=<B$H$O5UU}8~$N2<!;k@~$rH/$7!"$=$N;k@~$H$9$Y$F$NU*BN$H$N8rE@H=Dj$r<B9T$9$k!#
- H?<M=hM}!'8w8;$+$i$N8w$,J*BN$KC#$7$?E@$+$iH?<M8w$,H/@8$9$k>l9g!"$=$NE@$r:F$S8w8;$H8+$J$7$F!"5UU}8~$N2<!;k@~$rH/@8$5$;!"$=$N2<!;k@~$H$9$Y$F$NU*BN$H$N8rE@H=Dj$r9T$C$F;kE@$+$i0lHV<jA0$N8rE@$r5a$a!"$=$N8rE@$N51EY7W;;$r<B9T$9$k!#
- F)2a=hM}!'8w8;$+$i$N8w$,J*BN$KC#$7$?E@$+$iF)2a8w$,H/@8$9$k>l9g$K!"$V$D$+$C$?J*BN$,F)2a8w$r5/$3$9>l9g$K$O!"$=$NE@$+$i6~@^J}8~$K8~$1$F2<!;k@~$r=P$7!">e$NE@$HF1$8$h$&$K8rE@H=Dj$r<B9T$9$k!#

Whitted $N51EY7W;;<0$r:F5"E*$KE,MQ$9$l$P!"0l$D$N%T%/%;%k$KBP$9$k7W;;$G$"$C$b!"8w@~$NLZ9=B$$K=>$C$F;k@~$ND I@W$,I,MW$H$J$k!#=>$C$F!"%l%$!&H%l!<%7%s%0K!$O9bIJ<A$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$5$l$F$$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)$7$F=hM}$r9T$($kE@$,Bg$-$JFCD'$G$"$j!"=EMW$JJBNs2=$NMWAG$G$"$k!#%9%/%j!<%s$NAv::@~$J$I$KBP1~$7$?NN0h$N2hAG72$rDL2a$9$k;k@~72$K%W%m%;%C%5$r3d$jIU$1$F!"=hM}$NJBNs2=$r?^$k!#$3$NJBNs=hM}$O%W%m%;%C%5$,B?$/$J$l$P$=$l$@$13F%m!<%+%k%a%b%j$N%-%c%7%e$rB?$/:N$k$3$H$,$G$-$k$N$G!"DL?.$N%*!<%P!<%X%C%H$r:o8:$G$-$k$3$H$H$$&MxE@$,$"$k!#

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

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

3. NN0h:FJ,3d$K$h$k%l%$!&-%c&9%F%#%s%0$3$A$i$O!"$J$k$Y$/%l%$!&-%c&9%F%#%s%0$NK\?t$=$N$b$N$r:G>/2=$7$h$&$H$9$k<jK!$G$"$k!#$^$:!"%9%/%j!<%sA4BN$rE,Ev$J8D?t$N6k7A$N>.NN0h$KJ,3d$7!"$=$l$>$l$N>.NN0h$4$H$K!"0J2<$N<jB3$-$r9T$&!#

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

   *Step 2* :if(F@$i$l$?#4$D$N%T%/%;%k?'$N0c$$,4p='CM$r1[$($k!K then go to *Step 3*;else go to *Step 4*;

*Step 3* :>.NN0h$r4EyJ,J,3d$9$k!goto*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$rI,MW$H$5$l!"IJ<A$N9b$$2hA|$r5a$a$k$?$a$K$O1i;;NL$OHs>o$KB?$/$J$k!#=>Mh$+$i!"9bB.%l%s%@%j%s%0$r$O$+$k$?$a$K!"$5$^$6$^$JJBNs=hM}$,9T$o$l$F$-$?!#$h$/MQ$$$i$l$kJBNs=hM}!"2hA|@8@.$N<jK!$K$h$jA0J}Ej1FK!$H8eJ}Ej1FK!$NFs$D$N%+%F%4%j!<$K<jK!$,J,$1$i$l$k!#JBNs=hM}$NJ}<0$H$7$F$O!"?^2.5$K<($9$h$&$K;M$D$NJ}<0$,9M$($i$l$k[5][6]!#

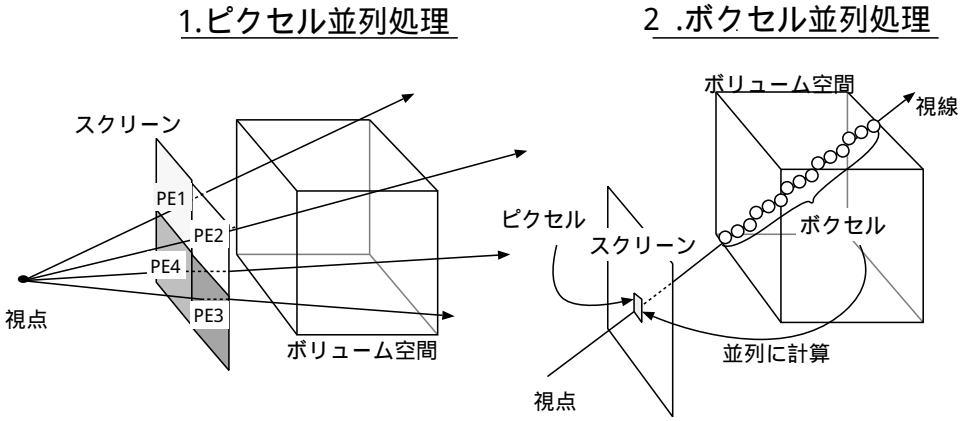
#### 2.3.1 2hA|@8@.$N<jK!

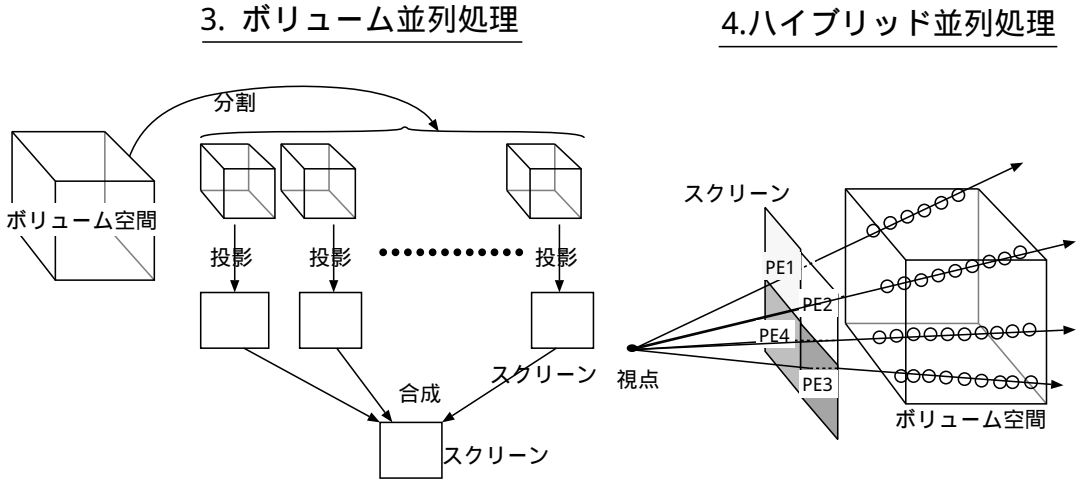
1. A08~$-%^%C%T%s%0 !&&&*%V%8%’%/%H=g$H$b8F$P$l$k!#%\%j%e!<%‘$r9=@.$9$k3F%\%/%;%k$r%9%/%j!<%s$KEj1F$7!"3F%\%/%;%k$,%9%/%j!<%s>e$N8D!9%T%/%;%k$K$I$l@$11F6A$rM?$($k$+$r7hDj$9$k$3$H$G!"3F%T%/%;%kCM$r5a$a$k%"%k%4%j%:%‘$G$"$k!#
2. 8e8~$-%^%C%T%s%0 !&&&2hA|=g$H$b8F$P$l$k!#;kE@$+$i%9%/%j!<%s>e$N3F%T%/%;%k$rDL$k;k@~%Y%/%H%k$r@8@.$7!";k@~$,%\%/%;%k6u4V$rDL2a$7$?;~$K;k@~$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

#### 2.3.2 JBNs=hM}$NJ}<0

%W%m%;%C%5Bf?tP!"%T%/%;%k?t$m^2$H%\%/%;%k$NAm?t$r$n^3$N$H$-!"3FJBNs=hM}J}<0$NFCD’$O<!$N$h$&$K$J$k!#ƀ^2.5!K

1. %T%/%;%kJBNs=hM}!9%9%/%j!<%s$N3F2hAGE@$4$H$K%W%m%;%C%5$r3d$jEv$F$k!#3F%W%m%;%C%5$O$=$N;k@~>e$N%\%/%;%kCM$r3<!852hA|%a%b%j$+$iC‘<!E*$KFI$_=P$7!"N_@Q$9$k!#3<!852hA|%a%b%j$N%3%T!<$rA4$F$N%W%m%;%C%5$,M-$7$F$*$l$P!"=hM};~4V$O$m^2n/P$H$J$j!"%W%m%;%C%5Bf?t$KHfNc$7$?Hs>o$K9bB.$J=hM}$,2DG=$K$J$k!#$7$+$7!"$3$l$O%3%9%HE*$K8+9g$o$J$$!#3<!852hA|%a%b%j$r%P%s/J,$1$7$?%7%9%F%‘$d%-&C%7%e%a%b%j$rM-8zMxMQ$7$?%7%9%F%‘$,;HMQ$5$l$k!#
2. %\%/%;%kJBNs=hM}!K\8&5f$G<g$KMQ$$$?JBNs=hM}<jK!$G$"$k!#0l$D$N;k@~$KBP$7!"3<!852hA|%a%b%j$+$iF1;~$K;k@~>e$N$9$Y$F$N%\%/%;%k!Am?t$On)$rFI$_=P$7!"N_@Q$9$k!#3<!852hA|%a%b%j$N9=B$$,=EMW$JLr3d$r2L$?$9!#




?^2.5: %\%j%e! <% '%l%s%@%j%s%0$NJBNs=hM}J}<0

n 8D$N%\%/%;%kCM$On/P 8D$KJ,3d$5$l!"3F%W%m%;%C%5$GItJ,N_@Q$5$l$k!#
3F%W%m%;%C%5$r%j%s%09=B$$G7k9g$7!"$=$l$i$r%Q%$%W%i%$%sJ}<0$GN_@Q$9
$k!#<B<AE*$K$O!"n/P ;~4V$Gn 8D$N%\%/%;%kCM$NN_@Q$r9T$($k!#=>$C$F=h
M};~4V$Om^2n/P$H$J$k!#G$0U;kE@$G3 <!852hA|%a%b%j$+$i%\%/%;%k$rFI$_
=P$72DG=!"%P%s%/%3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$,3+H/$5$l$k!#

3. %\%j%e!<% `UBNs=hM}!3F%\%/%;%k$K0l$D$:$D%W%m%;%C%5$r3d$jIU$1$k!#3F%\
%/%;%k$+$i;kE@$K8~$+$&5U;k@~$H%9%/%j!<%s$H$N8r:9$9$k2hAGE@$K$=$N%\
%/%;%kCM$rN_@Q$9$k!#3F%W%m%;%C%5$Gn^3/P8D$N%\%/%;%k$rC4Ev$9$k!#5U;k
@~>e$NP^1/38D$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%$%sE*$KEO$7F$$/J}<0$r$H$j!"$3$NJ?
6QE>Aw;~4V$rr7$H$9$k$H!"Am<B9T;~4V$O(n^3/P + P^1/3)r7$H$J$k!#

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

## 2.4 =>Mh$NJBNs2=<jK!

%\%j%e!<% `%l%s%@%j%s%0$NJBNs=hM}$G$O!"9b$$%W%m%;%C%5$NMxMQEY$*$h$S:G
>.$N%W%m%;%C%54VDL?.!"$h$Ii2Y%P%i%s%9$J$I$r9M$($J$1$l$P$J$i$J$$!#=>Mh
$NBeI=E*$JJBNs=hM}<jK!$K$O0J2<$N$h$&$J$b$N$,$"$k!#

- %;%0%a%s%H2=$5$l$?%l%$!&-%c%9%F%#%s%0[7]
$3$l$i$NJ}K!$G$O!"%W%m%;%C%5$O$G$-$k$@$1N)J}BN$N$h$&$J%\%j%e!<%
`!%G!<%?$N%5%V%V%m%C%/$r$b$D!#G$0U$K;k@~$N3QEY$rM?$($?;~!";k@~$,%\%j%e!<%
`$N$I$N%5%V%V%m%C%/$rDL2a$9$k$+$r7hDj$9$k!#$3$N$?$a$K!"%5%V%V%m%C
%/$NI=LL$r2hLL$KEj1F$7!"$I$N%T%/%;%k,%5%V%V%m%C%/$N1F$K$J$k,$rD4
$Y$k!#;k@~$H8r:9$N>pJs$r%P%C%U%!$KC_$($k$3$H$K$h$C$F!"%l%s%@%j%s%0
$,;O$^$kA0$K$9$Y$F$N;k@~$r=8$a*$k$3$H,$G$-!"Ii2Y%P%i%s%9$,$H$l$k!#
<!$K%l%$%;%0%a%s%H,%5%V%V%m%C%/$KFO$/$4$H$K?'$HITF)L@EYCM$r7W;;$7!"
<!$N%W%m%;%C%5$X$HAw$k!#%W%m%;%C%5$O=$l$>$lItJ,E*$J;k@~$NCM$N=g=x
IU$1$5$l$?9TNs$r7W;;$79g@.$5$l$F:G=*E*$J%T%/%;%kCM$H$J$k!#

- %G!<%?J,;6%l%$!&-%c%9%F%#%s%0[8]
%W%m%;%C%5$N"%$%I%k>uBV$rKI$0$?a!"binaray-swap 9g@.K!$H$$&J}K!$,
3+H/$5$l$?!#$3$l$O!"3F9g@.%9%F!<%8$G$=$l$>$l2hLL$rFs$D$KJ,3d$7!"Fs

