Randomization Using RandomPkg

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1 RandomPkg Overview

RandomPkg provides a set of utilities for randomizing a value in a range, a value in a set, or a value with a weighted distribution.

OSVVM's constrained random capability uses these utilities to randomize a value, operation, or sequence that is valid in a particular test environment. Since any constrained random methodology creates a significant amount of redundant stimulus (5X or more for small problems), in OSVVM, we use Intelligent Coverage randomization as our main randomization methodology, and constrained random as a refinement methodology in our tests.

These packages are updated from time to time and are freely available at http://www.synthworks.com/downloads.

2 Randomization Using IEEE.math_real.uniform = Yuck!

A basic form of randomization can be accomplished by using the procedure uniform the IEEE math_real package. However, this always results in randomization being a multi-step process: call uniform to randomize a value, scale the value, and then use the value.

```
RandomGenProc : process
  variable RandomVal : real ;                      -- Random value
  variable DataSent : integer ;
  variable seed1 : positive := 7 ;                 -- initialize seeds
  variable seed2 : positive := 1 ;
begin
  for i in 0 to 255*6 loop
    uniform(seed1, seed2, RandomVal) ;             -- randomize 0.0 to 1.0
    DataSent := integer(trunc(RandomVal*256.0)) ;  -- scale to 0 to 255
    do_transaction(…, DataSent, …) ;
    . . .
```

Optimally we would like to be able to call a function to do this so we can do this all in one step. Unfortunately we cannot write a normal VHDL function since we need to read and update the seed as well as return a randomized value.

3 Simplifying Randomization

RandomPkg uses a protected type, named RandomPType, to encapsulate the seed. Within a protected type, impure functions can read and update the seed as well as return a randomized value. To randomize values using the protected type, declare a variable of type RandomPType, initialze the seed, and randomize values.

```
RandomGenProc : process
  variable RV : RandomPType ;                  -- protected type from RandomPkg
```

```
begin
  RV.InitSeed (RV'instance_name)  ;              -- Generate initial seeds
  for i in 0 to 255*6 loop
    do_transaction(…, RV.RandInt(0, 255), …) ;  -- random value between 0 and 255
```

Note the calls to protected type methods (subprograms) include the protected type variable (RV) within the call (such as RV.RandInt(0, 255)).

4 Manipulating the Seeds

With protected types internal objects are private and accessible only through methods. The internal representation of the seed has a valid initial value, however, to ensure that each process' randomization is independent of each other, it is important to give each seed to a different initial value. As a result for a test that uses more than one randomization variable, initialize each seed once - if there is only one randomization variable, there is no need to initialize the seed.

The method InitSeed converts its argument value to RandomSeedType (the internal representation of the seed) and stores the value within the protected type. InitSeed is overloaded to accept either string or integer values. The preferred way to give each seed a unique value is pass the string value, RV'instance_name.

```
RV.InitSeed (RV'instance_name)  ;
```

The methods GetSeed and SetSeed are used to read and restore a seed value. The declarations for these are shown below.

```
impure function GetSeed return RandomSeedType ;
procedure SetSeed (RandomSeedIn : RandomSeedType ) ;
```

The function to_string and procedures write and read are used to write and read values of type RandomSeedType. The declarations for these subprograms are shown below. Note these are in RandomBasePkg.vhd and are separate from the protected type.

```
function  to_string(A : RandomSeedType) return string ;
procedure write(L: inout line ; A : RandomSeedType ) ;
procedure read (L: inout line ; A : out RandomSeedType ; good : out boolean ) ;
procedure read (L: inout line ; A : out RandomSeedType ) ;
```

For a long test, it may be advantageous to read the seed periodically and print it out. If a failure or other interesting condition is generated, the seed may be restored to a value that was recorded near the failure with the intent of generating the error quickly to assist with debug.