$D$N%W%m%;%C%5$,$=$N$&$A$N0l$D$KBP$7$F@UG$$r$b$D$3$H$K$h$j!"$9$Y$F
$N%W%m%;%C%5$,$9$Y$F$N%9%F!<%8$G=hM}$K;22C$9$k$H$$$&$b$N$G$"$k!#$3
$l$i$N=hM}<jK!$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]
  $3$NJ}K!$G$O!"%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$$$kBe$o$j$K!"%?%9%/$GI,MW$H$J$k%G!<%?$r%3%T!<$9$k!#
  $3$l$K$h$j!"ITMW$JDL?.$,$J$/$J$k!#%a%b%j$NI,MWNL$O:G>.$K$J$j!"%-%c%C
  %7%e$NCV$-49$($r9T$&I,MW$,$J$$!#$^$?!"Ii2Y$K1~$8$F%?%9%/$,M}A[E*$K
  J,3d$5$l$k$H$$$&MxE@$,$"$k!#
- %$%s%?%i%/%F%#%V$J2hA|@8@.%7%9%F%`[10]
  $3$N%"%k%4%j%:%'$O;0$D$N%U%'!<%:$r$b$D!#$=$l$>$l!"%0%j%C%I$NUQ2=$N
  =hM}!"%S%e!<$NUQ2==hM}!"2hA|$N%l%s%@%j%s%0$G$"$k!#%^%9%?%W%m%;%C%5
  $O%0%j%C%I!"%9%+%iCM!"%S%e!<!"E>Aw4X?t$N;XDj$N99?7$r9T$&$?$a!"%f!<%6
  %$%s%?%U%'!<%9$HD"Mm$r$H$k!#$^$?!"2hA|$N05=L$d%f!<%6%$%s%?%U%'!<%9
  $X$N2hA|Aw?.$b9T$$!"JBNs%?%9%/$K$b;22C$9$k!#%f!<%6$K$h$C$F?7$7$$0
  %j%C%I$,;XDj$5$l$k$H!"6&M-%a%b%j$K%U%!%$%k$+$i%G!<%?$r%k%'%I%U%'!<%9
  %k%U%'!<%9$N=i4|2=$,JBNs$K9T$o$l$k!#$=$N%?%9%/,3d$O%U%'!<%9%0%k!<
  %W$K$h$C$F9T$o$l!"$3$l$i$N%?%9%/$OF0E*$K@8@.$5$l$k!#
  $3$N%"%k%4%j%:%'$O;0!"UBNsMIMD7?$G%"%/;9~4V$N0[$J$k%m!<%+%k%a%b
  %j$H6&M-%a%b%j$r;}$D"!<%-%F%/%A%c$KBP$7$F@_7W$5$l$?!#

## 3 Ds0F$9$kJBNs%"%k%4%j%:%'$N35MW

### 3.1 JBNs%"%k%4%j%:%'$N35MW

K\8&5f$G$O!"<!$N$h$&$&$JFCD'$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
  $F07$($k$h$&$K$9$k!#
- 1s6aK!!;JkE@$+$i$N;k@~$,J?9T$G$J$$K<jK!$r:NMQ$7!"Bg$-$J6u4V$rI=<(
  $9$k:]$K!"N)BN46$r:n$j=P$9$3$H$,$G$-$k$h$&$K$9$k!#

- %l%$ !&-%c&9%F%#%s%05;=Q$K$h$j2hA|$r@8@.$9$k!#$3$l$O3F;k@~$4$H$K$D $$$FFHN)$J=hM}$r9T$($k$N$G!"JBNs2==hM}$,2DG=$G$"$k
- ;kE@JQ99$r<+M3$K9T$($k$h$&$K$9$k!#$3$l$r<B8=$9$k$K$O!"G$0UJ}8~$+$i H/@8$9$k;k@~$r07$($k$h$&$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~$X6Q 0l$KJ,3d$9$k!"%G!<%?$N3=E2=!#3%s%U%j%/%H%U%j!<$J%a%b%j9=B$!K$H<g <4Ey4V3V%5%s%W%j%s%0K![5][6]$rA*Br$9$k!#$3$l$K$h$j!"%\%/%;%kCM$rJBNs 2=$KFI$_=P$7$,2DG=$G$"$k!#

K\8&5f$G$O!"$3$l$i$NJBNs2=J}?K$r$=$l$>$l<B8=$9$k$3$H$K$h$C$F!"%\%j%e!< %'%l%s%@%j%s%0K!$NJBNs2=$rL\;X$9!#

### 3.2 4p$K$9$kC'<!%"%k%4%j%:%'

%\%j%e!<%'%l%s%@%j%s%0$r9T$&$?$a$K!"MM!9$J=hM}<jK!$,Ds0F$5$l$F$$$k!# $3$NCf$G$bLevoy[2]$K$h$jDs0F$5$l$?%\%j%e!<%'%l%$!&-%c&9%F%#%s%05;=Q$O $h$/MQ$$$i$l$k!#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]$K$h$jDs0F$5$l$?3 =E2=%a%b%j$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@$9$k!#

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

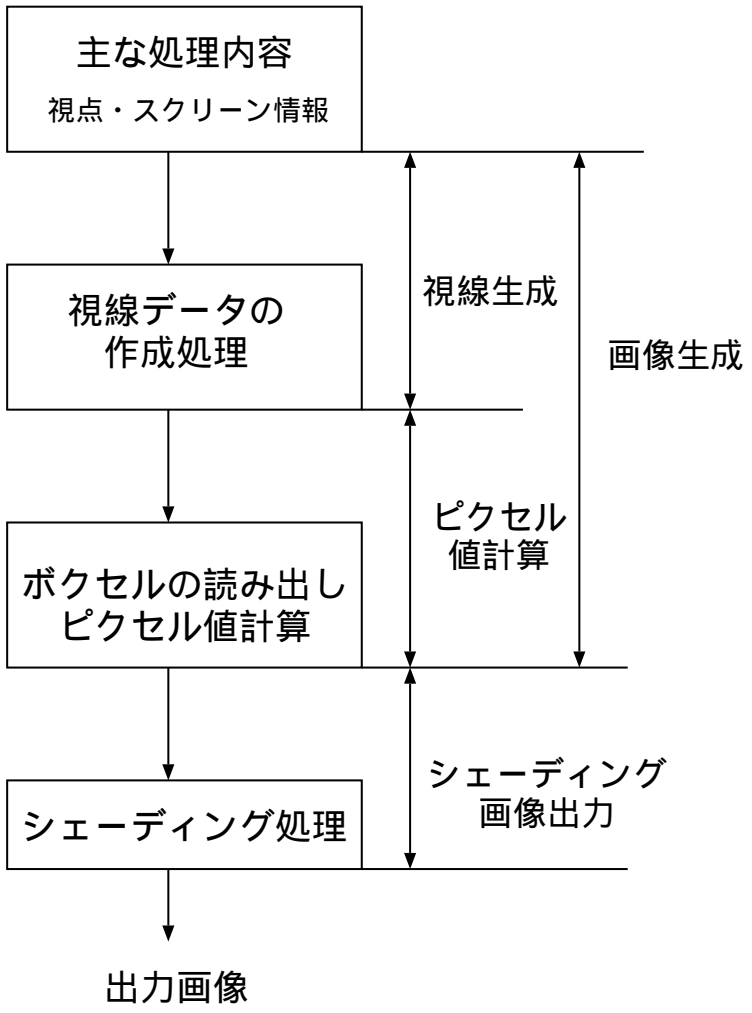
C'<!%"%k%4%j%:%'$N3F=hM}$H$3$N4V$rN.$l$k%G!<%?$r^3.1$K<($9!#%"%k%4%j %:%'$O;MCJ3,$+$i9=@.$5$l$k!#

=i4|@_Dj ;kE@$d%9%/%j!<%s>pJs$J$I$r@_Dj$9$k!#

;k@~%G!<%?N:n@.=hM} A0CJ3,$+$iAw$i$l$F$/$k;kE@!&9%/%j!<%s$N>pJs$h$j!" ;kE@$+$i3F%T%/%;%k$kDL$k;k@~$N8@.$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;;$5$l$?%T%/%;%kCM$H;k@~%G!<%?$r<u$1<h$j!"depth gradient shading[11]J}K!$K$h$j%7%'!<%G%#%s%0=hM}$r9T$&!#0J2<!"<g$J=hM}$N Cf$K;k@~$N7W;;$H%T%/%;%kCM$N7W;;$*$h$S%7%'!<%G%#%s%0=hM}<jK!$K$D$$$F@b L@$9$k!#




?^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@~$N@8@.$OCDj5A$5$l$?;kE@!"%9%/%j!<%s$J$I$N%Q%i%a!<%?$K$h$j7W;;$9$k$3$H$,$G$-$k!#6qBNE*$J7W;;J}K!$O<!$NDL$j$G$"$k[5]!#;HMQ$5$l$k3F<o%Q%i%a!<%?rI=3.1$KDj5A$7!"$=$l$i$N0LCV4X78$r?^3.2$K<($9!#

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

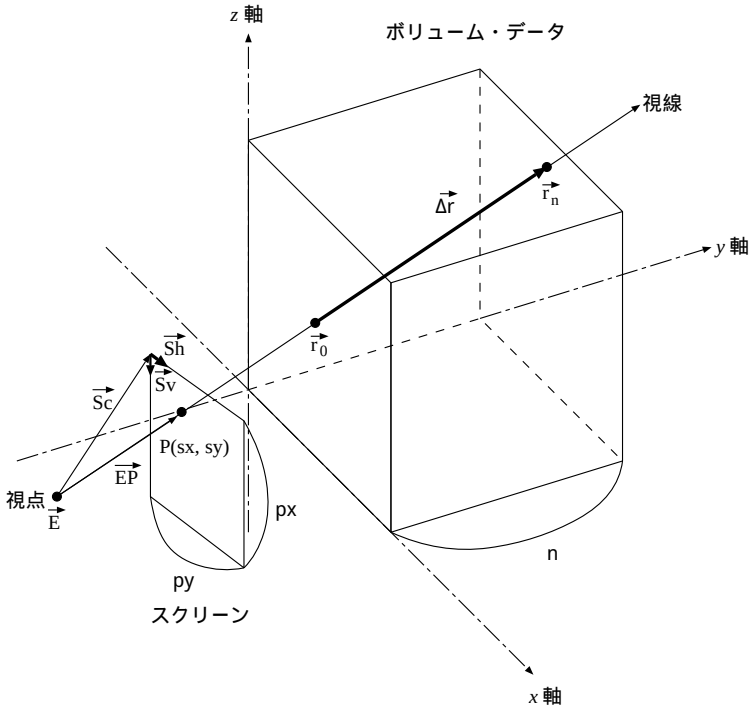
%\%j%e!<%`%G!<%?$O0lJU$KN 8D$N%\%/%;%kCM$+$i$J$kJ}BN$GI=$5$l$F$$$k$b$N$H$9$k!#$3$3$G,%\%j%e!<%`!&G!<%?$,N%;6%b%G%k$N>l9g$K$O,$v(x,y,z)$O,6u4V:BI8$(x+0.5,y+0.5,z+0.5)$G$N%G!<%?$NB0@-CM!#\%/%;%kCM!K$G$"$k$H$9$k!#O"B3%b%G%k$N>l9g$K$O,$v(x,y,z)$O,6u4V:BI8$(x,y,z)$G$N%G!<%?$NB0@-

I=3.1: %\%j%e!<%`!&l%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† | — |
| $c(v)$ | %\%/%;%kCM$v$KBP1~$9$k%\%/%;%k$N?′ | (R, G, B) |
| $\alpha(v)$ | %\%/%;%kCM$v$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 | $(Ex,Ey,Ez)$ |
| $\vec{Sc}$ | ;kE@$+$i%9%/%j!<%s$N:8>eC<$X$N%Y%/%H%k | $(Scx,Scy,Scz)$ |
| $\vec{Sh}$ | 2hLL>e$Nx J}8~1%T%/%;%kJ,$NJ}8~%Y%/%H%k | $(Shx,Shy,Shz)$ |
| $\vec{Sv}$ | 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% | — |
| $\Delta d$ | 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}

CM$G$"$k$H$9$k!#3F%\%/%;%kCM$KBP1~$7$F,%^%9%/!&U%i%0$m(x,y,z) $,Dj5A$5$l$k!#$3$N%U%i%0$O,BP1~$9$k%\%/%;%k$,M-8z$+L58z$+$r<($9%S%C%H$G$"$j!"1$N;~$OM-8z$H$J$k$,!"0$N;~$OF)L@$J%\%/%;%k$HG'<1$9$k!#%\%/%;%k$N?'c(v) $*$h$SF)L@EYα(v) $O!"FI$_=P$7$?%\%/%;%kCMv_i$r,H$C$FB0@-%F!<%V%k$r,2>H$9$k$3$H$K$h$j5a$a$i$l$k!#$3$N%F!<%V%k,2>H$O!"0J2<$N2DL$j$N$&A$$:$l$+$G9T$o$l$k!#

- D>@\:%\%/%;%kCM$rD>@\%$%s%G%C%/%9$H$7$F!"B0@-%F!<%V%k$r,2>H$9$k!#K\8&5f$G$O3$l$r,HMQ$9$k!#
- :9J,:NY@\%\%/%;%kCM$H$N:9J,$r%$%s%G%C%/%9$H$7$F!"B0@-%F!<%V%k$r,2>H$9$k!#

%9%/%j!<%s$O!"xJ}8~$Kpx 8D!"yJ}8~$Kpy 8D$N%T%/%;%k$r,}$D$b$N$H$9$k!#%9%/%j!<%s>e$N3F%T%/%;%k$KBP$7$F!"%T%/%;%kCMP(sx,sy) $,Dj5A$5$l$k!#$3$3G%T%/%;%kCM$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$9k@hF,$NF)L@$G$J$$%\%/%;%k$H%9%/%j!<%s$N5wN%$rI=$9!#$3$3G!"$3$N$h$&%\%/%;%k,B8:_$7$J$>l9g$K$O!"CMDMAX $,BeF~$5$l$k!#$^$?!"FVC

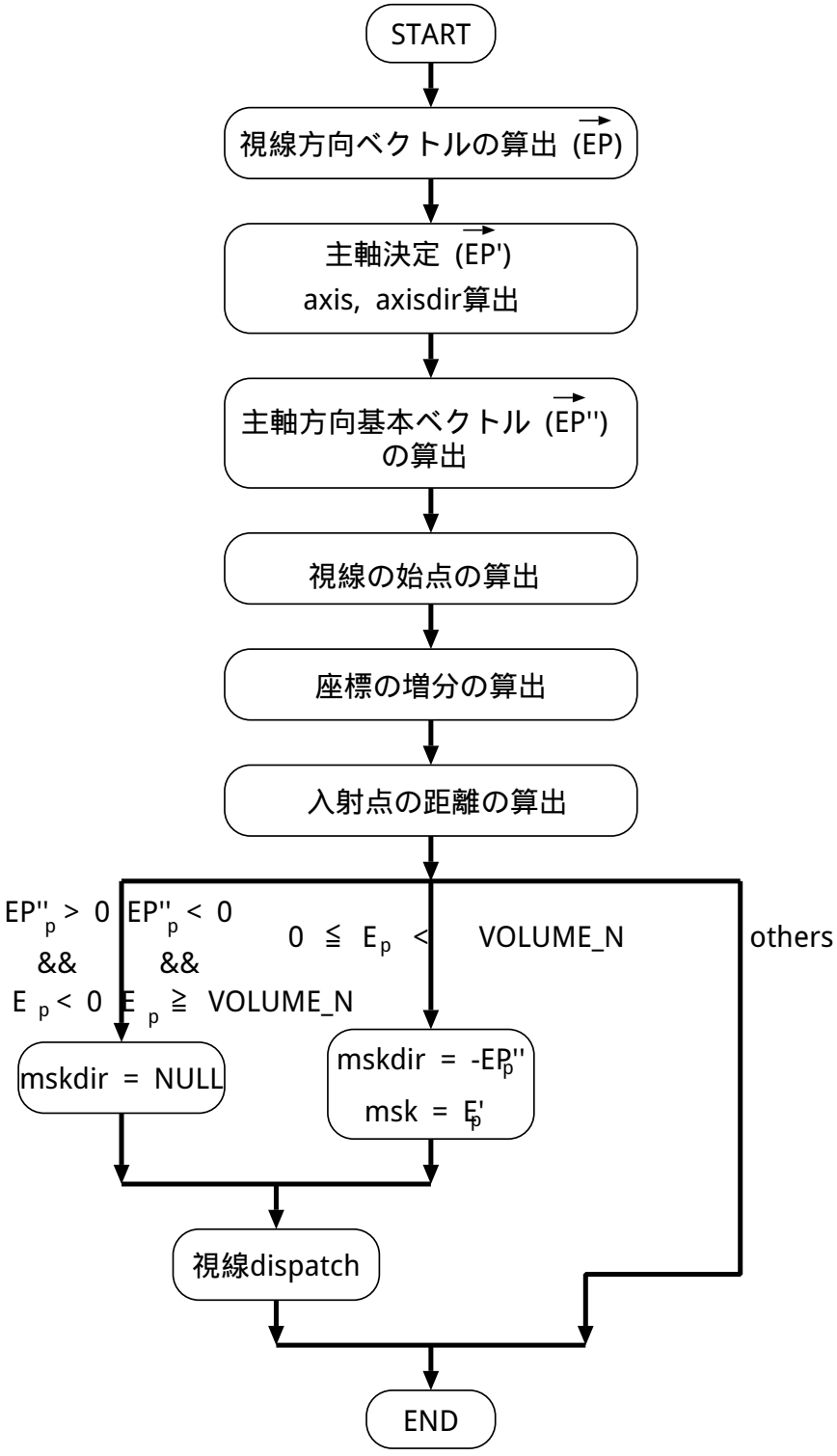
$O!"$3$N%\%/%;%k$N%\%/%;%kCM$G$"$k!#6u4VFb$K;kE@$\vec{E}$,Dj5A$5$l!"$3$NE@$+$i%9%/%j!<%s$rDL$7$F%\%j%e!<%'$r4Q;!$9$k!#%9%/%j!<%s$NA4$F$N%T%/%;%k$N6u4V:BI8$K$*$1$k0LCV$O!"6u4V:BI8$K$*$1$k;kE@$+$i%9%/%j!<%s:8>eC<$X$N%Y%/%H%k$\vec{S}c$!"$x$J}8~1%T%/%;%kJ,$NJ}8~%Y%/%H%k$\vec{S}h$!"$yJ}8~1%T%/%;%kJ,$NJ}8~%Y%/%H%k$\vec{S}v$$K$h$C$FI=$5$l$k!#$3$l$i$K$h$j!"$"$k%T%/%;%k$P(sx,sy)$r=hM}Cf$G$"$k;~!";k@~$NJ}8~%Y%/%H%k$\vec{EP}$O<0

$$\vec{EP} = \vec{Sc} + sx\vec{Sh} + sy\vec{Sv} \tag{3.1}$$

$K$h$j$H7W;;$5$l$k!#

$3$3$G!"I=3.1$K<($9$h$&$K!"axis $O!"<g<4<1JL;R$G$"$j!"<g<4$,x<4!"y<4$*$h$Sz<4$N;~$K!"$=$l$>$l00!"01!"10 $NCM$r$H$k!#$^$?!"axisdir $O!";k@~$NJ}8~$,<g<4@5J}8~$*$h$SIiJ}8~$G$"$k$3$H$r=$l$>$l1 $*$h$S-1 $NCM$K$h$C$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:_$9$k;~$K";kE@$N8eJ}$NA4%\%/%;%k$,%T%/%;%kCM$K1F6A$rM?$($J$$$h$&$K,$3$l$i$N%\%/%;%k$rF)L@$K$9$k$3$H$,$G$-$k!#;k@~@8@.$N%"%k%4%j%:%'$O!"0J2<$N$h$&$K$J$k!#(?^3.3!K

1. ;k@~%Y%/%H%k$N;=P:
   ;k@~%Y%/%H%k$r,$\vec{Sc}$,$\vec{Sh}$,$\vec{Sv}$,$\vec{P}$$r;H$C$F5a$a$k!#
2. <g<4$N7hDj:
   <g<4$H$O!";=P$7$?;k@~%Y%/%H%k$\vec{EP}$$N@.J,$NCf$G$(EPx,EPy,EPz)$$N@dBPCM$,:GBg$N$b$N$,<g<4$\vec{EP}'$J$k:BI8J}8~$G$"$j!#<g<4J}8~$N@.J,$r!J$EP'_x,EP'_y,EP'_z)$$H$7$F@_Dj$9$k!#
3. <g<4J}8~4pK\%Y%/%H%k$N;=P:
   <g<4J}8~4pK\%Y%/%H%k$\vec{EP}''$O<g<4:BI8$NA}J,$,$\pm 1$$H$J$k%Y%/%H%k$G$"$k!#$3$l$O,$\vec{EP}'$r$|EP'_p|$$G3d$k$3$H$K$h$j5a$a$i$l$k.<g<4J}8~$N@.J,$O;kE@$N:BI8$\vec{E}$,JQ$o$k$HJB$Y49$($k!#
4. ;k@~J}8~$N7hDj:
   ;k@~$NJ}8~$r<g<4J}8~%Y%/%H%k$N@5J}8~#1$NCM$HIiJ}8~$-1$NCM$GHD$j$7$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
&&
Ep < 0
EP''p < 0
&&
Ep ≧ VOLUME_N
0 ≦ Ep < VOLUME_N
others
mskdir = NULL
mskdir = -EP''p
msk = Ep'
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]!#

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

$?$@$7!"$c(v_i), \alpha(v_i)$ $O$=$l$>$l%\%/%;%kCM$v_i$r?'!"F)L@EY$KJQ49$7$?CM$G$"$k$3$H$r<($7$F$$$k!#%5%s%W%j%s%0$9$k%\%/%;%k?t$,$N$N>l9g!"<0(2.4) $K$h$C$F5a$a$i$l$k%T%/%;%kCM$O<0(3.2) $N$C_N$HF10l$NCM$H$J$k!#$D$^$j$C_N$r5a$a$k$3$H$K$h$G$F!"%T%/%;%kCM$r5a$a$k$3$H$,=PMh$k!#<0(3.2) $N$C_k, A_{k-1}$ $O$C_{k-1}, A_{k-1}, c(v_k), \alpha(v_k)$ $+$i5a$a$k$3$H$,$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$+$i5a$a$k$3$H$,$G$-$k!#

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

$=$3$G!"%Q%$%W%i%$%s$NC1J}8~2=$N$?$a!">o$K=hM}$NJ}8~$r@5$H$9$k$3$H$r!"<!$N$h$&$K7$F<B8=$7$?!#<0(2.4) $r<0(3.3) $KJQ7A$9$k!#

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

$h$G$F!";k@~J}8~$,Ii$N>l9g$Ki HV$N%\%/%;%k$K<0(3.3) $NC'_{N-i}$ $N7W;;$r9T$o$;$k$H!"%\%j%e!<%`!&G!<%?$,$N$3voxel$H$9$k$H!"0, 1, \cdots, N HV$N%\%/%;%k$N=g$G=hM}$,9T$($k!#

0J>e$h$j!";k@~J}8~$,@5$N;~$O<0(3.2) $r7W;;$7!";k@~J}8~$,Ii$N;~$O<0(3.3) $r7W;;$9$k$3$H$G!">o$K=hM}$NJ}8~$rC1J}8~$H$9$k$3$H$,2DG=$G$"$k!#

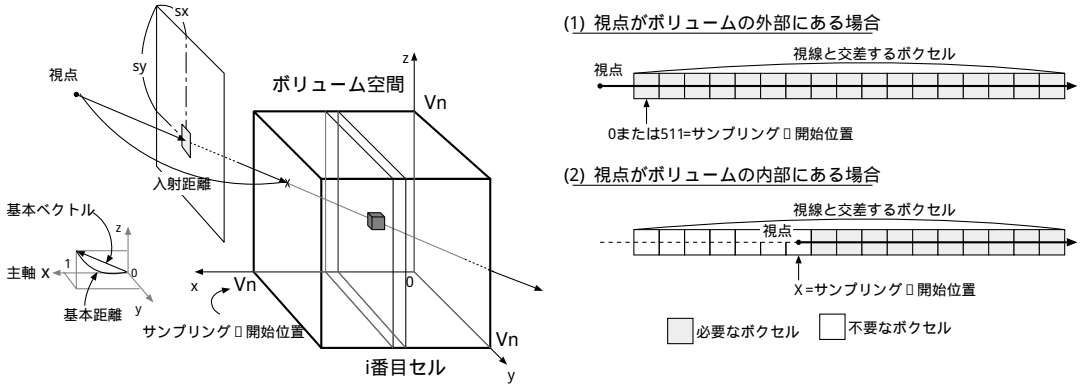
%T%/%;%kCM$N7W;;$O0J2<$N<j=g$G9T$o$l$k!#

1. ;k@~@8@.%"%k%4%j:%`$K$h$j;k@~$r@8@.$9$k!#
2. <!$N<0$K$h$C$F"i HVL\$(1 \le i \le N)$ %5%s%W%j%s%0$9$k%\%/%;%k$N%"%I%l%9$r7W;;$9$k!#<03.4F~<ME@:BI8$O?^3.4$K<($9$h$&$K!"Nc$($P<g<4$,$X<4$N>l9g!"J?LL$X = 0$ $H;k@~$H$N8rE@$N:BI8$G$"$k!#4pK\%Y%/%H%k$O;k@~%Y%/

%H%k$N<g<4@.J,$r#1$H$7$?;~$N;k@~%Y%/%H%k$G$"$k!#

$$F\sim<ME@+4pK\%Y%/%H%k\times i \tag{3.4}$$

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}$G$O!"8w8;>pJs$rMQ$$$F@8@.2hA|$N51EY$rJd@5$9$k$3$H$K$h$j!"2hA|$K8=<B46$r;}$?$;$k!#%\%j%e!<%'%l%s%@%j%s%0K!$K$*$$F$O!"%\%j%e!<%'%G!<%?$,85$N%G!<%?$rN%;6:BI8$G$N%\%/%;%kCM$K$h$C$FI=$7$?$b$N$G$"$k$?$a!";k@~$HJ*BN$N8rE@$K$*$1$kJ*BN$NK!@~$r6a;w$K$h$C$F5a$a$kI,MW$+$"$k!#

=>Mh!"depth gradient shading K!$,$h$/:NMQ$5$l$F$$$k!#3$NJ}K!$O!"%\%j%e!<%'%G!<%?$r2hLL$KEj1F$7?$H$-$K!"3F%T%/%;%kKh$K%T%/%;%kCM$HZ CM$r5-21$7$F$*$-!"3F;k@~$HJ*BN$N8rE@$K$*$1$kK!@~$O!";k@~$rDL$k%T%/%;%k$K$*$1$kZ CM$Hx!"y J}8~$KNY@\$9$k?t%T%/%;%k$NZ CM$H4X78$K$h$j6a;w$9$kJ}K!$G$"$k!#

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

;k@~$N7W;;ItJ,$G:n@.$5$l$?F~<M5wN%!";k@~$H3F%\%/%;%k$N8rE@:BI8$*$h$S4pK\5wN%$rMQ$$$F!"<0(3.5)$K$h$jdepth CM$r7W;;$7!"?<5%P%C%U%!!(Bdepth buffer!K$K3JG<$9$k!#

$$depth = F\sim<M5wN%!'\8rE@\times 4pK\5wN% \tag{3.5}$$

<!$K3F%T%/%;%k$N51EY$r5a$a$k!#6qBNE*$K$O$"$kP $K$*$1$kK!@~%Y%/%H%k$r5a$a$k>l9g!"X $HY $NN>J}8~$K$D$$$F;HMQ$9$k%T%/%;%k$NHO0O$r7h$a!"<P@~6u4V$NN>C<%T%/%;%k$N?<$5CMD !x,y) $r<h$j=P$7!"<0(3.6)[15] $K$h$j$3$NCM$N:9$H:BI8$N:9$r;H$G$F8{G[$r6a;w$9$k!#

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

5a$a$i$l$?CM$X_{min}, X_{max}, Y_{main}, Y_{max}$K$$$F!"<0(3.7) $K$h$j!"P $K$*$1$kK!@~%Y%/%H%k$r$\vec{v}_x = (P_x, 0, d_x)$ $H$\vec{v}_y = (0, P_y, d_x)$ $N30@Q!"$9$J$o$A$\vec{N}_p = \vec{v}_x \times \vec{v}_y = (-p_y!d_x, -p_x!d_y, p_x!p_y)$ $H$9$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$7!":G=*F@$i$l$?2hA|$rCRT $X=PNO$9$k!#

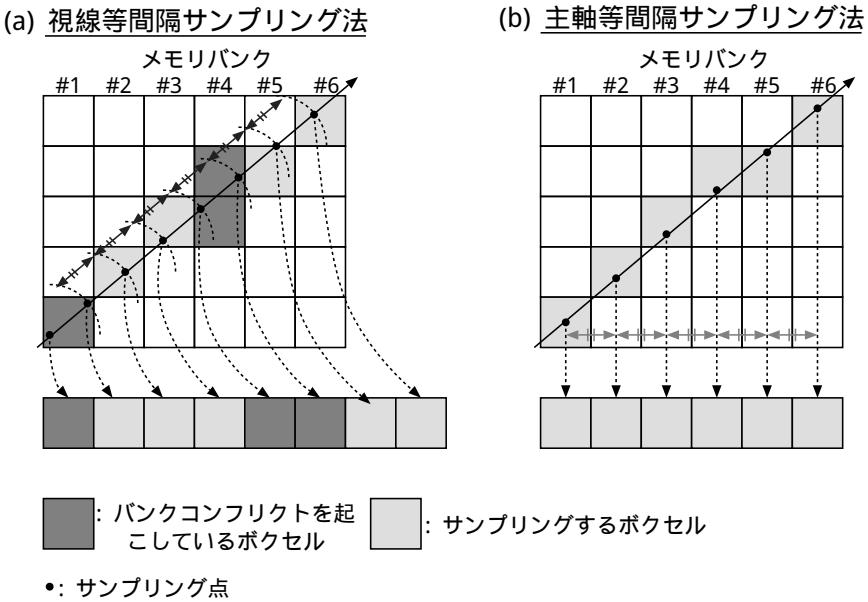
%\%j%e!<%`%l%s%@%j%s%0$O!";k@~@8@.=hM}!"%T%/%;%kCM=hM}$H%7%'!<%G%#%s%0=hM}$*$h$S2hA|$N=PNO=hM}$H$$$&9=@.$r$H$k$3$H$K$h$G$F!"FbIt=hM}$NFHN)@-$,9b$^$j!"JBNs7W;;5!$G<BAu$9$k$3$H$,2DG=$K$J$k!#$3$N7k2L9bB.2=$,F@$i$l$k$3$H$,M=A[$5$l$k!#