5 Basic Randomization

The basic randomization generates an integer value that is either within some range or within a set of values. The set of values and exclude values are all of type integer_vector (defined in VHDL-2008). The examples below show the basic randomization overloading. When a value of integer_vector is specifed, the extra set of parentheses denote that it is an aggregate value.

```
RandomGenProc : process
  variable RV      : RandomPType ;         -- protected type from RandomPkg
  variable DataInt : integer ;
begin
  RV.InitSeed (RV'instance_name)  ;         -- Generate initial seeds

  -- Generate a value in range 0 to 255
  DataInt := RV.RandInt(0, 255) ;
  . . .
  -- Generate a value in range 1 to 9 except exclude values 2,4,6,8
  DataInt := RV.RandInt(1, 9, (2,4,6,8)) ;
  . . .
  -- Generate a value in set 1,3,5,7,9
  DataInt := RV.RandInt( (1,3,7,9) ) ;  -- note two sets of parens required
  . . .
  -- Generate a value in set 1,3,5,7,9 except exclude values 3,7
  DataInt := RV.RandInt((1,3,7,9), (3,7) ) ;
```

The overloading for the RandInt functions is as follows.

```
impure function RandInt (Min, Max : integer) return integer ;
impure function RandInt (Min, Max: integer; Exclude: integer_vector)
    return integer ;
impure function RandInt ( A : integer_vector ) return integer ;
impure function RandInt ( A : integer_vector; Exclude: integer_vector)
    return integer ;
```

These same functions are available for types std_logic_vector(RandSlv), unsigned (RandUnsigned) and signed (RandSigned). Note that parameter values are still specified as integers and there is an additional value used to specify the size of the value to generate. For example, the following call to RandSlv defines the array size to be 8 bits.

```
  variable DataSlv : std_logic_vector(7 downto 0) ;
begin
  . . .
    DataSlv := RV.RandSlv(0, 255, 8) ; -- Generate a value in range 0 to 255
```

The overloading for RandSlv is as shown below. RandUnsigned and RandSigned have the same overloading

```
impure function RandSlv (Min, Max, Size : natural) return std_logic_vector ;
impure function RandSlv (Min, Max : natural ; Exclude: integer_vector ; Size :
natural)  return std_logic_vector ;
impure function RandSlv
```

```
    (A: integer_vector ; size : natural ) return std_logic_vector ;
impure function RandSlv (A: integer_vector ; Exclude: integer_vector ; Size :
natural)  return std_logic_vector ;
```

The function, RandReal supports randomization for type real. The function with a range, like the procedure Uniform, never generates its end values. RandReal has the following overloading:

```
impure function RandReal ( Min, Max : real ) return real ;
impure function RandReal ( A : real_vector ) return real ;
impure function RandReal ( A, Exclude : real_vector ) return real ;
```

The function, RandTime supports randomization for type time. RandTime supports the same overloading as RandInt. These are shown below:

```
impure function RandTime (Min, Max : time ; Unit : time := ns) return time ;
impure function RandTime
   (Min, Max : time ; Exclude : time_vector ; Unit : time := ns) return time ;
impure function RandTime (A : time_vector) return time ;
impure function RandTime (A, Exclude : time_vector) return time ;
```

The functions, RandBool, RandSl, RandBit, support randomization for types boolean, std_logic, and bit respectively. These are shown below:

```
impure function RandBool return boolean;
impure function RandSl return std_logic;
impure function RandBit return bit;
```

6 Large Vector Randomization

Integer randomization is only valid in the range of -2**31 to +2**31 - 1. Large vector randomization uses multiple randomizations to create a value. The following overloading is available for RandUnsigned, RandSlv, and RandSigned.

```
impure function RandUnsigned (Size : natural) return unsigned ;
impure function RandUnsigned (Max : unsigned) return unsigned ;
impure function RandUnsigned (Min, Max : unsigned) return unsigned ;
```

The size parameter specifies the number of bits in the vector. The Max parameter allows randomization between 0 and Max. The Min and Max parameters allow randomizing a range of values.