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

K\8&5f$K$*$1$k#1$D$NL\I8$O;kE@JQ99$,$G$-!"G$0UJ}8~$KH/@8$9$k;k@~$KBP$7$F2hA|$r@8@.$G$-$k$3$H$G$"$k!#$=$N$?$a$K!"%G!<%?J,3dK!$NA*Br$,=EMW$G$"$k!#K\8&5f$G$O!"%\%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$N%\%j%e!<%`%l%s%@%j%s%0$G$O;k@~>e$N%\%/%;%kCM$N%5%s%W%j%s%0$K$OFs$D$NJ}<0$,$"$k[16][17]!#

- ;k@~Ey4V3V%\%/%;%k%5%s%W%j%s%0J}K!:;k@~J}8~$K1h$G$FEy4V3V$K%5%s%W%j%s%0$r9T$&$h$&$K$9$k!#

- <g<4Ey4V3V%5%s%W%j%s%0J}K!!';k@~%Y%/%H%k$N3 $D$N@.J,(x,y,z @.J,) $N @dBPCM$rHf3S$7!":GBgCM$N@.J,$N:BI8<4$r<g<4$HDj$a!"$3$N<g<4J}8~$KBP $7$F;k@~>e$N%\%/%;%k$rEy4V3V%5%s%W%j%s%0$r9T$&$h$&$K$9$k!#



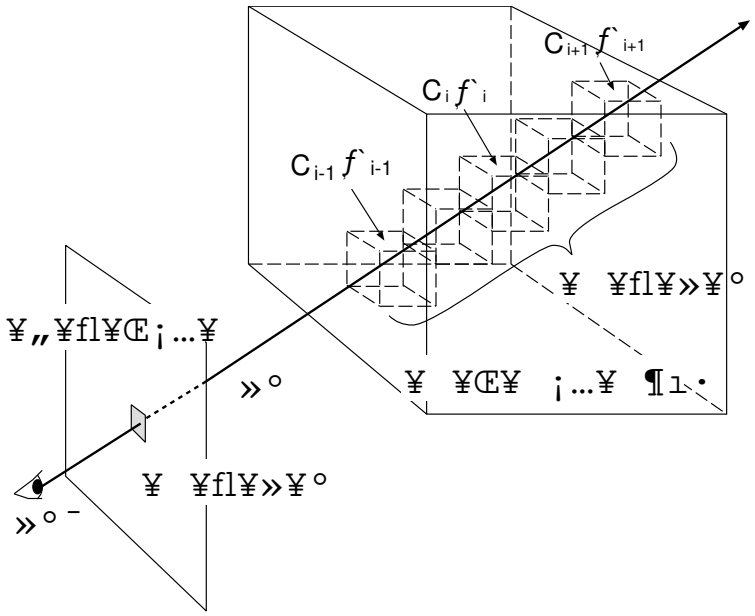

?^3.5: %5%s%W%j%s%0K!

;k@~Ey4V3V%5%s%W%j%s%0$O!"%\%/%;%kJBNs=hM};~$K!"%\%j%e!<%'%G!<%?$r%a %b%j%P%s%/$KJ,3d$7$F3JG<$9$k$H!"F10l;k@~>e$NJ#?t$N%\%/%;%k$,F10l%a%b%j %P%s%/$K3JG<$5$l$F$$k>u67$,H/@8$9$k$3$H$,$"$j!"JBNs<B9T$N9bB.2=$N>c32 $K$J$k!#(?^3.5)

$3$l$KBP$7$F!"<g<4Ey4V3V%5%s%W%j%s%0J}K!$r:NMQ$7!"%P%s%/%3%s%U%j%/%H $rKI$0$?$a$K!"%P%s%/%3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$,Ds0F$5$l$?!#

6qBNE*$K$O!"?^3.6$K<($9$h$&$K!"%\%j%e!<%'%6u4V$N1JU$N%\%/%;%k?t$rN $H$7$F!"%\%j%e!<%'%6u4V$rx,y,z<4$K?bD>$JN 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<$9$k!#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<$5$l$k!#

$3$N9=@.$K$h$j!"3FJ?LL72$NJ?LL$O$9$Y$F0[$J$C$?%a%b%j%P%s%/$K3JG<$5$l $k$N$G!"<g<4Ey4V3V%5%s%W%j%s%0$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&5f$G$O!"J,;6%a%b%j7?JBNs7W;;5!$N>e$GJBNs2=$9$k$3$H$,L\E*$G$"$k!#%\%j%e!<%'%G!<%?$,>.$5$>l9g$O!"%G!<%?$rJ,3d$;$:3FJ,;6%a%b%j$KF1$8%G!<%?$r3JG<$9$l$P!";k@~Ey4V3V%\%/%;%k%s%W%j%s%0K!$r:NMQ$9$k$H!"%T%/%;%kCM7W;;$NJBNs2=$,$G$-$k!#$7$+$7!"%\%j%e!<%'%G!<%?$,Bg$-$$>l9g$O!"%G!<%?$rJ,3d$9$kI,MW$,$"$k$N$G!"F10l;k@~>e$NJ#?t$N%\%/%;%k,F10l%W%m%;%C%5%a%b%j$K3JG<$5$l$k>u67$,H/@8$9$k2DG=@-$,$"$k!#

$3$3$GK\8&5f$O!"%\%/%;%kJBNs=hM}$K$h$k%T%/%;%kCM7W;;$N9bB.2=$,L\I8$G$"$k!#$3$N<g<4Ey4V3V%5%s%W%j%s%0K!$r%G!<%?J,3d$K1~MQ$9$k$3$H$K$h$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}$9$k$3$H$,$G$-$k!#<g<4Ey4V3V%5%s%W%j%s%0J}K!$K$h$k!"%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.$r:NMQ$9$k!#

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

# 4 JBNs%"%k%4%j%:% '$H<BAu

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

K\>O$G$O!"$^$:!"%\%j%e!<% '%l%s%@%j%s%0$rJBNs2=$9$k:]$KL\I8$H$9$Y$-;v 9'$K$D$$F=R$Y$k!#B3$$F!"0lHLE*$J%a%b%jJ,;67?JBNs7W;;5!$rBP>]$H$7$?!" JBNs%"%k%4%j%:% '$rDs0F$7!"$5$i$K!"$=$N%"%k%4%j%:% '$NAP1000 $X$N<BAu$K $D$$F=R$Y$k!#

%\%j%e!<% '%l%s%@%j%s%0$O!"=hM}NL$,Hs>o$KBg$-$$N$G!"$h$j9b$$JBNs@-$r F@$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*$JL\I8$K$D$$F=R$Y$k!#

JBNs2=$NL\I8 3.1@a$K=R$Y$?$h$&$K!"K\8&5f$G$O!"9bB.$K%\%j%e!<% '%l%s%@%j %s%0$r<B9T$9$k$?$a!"<!$N$h$&$J4pK\L\I8$r@_Dj$9$k!#

K\<jK!$G$O!"%\%j%e!<% '$rH>F)L@$JJ*BN$H$7$F07$$!"1s6aK!<jK!$H%3%s%U%j%/ %H%U%j!<$J%a%b%j9=B$$K4p$E$/%G!<%?J,3dK!$r:NMQ$9$k!#$^$?!"9bB.$J%\%j%e!< % '%l%s%@%j%s%0$r<B8=$9$k$?$a$K!"9bB.=hM}$9$kMWAG$r9M$($J$1$l$P$J$i$J$$!# J,;6%a%b%j7?JBNs7W;;5!$G$O!"Ii2YJ,;6$,=hM}B.EY$KM?$($k1F6A$,6K$a$FBg$- $$!#$=$7$F!"%W%m%;%C%5$NMxMQN($r9b$a$k%W%m%0%i% '$r:n@.$9$k$?$a$K!"DL?. %l%$%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$H$J$k$3$H$b$"$k!#

$3$l$i$NL\I8$r$=$l$>$l<B8=$9$k$3$H$K$h$C$F!"%\%j%e!<% '%l%s%@%j%s%0K! $rJBNs2=$9$k!#

JBNs2=$N4pK\<jK! %\%j%e!<% '%l%s%@%j%s%0$O!"%l%$!&-%c%9%F%#%s%0K!$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!"$=$l$>$l $,=jM-$9$k%G!<%?$NLi;;$rC4Ev$9$k!#$^$?!";kE@JQ99$r9T$($k$h$&$K9$k$?$a!" %3%s%U%j%/%H%U%j!<$J%a%b%j9=B$$K4p$E$/%G!<%?J,3dK!$rMxMQ$9$k$H!"%\%/%; %kCM$rJBNs$KFI$_=P$72DG=$G$"$k!#

BP>]$r$9$kJBNs4D6- K\%"%k%4%j%:% 'O!"0J2<$NFCD'$r;}$D!#

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

- 8D!9$N%W%m%;%C%54V$N%G!<%?$N<uEC$7$O%a%C%;!<%8$NAw<u?.$K$h$C$F<B8=$5$l$k!#
- Aw?.B&%W%m%;%C%5$+$iAw$i$l$?%a%C%;!<%8$O!"%O!<%I%&%'%"$+OS %l%Y%k$G<u?.B&$N%P%C%U%!$KF~$l$k$3$H$,$G$-$k!#

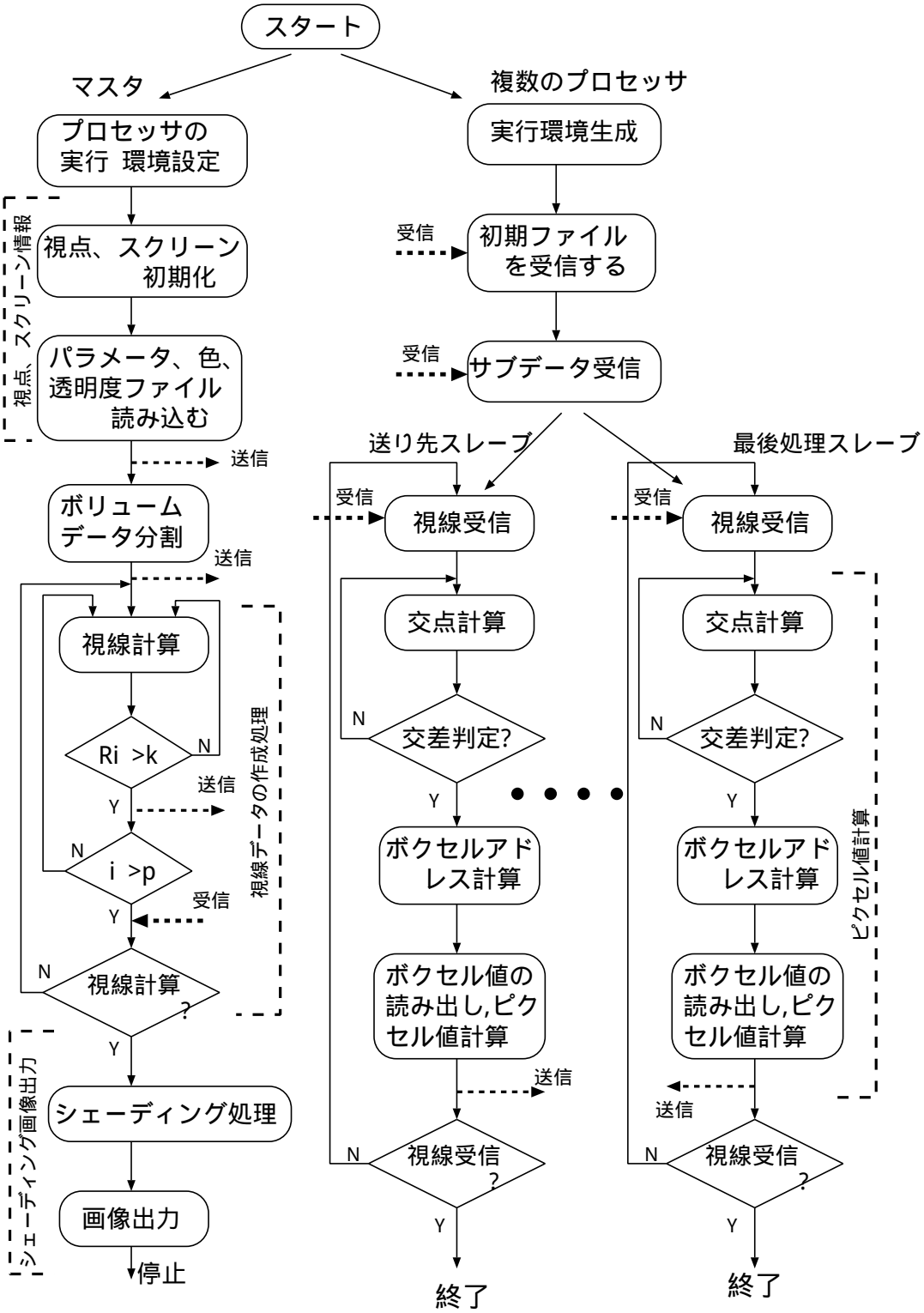
$3$N$h$&$J%7%9%F%'$K$OAP1000 $N$h$&$JJBNs7W;;5!$@$1$G$O$J$/!"$[$\F1Ey$N@-G=$r !GPU!"%G%#%9/!"%a%b%j;q8;!K;}$C$?J#?t$N7W;;5!$,!"8_$$K%M%C%H%o!<%/$G\B3$5$l$?J,;64D6-$b4^$^$l$k!#

### 4.2 JBNs%"%k%4%j%:%'

K\8&5f$GDs0F$9$kJBNs%"%k%4%j%:%'$O!"#1Bf$N%^%9%?7W;;5!$HJ#?t$N%9l!<%V7W;;5!$,F14|!ØL?.$rDL$8$F!"JBNs$K=hM}$r9T$&$b$N$G$"$k!#0J2<!"0lHIE*$J%a%b%jJ,;67?JBNs7W;;5!%7%9%F%'$rBP>]$H$7$?$3$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!"p $O$=$l$>$l;k@~$N%G!<%?t!"%W%m%;%C%5Bf?t$r<($9!#

K\<jK!$G$O!"%^%9%?$H%9l!<%V$G$=$l$>$l0[$J$k%W%m%0%i%'$r<B9T$9$k!#%^%9%?MQ%W%m%0%i%'$O%9l!<%V$N<B9T4D6-@_Dj!"=hM}$N=i4|2=!"%G!<%?$NJ,3d!";k@~$N8@.$H%7%'!<%G%#%s%0=hM}$*$h$S2hA|$N=PNO$J$I$N=hM}$r9T$&!#%9l!<%VMQ%W%m%0%i%'$OB>$N%9l!<%V$d^%9%?7W;;5!$HDL?.$7$J$,$i!"%T%/%;%kCM$rJBNs$K7W;;$9$k!#<g$J=hM}$NN.$l$r%^%9%?$H%9l!<%V$NN>J}$KJ,$1$F@bL@$9$k!#%^%9%?7W;;5!B&$N=hM}!'

1. %9l!<%V$N<B9T4D6-$r@_Dj$9$k!#
2. ;kE@!"%9%/%j!<%s>pJs$N@_Dj!"=hM}Cf$K07$&%Q%i%a!<%?%U%!%$%k!"%\%/%;%kCM!Ø'!"F)L@EY!K"B0@-%F!<%V%k%U%!%$%k$rFI$_9~$_!"A4%9l!<%V$KAw?.$9$k!#
3. %\%j%e!<%'!&G!<%?$N%U%!%$%k$rFI$_9~$_!"%G!<%?$NJ,3d$r9T$&!#J,3d$5$l$?%G!<%?$r8D!9$N%9l!<%V$X=gHV$KAw?.$9$k!#
4. ;k@~%G!<%?$N:n@.=hM}$r9T$&!#%9%/%j!<%s%:$K$h$k!"3.3.1@a$K=R$Y$?;k@~@8@.J}K!$rMQ$$F!"7+$jUV$7$F;k@~%G!<%?$r7Aw$j@h$N%9l!<%V$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$N%9l!<%V$+$iAw$i$l$?%T%/%;%kCM$r<u?.$9$k!#$^$?!";k@~%G!<%?rAw?.=*N;$7$?$H$-$K!"%9l!<%V$+$i%T%/%;%kCM$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?.$5$l$F$-$?;kE@$H%9%/%j!<%s>pJs!"%Q%i%a!<%?%U%!%$%k!"%\%/%;%kCM$*$h$SB0@-%F!<%V%k%U%!%$%k$r<u?.$9$k!#
2. J,3d$5$l$FAw?.$5$l$?$-$?%5%V%\%j%e!<%`!&G!<%?$N<+J,$NC4EvNN0h$r<u?.$7!"%a%b%j$K=q$-9~$`!#
3. %Q%$%W%i%$%sJ}<0$GJBNs$K%T%/%;%kCM$N7W;;$r<B9T$9$k!#(%Q%$%W%i%$%s<jK!$N6qBNE*$J=hM}$O4.4.1@a$G=R$Y$k!K":G=i!"%^%9%?$+$i;XDj$5$l$?%9%l!<%V$OAw$i$l$?;k@~$r<u?.$9$k!#%9%l!<%V$O$=$l$>$l$NC4EvNN0h$rDL2a$7$F$$$l$P!"8rE@H=Dj$K$h$j!"%T%/%;%kCM7W;;$r9T$&!#
4. %T%/%;%kCM$H;k@~$rNY@\%9%l!<%V$KAw?.$9$k!#Aw?.$5$l$?%9%l!<%V$O!"A0$N$b$N$r7W;;=*N;8e!"Aw?.$5$l$?;k@~%G!<%?$H%T%/%;%kCM$r<u?.$9$k!#
5. :G8e$N%9%l!<%V$O!"N_@Q$7$?%T%/%;%kCM$r^%9%?$KAw?.$9$k!#

<!$K!"Ds0F$9$k%"%k%4%j%:%'$NFCD'$*$h$S6qBNE*$JJBNs2=<jK!$K$D$$F=R$Y$k!#

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$-$$$?a!"3F%W%m%;%C%5$KBP$7$F%\%j%e!<%'%G!<%?$,J,;6$5$l$F$$k$3$H$,A0Ds$H$J$k!#K\8&5f$K$D$$F!"%3%s%U%j%/%H%U%j!<$J%a%b%j9=@.$K4p$E$-%G!<%?J,3dK!$r:NMQ$9$k$?a!"%G!<%?J,3d$OX!"Y!"Z<4$N;0J}8~$KEyJ,%9%i%$%9$GJ,3d$7!"3F%W%m%;%C%5(%W%m%;%C%5?tP $H$9$k)$N%a%b%j$K3d$jEv$F$k!#%T%/%;%kCM7W;;$r%Q%$%W%i%$%s2=$7$d$9$$$h$&$K!"%W%m%;%C%59=@.$r0l<!85$K$H$k!#$D$^$j3<!85%\%j%e!<%'%G!<%?!N3$H$9$k!K$r%^%9%?B&$G$=$l$>$l1X!"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!#$9$Y$F$N%W%m%;%C%5$KBP$7$FIi2Y%P%i%s%9$r6Q0l$K$5$;$k$h$&$K3d$jEv$F$k$3$H$H$9$k!#$3$NJ,3d$r:NMQ$9$k$H!";k@~$=$l$>$l$N%C3F%W%m%;%C%5$K1h$C$F3d$jEv$F$i$l!"FCDj%W%m%;%C%5$X$N;k@~$N=8CfEy$r$"$kDxEY8:>/$5$;$k8z2L$,4|BT$G$-$k!#%T%/%;%kCM7W;;$N%Q%$%W%i%$%s2=$K$h$j%^%9%?$+$i=gHV$KAw$i$l$F/$k;k@~>pJsEy$r8D!9$N%W%m%;%C%5$G=gHV$K=hM}$,$G$-$k!#

$N^3$8D$N%G!<%?$K4X$7$FJ,3d$,;\$5$l$?;~!"3F%W%m%;%C%5$,=jM-$9$k%m!<%+

%k$J%G!<%?LOCAL_CELL($Vn_i$) $O<!$N<0$GM?$(B($i$l$k!#

$$
\begin{aligned}
&\mathrm{LOCAL\_CELL}(i \text{ HV\%W\%m\%;\%C\%5\$,;}\}\$D\%5\%V\%\backslash\%j\%e!<\%\text{`}\%G!<\%?) \\
&= (N_x \times N_y) \times (\frac{N_z}{P}) \\
&\quad + (N_x \times N_z) \times (\frac{N_y}{P}) \\
&\quad + (N_y \times N_z) \times (\frac{N_x}{P}) \\
&= \frac{3N^3}{P}
\end{aligned}
$$

2. 3F%W%m%;%C%5$X$N3d$jIU$1

%\%j%e!<%`!&G!<%?$rJ,;6$5$;$k:]!"%G!<%?$,Bg$-$$$N$G!"%U%!%$%k$+$i%^%9%?$KFI$_9~$`$H%a%b%jIB-$,5/$3$kLdBj$,$"$k!#$3$3$G!"%G!<%?$NJ,;6$,9T$o$l$k>l9g!"%^%9%?$O3<4J}8~$K%\%j%e!<%`G!<%?$rJ,3d$7!"9TNs$N%V%m%C%/9=B$$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$-$5$HDL?.2s?t$O!"DL?.;~4V$KB?Bg$J1F6A$r5Z$\$9!#Nc$(B$P!"0l3g$7$FE>Aw$9$k>l9g$KBP$7!"%5%V%\%j%e!<%`!&G!<%?$NE>Aw%V%m%C%/$N%5%$%:$,>.$5$/$J$k$[$I!"%^%9%?$NI,MW$J%a%b%j$O>/$J$/$J$k$,!"DL?.2s?t$OA}2C$7!"B.EY$,Dc2<$9$k!#0J2<!"%G!<%?E>Aw$N4v$D$+$NJ}K!$K$D$$F$r8!F$$9$k!#

(a) $J$k$Y$/DL?.2s?t$N8:$i$9$3$H$r9M$(B$k$H!"J,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$K$D$$F!"3<4J}8~$N%G!<%?3 8D$r$^$H$a$F1 %V%m%C%/$GAw?.$9$l$P!"DL?.2s?t$O%W%m%;%C%5?tP $KEy$7$/$J$k!#$?$@$7!"%^%9%?$NI,MW$J%a%b%j$O3 $\times$ $\frac{N}{P}$ $\times$ $N$ $\times$ $N$ $G$"$k!#

(b) %\%j%e!<%`G!<%?$,Bg$-$/!"(a)$,$G$-$J$$>l9g$O!"3 8D$N%G!<%?$r=$l$>$lAw?.$9$k!#DL?.2s?t$O3P $G!"%^%9%?$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<!851%U%l!<%`H9M$(BFAw?.$9$l$P!"DL?.2s?t$O3N $G!"%^%9%?$NI,MW$J%a%b%j$O$N^2$G$"$k!#

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

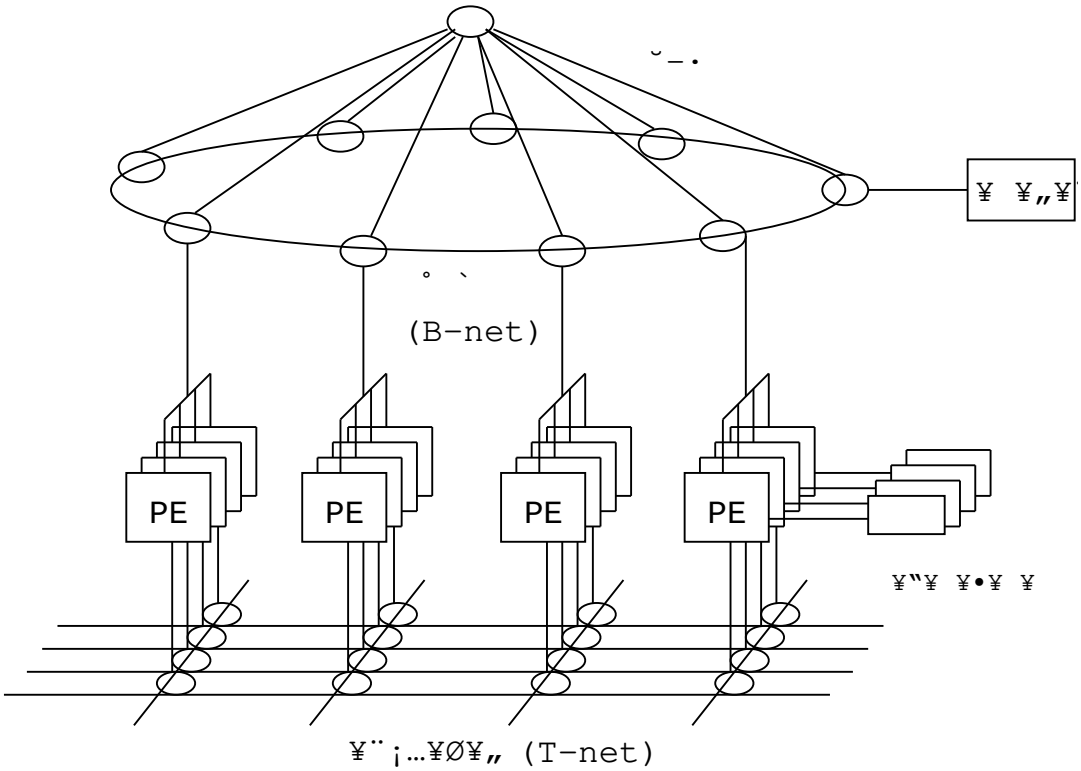
%?$r:FU,3d$7!#DL?.2s?t$O3$N^2$G!"%^%9%?$NI,MW$J%a%b%j$ON $G$"$k!#
N 8D$NMWAG$r;}$D1<!85G[NsKh$K%G!<%?$rAw?.$9$k!#

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

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

#### 4.3.1 AP1000 $N9=@.$*$h$SDL?.@-G=

K\8&5f$G$O!"16Bf$+$i1024Bf$^$G@\B32DG=$NJ,;6%a%b%j7?JBNs7W;;5!AP1000[12] >e$K<BAu$r9T$C$?!#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!MISC!K$,MQ0U$5$l$F$$k!#AP1000 $N9=B$$r?^4.2$K<($9!#




?^4.2: AP1000 $N9=B$

- T-net:3F%W%m%;%C%54V$N#1BP#1DL?.$K;HMQ$9$k$O2<!85%H!<%i%9LV$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$$$F:n@.$9$k!#DL?.$dF14|$J$I$NJBNs=hM}$r9T$&>l9g!"%M%C%H%o!<%/9=@.$r0U<1$7$?5-=R$,$G$-$k$h$&$K!"MM!9$J%i%$%V%i%j$,MQ0U$5$l$F$$$k!#AP1000 $G$O!"<B9T%W%m%0%i%`$O%^%9%? !0JJ2<!"%[%9%H$H8F$V!K7W;;5!MQ$HJ#?t$N%W%m%;%C%5 !0JJ2<!"%;%k$H8F$V!KMQ$N2<oN`$,I,MW$G$"$k!#$=$l$>$l$NLr3d$O<!$NDL$j$G$"$k!#

- %[%9%H%W%m%0%i%`$O%;%k$N<B9T4D6-$N@_Dj!"%;%k$G<B9T$5$l$k%?%9%/$N@8@.!"%;%k$X$N%a%C%;!<%8Aw?.!"%;%k$+$i$N%a%C%;!<%8<u?.!"%;%k$N>uBV4F;k$J$I$r9T$&!#
- %;%k%W%m%0%i%`$O3F%;%k>e$GJBNs<B9T$5$l!"L\E*$H$9$k7W;;$rJBNs$K=hM}$9$k!#

### 4.3.2 <BAu<jK!

K\@a$G$O!"Ds0F$9$kJBNs2=%"%k%4%j%:%`$rAP1000 $G<BAu$9$kJ}K!$K$D$$$F=R$Y$k!#?^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, !!&&&) $O%;%k$NHV9f$G$"$k!#

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

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

1. %;%k$N<B9T4D6-$r@_Dj$9$k!#%Q%$%W%i%$%sJ}<0$rMQ$$$k$?$a$K!"%;%k$NO@M}9=@.$O1 <!85$H$7!"A4$F$N%;%k$N=i4|2=$r9T$&!#
2. ;kE@!"%9%/%j!<%s>pJs$N@_Dj!"=hM}Cf$K07$&%Q%i%a!<%?%U%!%$%kParafile()!"%\%/%;%kCM!?J'Colorfile()!"F)L@EYTransfile()!K$NB0@-%F!<%V%k%U%!%$%k$rFI$_9~$_!"A4%;%k$K%V%m!<%I%-%c%9%H$9$k!#
3. %\%j%e!<%`!&G!<%?%U%!%$%kVolumefile() $+$i!"%G!<%?$NJ,;6$r9T$&!#J,;6$5$l$?%G!<%?$r8D!9$N%;%k$X=gHV$KAw?.$9$k!#K\<BAu$G!"MQ$$$?%\%j%e!<%`!&G!<%?%5%$%:$,Bg$-$$>l9g$O!"4.2@a$G=R$Y$?(c) $NJ}K!$r:NMQ$7$?!#$^$?!"E>AwNL$KBP$7DL?.B.EY$N1F6A$r5.1@a$G(c) $H !dJ) $NN>J}J}<0$K$D$$$FB,Dj$7$?!#
4. %9%/%j!<%s%5%$%:$NBg$-$5$K$h$j for %k!<%W$G;k@~$H<g<4$r7W;;$9$k!#$3$3$G8zN($N$h$$JBNs2=$r$9$k$?$a!"4v$D$+$N2~NIJ}K!$rMQ$$$F<BAu$r9T$&!#
   - ;k@~%G!<%?$O%[%9%H$+$i%;%k$N0 HV$XAw?.$7!"3F%;%k$G$N%Q%$%W%i%$%sJ}<0$G<B9T$9$k!#;k@~%G!<%?$H%T%/%;%kCM$NDL?.2s?t$r8:$i$9$?$a