7 Randomizing Sets of Values

A set of values can be represented by integer_vector, real_vector, or time_vector. The following illustrates the capability supported for integer_vector.

```
RandomGenProc : process
  variable RV      : RandomPType ;         -- protected type from RandomPkg
  variable IntV : integer_vector(1 to 15) ;
begin
  RV.InitSeed (RV'instance_name)  ;         -- Generate initial seeds
```

```
  -- Generate 10 integer values in the range 0 to 255
  IntV(1 to 10) := RV.RandIntV(0, 255, 10) ;
  . . .
  -- Generate 15 integer values in range 1 to 9 except exclude values 2,4,6,8
 IntV := RV.RandIntV(1, 9, (2,4,6,8), 15) ;
  . . .
  -- Generate 5 integer values value in set 1,3,5,7,9
  IntV(1 to 5) := RV.RandIntV( (1,3,7,9), 5 ) ;
  . . .
  -- Generate 15 integer values in set 1,3,5,7,9 except exclude values 3,7
  IntV := RV.RandIntV((1,3,7,9), (3,7), 15) ;

  -- Generate 10 integer values in the range 0 to 99, do not repeat the last value
  IntV(1 to 10) := RV.RandIntV(0, 99, 1, 10) ;
  . . .
  -- Generate 15 integer values in range 1 to 9 except exclude values 2,4,6,8
  -- Do not repeat the last 3 values
 IntV:= RV.RandIntV(1, 9, (2,4,6,8), 3, 15) ;
  . . .
  -- Generate 5 integer values in the set 1,3,5,7,9, do not repeat the last value
  IntV(1 to 5) := RV.RandIntV( (1,3,7,9), 1, 5 ) ;
  . . .
  -- Generate 15 integer values in set 1,3,5,7,9 except exclude values 3,7
  -- Do not repeat last value
  IntV := RV.RandIntV((1,3,7,9), (3,7), 1, 15) ;
```

The overloading for integer_vector, real_vector, or time_vector are as follows.

```
-- Range and Exclude
impure function RandIntV (Min, Max : integer ; Size : natural) return
integer_vector ;
impure function RandIntV (Min, Max : integer ; Exclude : integer_vector ; Size :
natural) return integer_vector ;
-- Range, Exclude, and Unique
impure function RandIntV (Min, Max : integer ; Unique : natural ; Size : natural)
return integer_vector ;
impure function RandIntV (Min, Max : integer ; Exclude : integer_vector ; Unique :
natural ; Size : natural) return integer_vector ;
-- Set and Exclude
impure function RandIntV (A : integer_vector ; Size : natural) return
integer_vector ;
impure function RandIntV (A, Exclude : integer_vector ; Size : natural) return
integer_vector ;
-- Range, Exclude, and Unique
impure function RandIntV (A : integer_vector ; Unique : natural ; Size : natural)
return integer_vector ;
impure function RandIntV (A, Exclude : integer_vector ; Unique : natural ; Size :
natural) return integer_vector ;
```

Overloading for time_vector:

```
impure function RandTimeV (Min, Max : time; Size : natural; Unit : time := ns)
return time_vector;
impure function RandTimeV  (Min, Max : time ; Exclude : time_vector ; Size :
natural) return time_vector ;
```

```
impure function RandTimeV (Min, Max : time; Unique : natural; Size : natural; Unit
: time := ns) return time_vector ;
impure function RandTimeV (Min, Max : time; Exclude : time_vector; Unique :
natural; Size : natural) return time_vector;
impure function RandTimeV (A : time_vector; Size : natural) return time_vector ;
impure function RandTimeV (A : time_vector; Unique : natural ; Size : natural)
return time_vector;
impure function RandTimeV (A, Exclude : time_vector; Size : natural) return
time_vector ;
impure function RandTimeV (A, Exclude : time_vector; Unique : natural; Size :
natural) return time_vector ;
```

Overloading real_vector

```
impure function RandRealV (Min, Max : real ; Size : natural) return real_vector ;
impure function RandRealV (A : real_vector ; Size : natural) return real_vector ;
impure function RandRealV
   (A : real_vector ; Unique : natural ; Size : natural) return real_vector ;
impure function RandRealV
   (A, Exclude : real_vector ; Size : natural) return real_vector ;
impure function RandRealV (A, Exclude : real_vector ; Unique : natural ; Size :
natural) return real_vector ;
```

8 Weighted Randomization

A weighted distribution randomly generates each of set of values a specified percentage of the time. RandomPType provides a weighted distribution that specifies a value and its weight (DistValInt) and one that only specifies weights (DistInt).