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

- $^$?!"8zN($h$/JBNs2=$9$k$?$a! "$3$N9=B$BN$rk 8D$N9=B$BNG[Ns$H$9$k!#
- $5$i$K! "DL?.;~4V$r1#JC$9$k$?$a! "; k@~%G! <%?$H%T%/%;%kCM$,8_$$$K 0MB8$7$J$$$N$G! ">e5-$Nmes_pixel 9=B$BN$KBP$7!"; k@~%G! <%?$H%T%/ %;%kCM$r$=$l$>$l$N9=B$BN$H$9$k!#!4J.4.3@a$G6qBNE*$K=R$Y$k!K

$3$l$i$N<BAuJ}K!$K$D$$$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$Gn !<#1HVL\$N%;%k$+$iAw$i$l$?%T%/%;%kCM$r<u?.$9$k!# $^$?!"%Q%$%W%i%$%sJ}<0$K$h$j;k@~%G! <%?$rAw?.=*N;$H$-$K! ":G8e0l2s$N %k!<%W$G%;%k$NCf$K;D$G$?%T%/%;%kCM$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!#

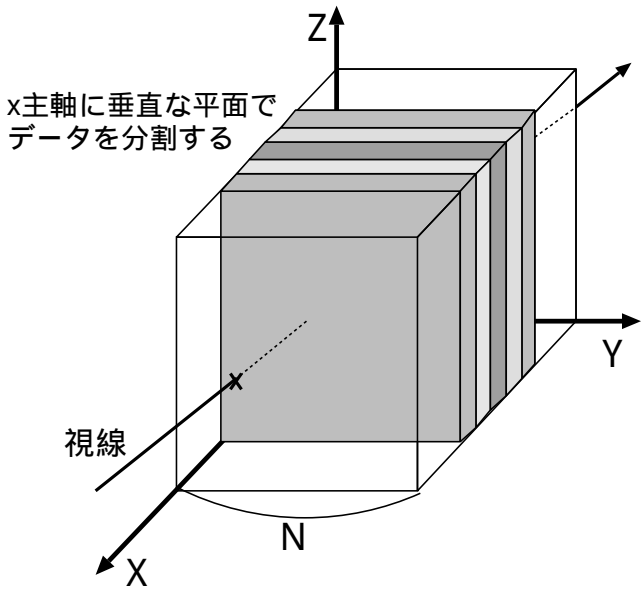
%;%kB&$N=hM}: 6qBNE*$J<j=g$O4.2@a$G=R$Y$?$h$&$K! "8D!9$N%;%k$O%Q%$%W%i%$ %sJ}<0$GJBNs$K%T%/%;%kCM$N7W;;$r<B9T$9$k!#

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$, $G$-$k!#K\<BAu$G$O! "%Q%$%W%i%$%s2=$7$d$9$$?$a! "%W%m%;%C%59=B$ !$X_{cell}$H $9$k!K$,C10lJ}8~$K$H$k!#3F%;%k$N%a%b%j$K3JG<$5$l$?%5%V%\%j%e! <%`!&G! <%?$O$=$l$>$lX! "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?t$K$h$j7h$a$k!#

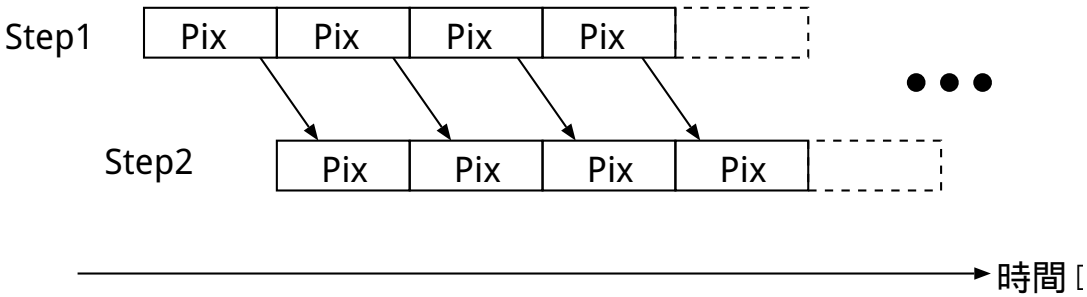
## 4.4 AP1000 $G$N:GE,2=<jK!

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

Bh4.3.2@a$K=R$Y$?$h$&$K! "%\%j%e! <%`%G! <%?$O$9$Y$F$N%W%m%;%C%5$KJ,;6$5 $l$k!#%l%$$!&-%c%9%F%#%s%05;K!$K$h$k%\%/%;%kJBNs=hM}$O;k@~$K1h$C$F;kE@ $K6a$$=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<!$N%W%m%;%C%5$X EO$9!#?^4.4$K<($9$h$&$K%G! <%?E>Aw$H%T%/%;%kCM$N7W;;$O%Q%$%W%i%$%s2=$,2D G=$G$" $j! "3F%W%m%;%C%5$OEv3:%T%/%;%kCM7W;;$9$k;~4V$K<!$N%G! <%?$,E~Ce$9




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




ピクセル値計算　Pix:アドレス計算+メモリアクセス

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

$l$P!"%P%C%U%!%j%s%0$r$9$k$3$H$K$h$j!"%G!<%?E>Aw;~4V$N0lItJ,$r1#JC$9$k$3$H$,$G$-$k!#K\8&5f$G$O!"%\%j%e!<%`%l%s%@%j%s%0$N%\%/%;%kJBNs=hM}$K4p$E$$F%Q%$%W%i%$%sJ}<0$r9T$&!#A0=R$7$?$h$&$K%[%9%HB&$O<B9T=hM}$NA4BN$N>uBV$r4F;k$9$k!#;k@~%G!<%?$r@8@.$7$F%;%k$HDL?.$7$J$,$i!"%T%/%;%kCM$r=gHV$K<}=8$9$k!#$3$3$G!"4.3.2@a$G=R$Y$k$h$&$K!";k@~%G!<%?$H%T%/%;%kCM$O1l$D$N9=B$BNmes_pixel $H$7$F3JG<$9$k!#6qBNE*$J%T%/%;%kCM7W;;$N%Q%$%W%i%$%s$O0J2<$N<j=g$G9T$o$l$k!#!J^4.6!K

1. $^$:!"%[%9%H$G$O!"%9%/%j!<%s%:$K$h$jfor %k!<%W$G;k@~@8@.ItJ,$r9T$&!#@8@.$5$l$?;k@~%G!<%?$O 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$N%W%m%;%C%5$O$9$Y$F<u?.BT$A>uBV$K$J$k!#$O$8$a$K!"0 HV$N%W%m%;%C%5$,!"%[%9%H$+$iAw?.$5$l$?;k@~%G!<%?$r<u$1<h$C$F%P%C%U%!$KF~$l$k!#
3. %W%m%;%C%5$OC4Ev$9$kHOO$N;k@~$H8r:9$9$k%\%/%;%k$N8r:9E@$r7W;;$9$k!#3.3.2@a$GM?$($?<03.4$N;k@~%G!<%?HF~<M5wN%$K$h$j5a$a$k!#Nc$($P!"<g<4$,X<4$N>19g!"J?LLX = 0 $H;k@~$H$N8rE@$N:BI8$G$"$k!#;k@~$Hi HVL\%W%m%;%C%5$N%\%/%;%k8rE@:BI8$Ox_i = i, y_i = y_0 + i\Delta y, z_i = z_0 + i\Delta z$r5a$a!"$\Delta y = \frac{y_n - y_0}{N}_y, \Delta z = \frac{z_n - z_0}{N}_z$K$h$k7W;;$r9$k!#$3$3G!"N_x, N_y, N_z$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 !iJ=0,1, !kk&)!#
4. 7W;;$7$?8r:9E@$,!"3.3.2@a$GM?$($?<03.4$K$h$j%\%/%;%k$N%"%I%l%9 !0CL CV!K$r7W;;$9$k$3$H$,$G$-$k!#Nc$($P!"<g<4X $H$7$F!"%\%j%e!<%\$NCf?4:BI8$OV(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>19g!"%a%b%j$N%"%I%l%9cid = (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$3G!"%\%/%;%k:BI8$,%\%j%e!<%\30$G$"$k$H$-!"$^$?$O!"%\%/%;%k$,%^%9%/$5$l$F$$$k$H$-$K$O!"%\%/%;%kCM$r#0$H$7$F07$&!#
5. 4.$G7W;;$7$?%\%/%;%k%"%I%l%9$K$h$j!"%\%/%;%kCM$rFI$_=P$9!#<02.4$K$h$j%T%/%;%kCM7W;;$r9T$&!#0 HV$N%W%m%;%C%5$O%T%/%;%kCM7W;;$9$kA0$K%T%/%;%kCM$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,$,%;%k#0$@$C$?$i*/
        %[%9%H$+$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$9$kHCOO$N%T%/%;%kCM$r7W;;=*N;8e!"<!$N%W%m%;%C%5$K;k@~%G!<%?$H%T%/%;%kCM$rEO$9!#HV$N%W%m%;%C%5$O<u?.>uBV$K$J$C$?$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_@Q$7$?%T%/%;%kCM$r%[%9%H$KE>Aw$9$k!#

### 4.4.2 DL?.2s?t$NDc8:

%a%C%;!<%88r497?JBNs7W;;5!$G$ODL?.=hM}2s?t$r8:$i$9$3$H$,=EMW$G$"$k!#C;$$%a%C%;!<%8$r$?$/$5$sDL?.$9$k$H!"=hM}%3%9%H$,Hs>o$KBg$-$/$J$k!#$3$3$G!"Aw?.%G!<%? !JJ,3d$5$l$?%5%V%\%j%e!<%`%G!<%?!";k@~%G!<%?!"%T%/%;%kCM$J$I!K$r!"$J$k$Y$/$^$H$a$F#1$D$ND9$$%a%C%;!<%8$H$7$FAw?.$9$l$P!"DL?.=hM}$N2s?t$r8:$i$9$3$H$,$G$-$k!#8zN($N$h$DL?.=hM}$r<B8=$9$k$?$a$K!"K\8&5f$G$O!"0J2<$N$h$&$K:GE,2=$r9T$&!#

1. %5%V%\%j%e!<%`%G!<%?$NAw?.
   J,3d$5$l$?%5%V%\%j%e!<%`%G!<%?$O8D!9$N%W%m%;%C%5$K3d$jIU$1$J$l$P$J$i$J$$!#%[%9%H$GJ,3d$5$l$?%G!<%?$r3F%W%m%;%C%5$KE>Aw$9$k>l9g$O!"Aw?.%G!<%?$NBg$-$5$K$h$j!"DL?.;~4V$,1F6A$rM?$($k!#
   4.2@a$G=R$Y$?$h$&$K!"K\8&5f$G$O!"J,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$N E>Aw$O(c) J}K!$r:NMQ$7!"MQ$$$?Fs=E$Nfor %k!<%W9=J8$+$i<B8=$7$?!#;0=E$Nfor 9=J8$+$i9=@.$5$l$?(d) J}K!$HHf3S$9$k$H !dJBAu7k2L$O5.1$K<($9)DL?.=hM}$N2s?t$,8:>/$9$k$3$H$,$o$+$k!#

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

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

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

$^$?!";k@~%G!<%?$r$^$H$a$FAw?.$9$k$3$H$G:GE,2=$9$kJ}K!$r9M;!$9$k$H!"%\%j%e!<%`%G!<%?$N=hM}$K$OB?$/$N7W;;$rI,MW$H$7!"#1;k@~$4$H$N=hM}$O%a%b%j$X$N%"%/;%9$KHf3SE*;~4V$rMW$7!"$^$?!"$3$N=hM}$r9T$o$l$k>l9g$N#12hLL

$r@8@.$9$k$N$KMW$9$k;~4VT $O

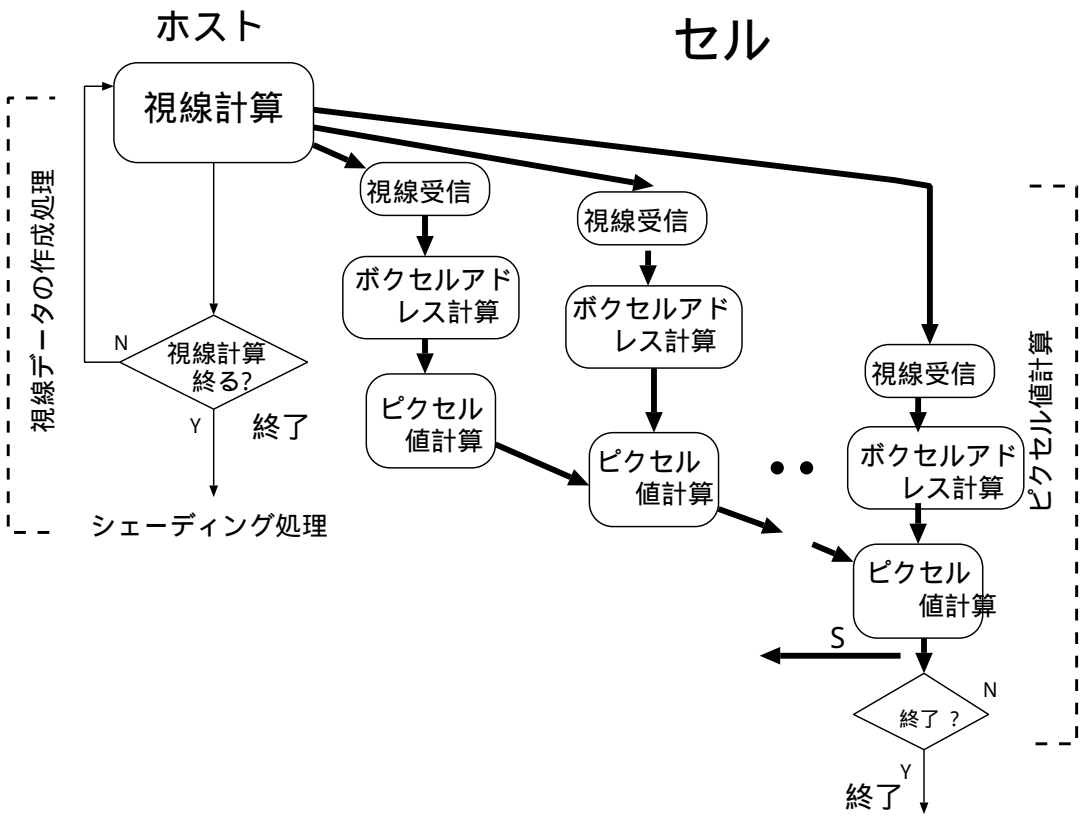
$$T = (T\_hcom + T\_comm + T\_run + T\_wait) * m^2 nP \tag{4.1}$$

$GI=$5$l$k!#$3$3$G!"$T\_hcom$ $O%[%9%H$+$i;k@~%G!<%?$r%;%k$KE>Aw!"$"$k$$
$O%;%k$+$i7W;;7k2L$r%[%9%H$K<}=8$9$k$N$K$+$+$kDL?.;~4V$G$"$k!#$T\_comm$
$O%;%k$H%;%k$"$?$j$N;k@~%G!<%?$*$h$S%T%/%;%kCM$NCf4V7k2L$rE>Aw$K$+$+$k
;~4V$G$"$k!#$T\_run$ $O3F%;%k$G%T%/%;%kCM7W;;$9$k=hM};~4V$G$"$k!#$T\_wait$ $O
3F%;%k$N%a%C%;!<%8$rBT$A;~4V$G$"$k!#$^$?!"%9%/%j!<%s$N2hAG?t$r$m^2$!"%\
%j%e!<%`%G!<%?$r$n^3$!"%;%k$NBf?t$rP $H$9$k!#1;k@~$4$H$K=hM}$r9T$&$HDL?.
;~4V$,$+$J$j$+$+$k$N$G!"DL?.;~4V$N1#JC$,$G$-$J$/$J$k!#$=$N$?$aDL?.BT$A
;~4V$,B?$/$J$j!"=hM};~4V$NA}2C$r>7$-!"JBNs=hM}$K$h$kB.EY8~>e$rK8$2$k7k
2L$H$J$k!#$=$3$G!"$3$l$r2~A1$9$k$?$a!"DL?.;~4V$N:o8:$*$h$SDL?.;~4V$N1#
JC$r9T$$!"9bB.2=$r$O$+$k=hM}$N%"%k%4%j%:%`$rDs0F$9$k!#

$^$:!"DL?.;~4V$N1#JC$9$k$3$H$r9M$($k!#%\%j%e!<%`%l%s%@%j%s%0$N%"%k%4
%j%:%`$K$*$$$F!"<02.4$K<($9$h$&$K!"%\%/%;%kCM$N%"%I%l%97W;;$H%T%/%;%kCM
7W;;$OD>@\4X78$J$/!"FI$_=P$9%\%/%;%kCM$N%"%I%l%97W;;$K$O!"%T%/%;%kCM7W
;;%9%F!<%8$G5a$a$i$l$k!#%T%/%;%kCM$NCf4V7k2L$OI,MW$J$/!";k@~%G!<%?$N$_
$+$i7W;;$9$k$3$H$,$G$-$k!#$3$N$3$H$rMxMQ$7$F!"?^4.7$K<($9$h$&$K!"%[%9%H
$Ok K\;k@~$N@8@.$r$^$H$a$F7W;;$7!"%P%C%U%!$K3JG<$9$k!#<!$K%V%m%C%/7A$G
K K\$N;k@~%G!<%?$r0 HV%;%k$N%P%C%U%!$KE>Aw$9$k$N$G$O$J$/!"A4%;%k$XAw?.
$9$kDL?.4X?t**cbroad()** $G;k@~%G!<%?$NAw?.$r9T$&!#K\O@J8$G$O!"$3$NJ}K!$r
@h9TAw?.K!$H8F$V!#$3$N@h9TAw?.K!$K$h$j!"3F%;%k$O;k@~%G!<%?$r<u?.$7$?8e!"
%\%/%;%kCM$,<B:]$KI,MW$H$J$k0JA0$K!"<!$KFI$_=P$9%\%/%;%k$N3JG<$5$l$F$$
$k%a%b%j%"%I%l%9$r7W;;$7!"$=$NCM$rJ];}$7$F$*$/!#$=$7$F!"A0$N%;%k$+$iAw
?.$-$?%a%C%;!<%8$,$"$G$?$i!"$=$N%T%/%;%kCM$NCf4V7k2L$r<u?.$7!"%l%8%9%?
$+$i%\%/%;%kCM$rFI$_=P$7!"%T%/%;%kCM$N7W;;$H<u?.$7$?Cf4V7k2L$+$i?7$?$J
%T%/%;%kCM$r7W;;$9$k!#$3$l$K$h$j!"%\%/%;%k%"%I%l%9$N7W;;$H!"A0CJ$N%;%k
$G$N%T%/%;%k7W;;$HDL?.;~4V$r%*!<%P!<%i%C%W$9$k$3$H$,$G$-$k!#

K K\$N;k@~%G!<%?$N0l3gAw?.$H@h9TAw?.K!$NJ;MQ=hM}$r9T$&>l9g!"#12hLL$N
@8@.$KMW$9$k;~4VT $O

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




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

$H$J$k!#%T%/%;%kCM7W;;$N%Q%$%W%i%$%s2=<B9T$b$G$-$k!#=hM}$N9bB.2=$,$O$+$l$k!#

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

### 5.1 <B9T7k2L

K\@a$G$O!"K\8&5f$GDs0F$7$?%\%j%e!<%'1%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$-$5$r256^2$H$9$k!#

JBNs@-G=I>2A$O0J2<$G<($7$?9'L\$N@-G=$X$N1F6A$r9M$($F!"<B9T$r9T$&!#

- %\%j%e!<%'G!<%?%5%$:$HMQ$$$?%;%kBf?t$X$N1F6A!#
- J,3d$5$l$?%5%V%\%j%e!<%'!&G!<%?$r%;%k$KAw?.$9$k:]!"%G!<%?$NBg$-$5$K$h$j!"DL?.;~4V$N1F6A!#
- %[%9%H$G@8@.$7$?;k@~%G!<%?$r%;%k$KAw?.$9$k:]!"n K\$N;k@~%G!<%?$r0l=o$KAw?.$9$k$3$H$K$h$k8z2L!#

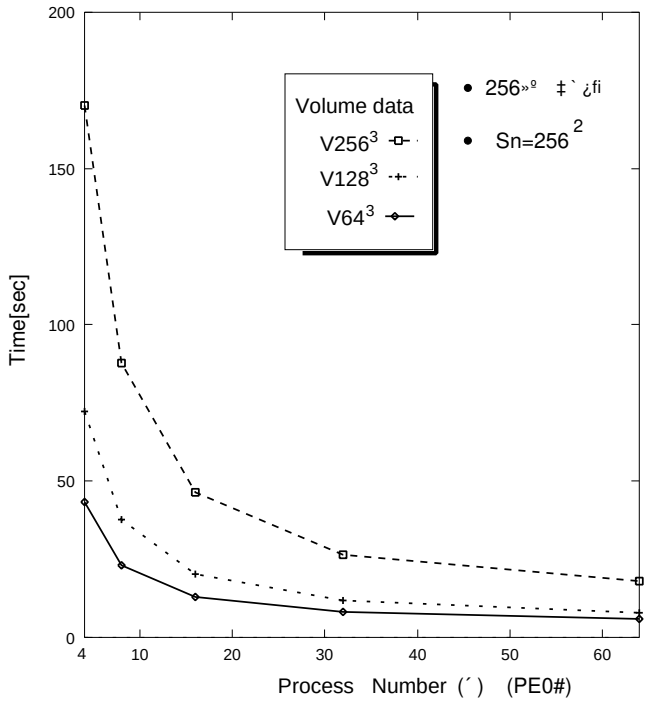
- DL?.;~4V$r1#JC$9$k$?$a!";k@~%G!<%?$r@h9TAw?.$9$k8z2L!#

I=5.1: AP-1000 $K$*$1$k%\%j%e!<%`!&l%s%@%j%s0$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

$3$N@a$G$O!"%\%j%e!<%`$G!<%?%5$$:$H%;%kBf?t$NJQ49$K$D$$$F!"K\<BAu$NJBNs=hM}8z2L$r9M;!$9$k!#I=5.2$G$O!"%\%j%e!<%`$G!<%?$O$64^3, 128^3, 256^3$rMQ$$$F!"%9%/%j!<%s5%$$:$O$256^2$H$7$F!"%;%kB&$G;k@~%G!<%?$r256 K\$^$H$a$K<u?.$7!"<B9T$r10 2s9T$C$?(L=10) $N<B837k2L$G$"$k!#$?$@$7!"@-G=I>2A$N$?$a!"<($7$?;~4V$O AP1000 $N>e$G%H%l!<%9$r9T$C$?;~4V$G$"$k!#0[$J$k%5%$:$N%\%j%e!<%`!&l%G!<%?$KBP$9$kJBNs=hM}$N8z2L$r?^5.1$K<($9!#



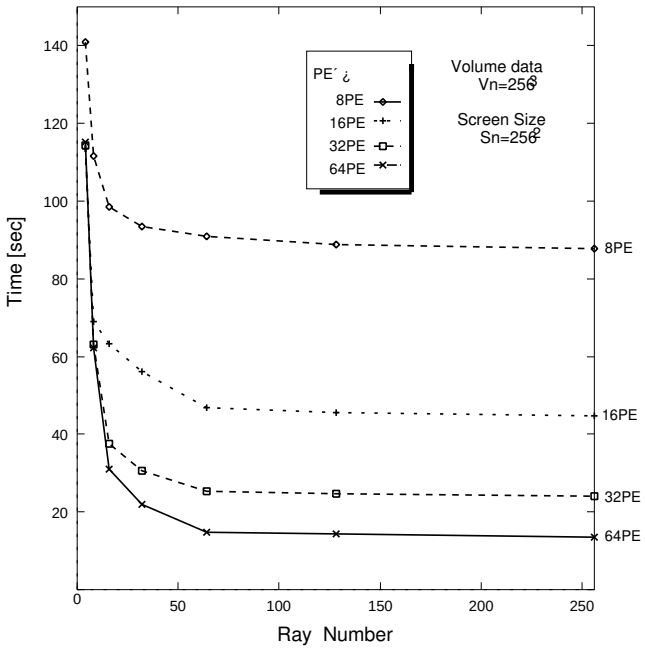

?^5.1: JBNs=hM}8z2L

I=5.2: AP1000 $K$*$1$k%\%j%e!<%`!&l%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 |

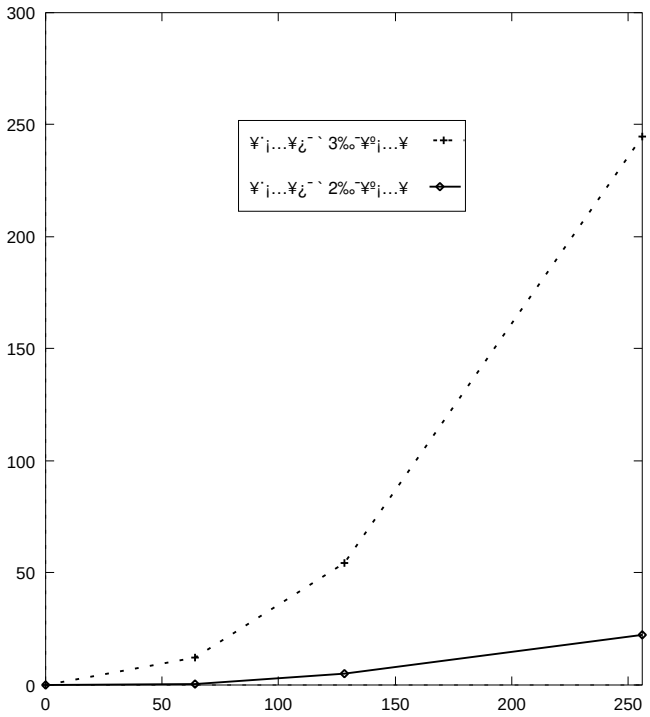



?^5.2: ;k@~%G!<%?$N0l3gAw?.8z2L

- 3F%\%j%e!<%`%G!<%?$O%G!<%?%5%$%:$r0lDj$H$7$F!"%W%m%;%C%5Bf?t$rJQ2=$5$;$?>l9g!"<B9T;~4V$K$[$\@~7A@-$,F@$i$l$?!#$D$^$j!"%;%k$NBf?t$r8:$i$9;~!"3F%W%m%;%C%5$NIi2Y=hM}NL$,B?$/!"%?%9%/=hM};~4V$NHfN($,9b$/!"<B9T;~4V$,CY$/$J$k!#$H$3$m$,%;%k$NBf?t$rA}$d$9$H!"Ii2YJ,;6$N7Z8:$K$h$j!"$h$$Bf?t8z2L$rC#@.$9$k$3$H$,$o$+$k!#
- $^$?!"DL?.;~4V$rD4$Y$k$H!"I=5.2$K<($9$h$&$K!"$3$l$O%\%j%e!<%`%G!<%?$NBg$-$5$H4X78$J$/!"DL?.NL$O%9%/%j!<%s$N%5%$%:$G7h$^$k$N$G!"%W%m%;%C%5Bf?t$,A}2C$7$F$b!"%;%kKh$NDL?.NL$,$[$\0lDj$G$"$k$3$H$,$o$+$k!#

### 5.1.2 Aw?.C10L$H$NI>2A

- $^$:!"%[%9%H$GJ,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$r%;%k$KAw?.$9$k:]!"4.2@a$G=R$Y$?$h$&$K!"!cJ!KJ}K!$N1%U%l!<%`$G%G!<%?$rAw?.$9$k$H!cJ!KJ}K!$N1<!85G[NsKh$K%G!<%?$rAw?.$9$k!#3F%\%j%e!<%`!&G!<%?%5%$%:$NB,Dj$7$?7k2L$r?^5.3$K<($9!#
  7k2L$r9M;!$9$k$H!"0l3gE>Aw1%U%l!<%`$N%G!<%?$N$[$&$,DL?.2s?t$r8:$i$9!"1<!85G[NsKh$K%G!<%?Aw?.J}K!$h$j10G\B.$5$,F@$i$l$?!#
- Aw?.C10L(;k@~%G!<%?!K$NBg$-$5$K$h$j=hM}B.EY$N1F6A$rD4$Y$k$?$a$K!"%\%j%e!<%`%G!<%?$r256³!"%9%/%j!<%s%5%$%:$O256²$H$7!"Aw?.C10L$rJQ2=$5




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

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

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

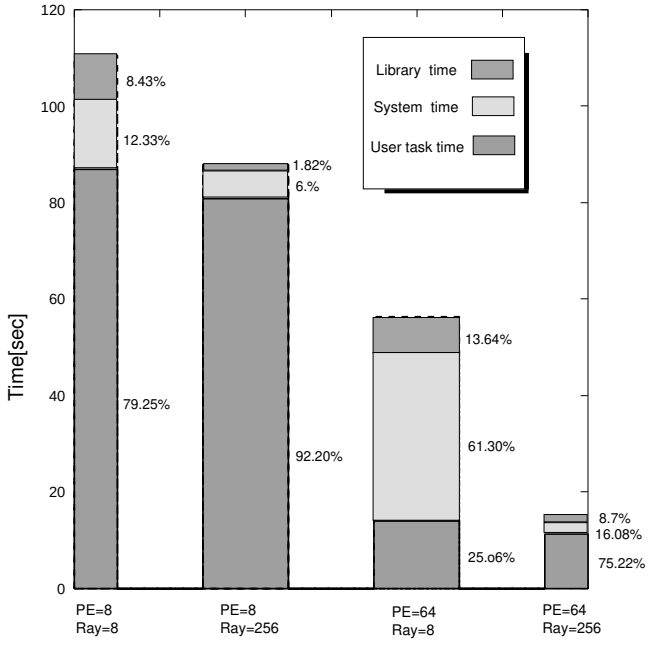
| ;k@~?t | <B9T;~4V[sec] | | | | |
|---|---|---|---|---|---|
| | 4 Bf | 8 Bf | 16 Bf | 32 Bf | 64 Bf |
| 4 | 250.5 | 140.9 | 113.6 | 114.3 | 115.2 |
| 8 | 204.7 | 111.6 | 68.9 | 63.0 | 62.3 |
| 16 | 184.1 | 98.6 | 63.2 | 37.6 | 31.1 |
| 32 | 178.7 | 93.5 | 56.2 | 30.6 | 21.9 |
| 64 | 177.2 | 90.9 | 46.8 | 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 |

$3$N7k2L$r9M;!$9$k$H!"E>Aw%G!<%?NL$,>/$J$/$J$k$HDL?.2s?t$,A}2C$7!"=hM};~4V$O$+$J$jCY/$J$k!#JBNs2=$N8z2L$,8+$i$l$J$$!#$7$+$7!"E>Aw%G!<%?NL$r

A}$d$9$H!"=hM};~4V$,@~7AE*$KB.$/$J$k!#$^$?!"E>AwNL!;Jk@~%G!<%?$R$!a$256$!K$H%;%k$NBf?t!$P = 64$) $NN>J}$,A}2C$9$k$H!"=hM}$,$5$i$K9bB.2=$K$J$j!"JBNs2=$N8z2L$,8+$i$l$k!#

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

MQ$$$k%\%j%e!<%`!&G!<%?$O$256^3$H%9%/%j!<%s$N%5%$%:$O$256^2$G$"$k!#%;%kBf?t$N8z2LI>2A$K$D$$$F$O8 Bf$H64 Bf$r07$&!#0l3g$7$FAw?.$9$k;k@~%G!<%??t$O$=$l$>$l8 K\$H256 K\$G$"$k!#0J2<!"=hM};~4V$HDL?.;~4V$N3d9g$O?^5.4$G!"<B9T;~4V$NFbLu$OI=5.5$N$=$l$>$l$r<($9!#




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

1. %;%kBf?t$,>.$5$$>l9g!"0l3gAw?.$9$k;k@~%G!<%??t$,>/$J$$$H!"%[%9%HB&$O%;%k$X$NAw?.;~4V!Jhs!K"%;%k$+$i<u?.;~4V!Jhr!K$H%;%kB&$O!"%[%9%H$+$i!Jcor) 0?$OB>$N%;%k$+$i$N<u?.;~4V!Jcnr)!"%[%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¥ŒE | †¿ | …´„»· | †¿ | …´„»· | †¿ | …´„»· | †¿ | …´„»· |
| 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 !Tcns) $J$I$bA}Bg$7!"DL?.2s?t$,B?$$!#$^$?!"%\%j%e!<%`%G!<%?$,Bg$-$$>l9g!"Bf?t$N8z2L$,8+$i$l$J$$H!"%;%kB&$O7W;;~4V$,D9$/$J$k!#

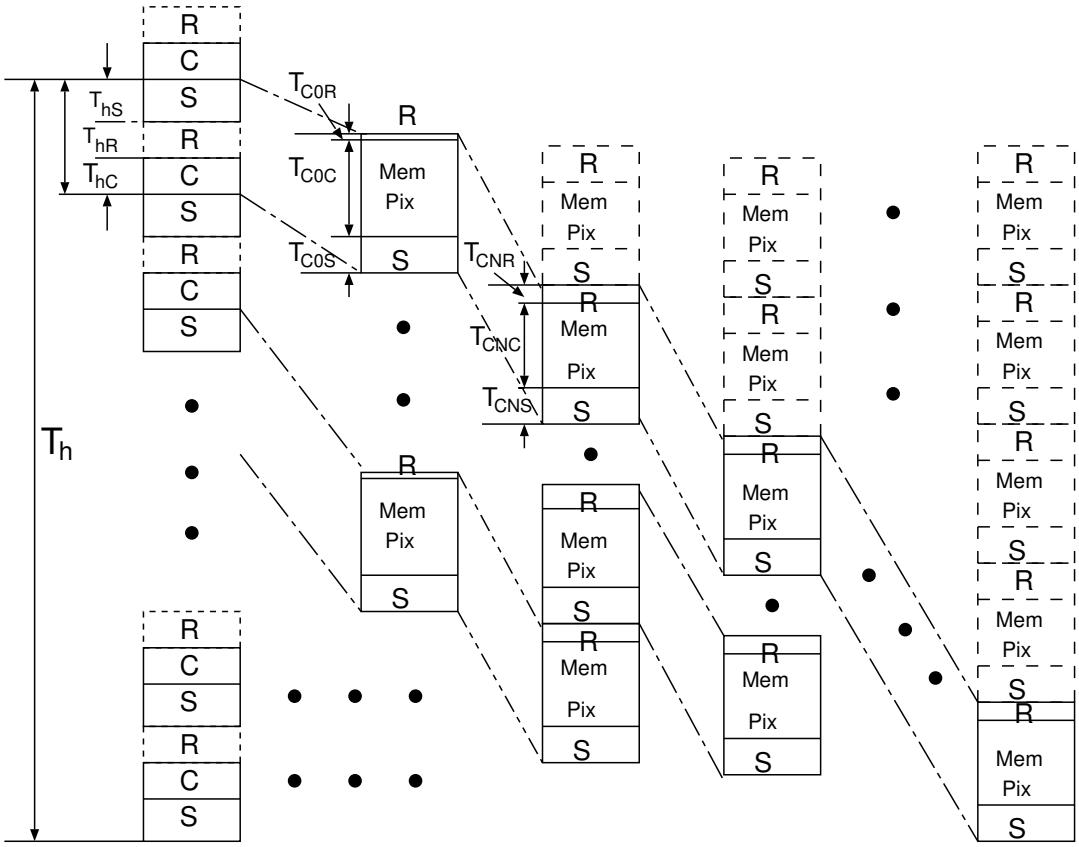
2. %;%kBf?t$,JQ$o$i$:!"0l3gAw?.$9$k;k@~%G!<%?$rA}$d$9$H!"%[%9%H$H%;%k$NN>J}$GDL?.%i%$%V%i%j;~4V$,==J,$K8:$i$9!"$7$+$b!"Bf?t$,>/$J$$H!"%;%kB&$N=hM};~4V$H%[%9%HB&$NBT$A;~4V$N%P%i%s%9$,0-$/!"7k6I=hM}B.EY$,$"$^$jB.$/$J$i$J$+$C$?!#

3. %;%kBf?t$HE>AwNL$,5U$K!"Bf?t$,A}$d$7!"E>AwNL$,>/$J$$>l9g$O!"#1%;%kEv$?$j$N7W;;NL$,8:>/$7$F!"Bf?t8z2L$,8+$i$l$k!#$7$+$b!"E>AwNL$,A}2C$7$J$$$H!"%[%9%HB&$NDL?.2s?t$rA}$d$9!"%;%k$NBT$A;~4V$,Am=hM}<B9T;~4V$N3d9g$NB?$/$r@j$a$k!#

4. 0lJ}!"%;%k$NBf?t$HE>AwNL$rN>J}A}$d$9$H!"1 %;%kEv$?$j$N1i;;NL$,6K$a$F8:>/$7!"DL?.%i%$%V%i%j;~4V$bAw?.NL$,>/$J$$>l9g$N$\frac{1}{30}$KDc2<$7!"JBNs2=$N8zN($,$h$$$H$$($k!#$3$N>l9g$N%[%9%H%;%k$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($O@-G=$r7hDj$E$1$k3FMW0x$NAj8_:nMQ$K0MB8$9$kNL$G$"$j!"8zN($=$N$b$N$rD>@\%b%G%k2=$9$k$3$H$O:$Fq$G$"$k$,!"<B9T;~4V$K4p$E$$$F@-G=M=B,%b%G




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

%k$r9M$($k$H!"3FMW0x$4$H$KJ,3d$7$F9M$($i$l$k$N$GM}2r$7$d$9$$!#K\8&5fDs
0F$7$?JBNs%"%k%4%j%:%`$OJBNs7W;;5!>e$G<B9T$7$?7k2L$+$i!"%"!<%-%F%/%A%c
$K1~$8$F!"E,@Z$J%\%j%e!<%`!&G!<%?%5%$%:!"%W%m%;%C%5?t$rA*Br$9$k$K$h$j!"
@-G=M=B,%b%G%k$rF@$k$3$H$,2DG=$H$J$k!#K\@a$G$O!"$3$l$K$D$$$F=R$Y$k!#

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

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

$H8+@Q$b$l$k!#$?$@$7!"$P_i$$O%W%m%;%C%5Bf?t$G$"$k!#L $O%9%/%j!<%s$N%5%$%:$Sn^2$
$H;k@~%G!<%?$NAw?.NL!R!K$O$L = \frac{Sn^2}{R}$$rDL?.2s?t$K$J$k!#$T_{ho} = Ths + Thr + Thc$
$G$"$k!#$T_p$$O%W%m%;%C%5$G$N1i;;;~4V$G$"$k!#$T_{comm} = Tcnr + Tcns$$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[%] |
|---|---|---|---|---|
| $64^3$œ,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 |
| $128^3$œ,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 |
| $256^3$œ,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#JC$9$k$?$a$K!"%"%k%4%j%:%`$r<B8=$9$k$H$-$K!";k@~%G!<%?$NAw?.J}K!$r2<cN`$r9M$(B$?!#I=5.6$O!"@h9TAw?.K!$HJ?9TAw?.K!$N$=$l$>$l$N%\%j%e!<%`!&G!<%?%5%$%:$KBP$9$k!"<B9T;~4V$NHf3S$G$"$k!#I=$N7k2L$+$i9M;!$9$k$H!"@h9TAw?.K!$[$&$,9b$$8z2L$,F@$i$l$?$H$$(B$k!#%G!<%?%5%$%:$,>.$5$$>l9g$G$b!"@h9TAw?.K!$OJ?9TAw?.K!$h$j2%0J>e<B9T;~4V$,C;$$!#%\%j%e!<%`%5%$%:$,$128^3$N$H$-$K!"$[$\20%$N2~A1$rC#@.$G$-$?!#DL?.1#JC$,4|BT$5$l$k@h9TAw?.K!$N%"%k%4%j%:%`$N<B8=$,$G$-$k!#

# 6 $*$o$j$K

K\8&5f$G$O!"%a%b%jJ,;67?JBNs7W;;5!$rBP>]$H$9$k%\%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$5$l$?3%s%U%j%/%H%U%j!<$J%a%b%j9=@.K!$r%G!<%?J,3d$K;HMQ$7F$$$k!#$3$l$K$h$j!"%G!<%?$N:FJ,3d$r9T$&$3$H$J$/G$0UJ}8~$+$i$N;k@~$r=hM}$9$k$3$H$,$G$-!";kE@JQ99$r9T$C$?>19g$K$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@hAw$j$K$h$kDL?.$N1#JC$r?^$k$J$I$N:GE,2=$K$h$j!"9b$$@-G=$,F@$i$l$?!#

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

- %5%$%:64³,256³$N%\%j%e!<%`G!<%?$+$i2hAG?t256²$N2hA|$r@8@.$9$k$N$K!"64 %W%m%;%C%5$G$O4 %W%m%;%C%5$KBP$7!"$=$l$>$lLs8 G\$H12.5 G\$H!"9b$$JBNs@-$,F@$i$l$?!#
- %\%j%e!<%`!&G!<%?$,Bg$-$$>19g$O!"J,3d$5$l$?%5%V%\%j%e!<%`!&G!<%?$r1 %U%l!<%`$GAw?.$9$k$[$&&$,DL?.2s?t$r8:$i$9!"1<!85G[NsKh$K%G!<%?Aw?.J}K!$h$j10 G\B.$5$,F@$i$l$?!#
- 0l3gAw?.$9$k;k@~%G!<%??t$O64 %W%m%;%C%5$G;k@~%G!<%??t$,256 $O4 $KBP$7!"=hM}B.EY$,8.5 G\$H$J$C$?!#
- $^$?!"@h9TAw?.K!$O0l3gAw?.K!$h$jAw?.$9$k%a%C%;!<%8$ND9$5$,C;$/$N$G!"DL?.;~4V$KBP$7$F!"@h9TAw?.K!$O0l3gAw?.K!$h$j$"$kDxEYDL?.;~4V$,8:$i$9$3$H$,$o$+$k!#
- $5$i$K!"%5%$%:64³$N%\%j%e!<%`G!<%?$KBP$7!"2hAG?t256²$N2hA|@8@.;~4V$r%o!<%/%9%F!<%7g&s !Ültra SPARC 167MHz <g5-21128MB!K$G$NC`<!<B9T$HHf3S$7$?7k2L!"64 %W%m%;%C%5$G4.1 G\$H$J$j!"K\J}<0$K$h$kJBNs%\%j%e!<%`%l%s%@%j%s%0$NM-8z@-$,<($5$l$?!#

<UK-

K\8&5f$N5!2q$rM?$($F2<$5$j!"E,@Z$J8f;XF3$r;r$o$C$?IYEDbC<#65<x$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<j$J$i$S$K=yMx;a$K?<$/46<UCW$7$^$9!#

%W%m%0%i%'$N<B9T$K$"$?$j!"JBNs7W;;5!AP1000 $N<B9T4D6-$r8fDs6!$$?$@$-$^$7$? !3t!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!#

$5$i$K!"F|:"8fF$O@$$?$@$$?IYED8&5f<<$N=t;a$K46<UCW$7$^$9!#

;29MJ88%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