DistValInt is called with an array of value pairs. The first item in the pair is the value and the second is the weight. The frequency that each value will occur is weight/(sum of weights). As a result, in the following call to DistValInt, the likelihood of a 1 to occur is 7/10 times or 70%. The likelihood of 3 is 20% and 5 is 10%.

```
variable RV : RandomPType ;
. . .
DataInt := RV.DistValInt(  ((1, 7), (3, 2), (5, 1)) ) ;
```

DistInt is a simplified version of DistValInt. The input to DistInt is an integer_vector of weights. The return value is the index of the selected weight. For a literal value, it will return a value from 0 to N-1 where N is the number of weights specified. As a result, the following call to DistInt the likelihood of a 0 is 70%, 1 is 20% and 2 is 10%.

```
variable RV : RandomPType ;
. . .
DataInt := RV.DistInt(  ((7, 2, 1)) ;
```

Simple weighted distributions are overloaded to also support the following forms:

```
impure function DistSlv ( Weight : integer_vector ; Size  : natural ) return
std_logic_vector ;
```

```
impure function DistUnsigned ( Weight : integer_vector ; Size  : natural ) return
unsigned ;
impure function DistSigned ( Weight : integer_vector ; Size  : natural ) return
signed ;
impure function DistBool ( Weight : NaturalVBoolType ) return boolean ;
impure function DistSl ( Weight : NaturalVSlType ) return std_logic ;
impure function DistBit ( Weight : NaturalVBitType ) return bit ;
```

Simple weighted distributions are overloaded to support exclude values.

```
impure function DistInt ( Weight : integer_vector ;
        Exclude : integer_vector ) return integer ;
impure function DistSlv ( Weight : integer_vector ;
        Exclude : integer_vector ; Size  : natural ) return std_logic_vector ;
impure function DistUnsigned ( Weight : integer_vector ;
        Exclude : integer_vector ; Size  : natural ) return unsigned ;
impure function DistSigned ( Weight : integer_vector ;
        Exclude : integer_vector ; Size  : natural ) return signed ;
```

9 Usage

Each randomization result is produced by a function and that result can be used directly in an expression. Hence, we can randomize a delay that is between 3 and 10 clocks.

```
wait for RV.RandInt(3, 10) * tperiod_Clk - tpd ;
wait until Clk = '1' ;
```

The values can also be used directly inside a case statement. The following example uses DistInt to generate the first case target 70% of the time, the second 20%, and the third 10%.

```
variable RV : RandomPType ;
. . .
StimGen : while TestActive loop     -- Repeat until done
  case RV.DistInt( (7, 2, 1) ) is
    when 0 =>  -- Normal Handling   -- 70%
       . . .
    when 1 =>  -- Error Case 1      -- 20%
       . . .
    when 2 =>  -- Error Case 2      -- 10%
       . . .
    when others =>
      report "DistInt" severity failure ;  -- Signal bug in DistInt
  end case ;
end loop ;
```

The following code segment generates the transactions for writing to DMA_WORD_COUNT, DMA_ADDR_HI, and DMA_ADDR_LO in a random order that is different every time this code segment is run. The sequence finishes with a write to DMA_CTRL. When DistInt is called with a weight of 0, the corresponding value does not get generated. Hence by initializing all of the weights to 1 and then setting it to 0 when it is selected, each case target only occurs once. The "for loop" loops three times to allow each transaction to be selected.

```
variable RV : RandomPType ;
. . .
Wt0 := 1;  Wt1 := 1;  Wt2 := 1;  -- Initial Weights

for i in 1 to 3 loop             -- Loop 1x per transaction

  case RV.DistInt( (Wt0, Wt1, Wt2) ) is  -- Select transaction

    when 0 =>                    -- Transaction 0
      CpuWrite(CpuRec, DMA_WORD_COUNT, DmaWcIn);
      Wt0 := 0 ;                 -- remove from randomization

    when 1 =>                    -- Transaction 1
      CpuWrite(CpuRec, DMA_ADDR_HI, DmaAddrHiIn);
      Wt1 := 0 ;                 -- remove from randomization

    when 2 =>                    -- Transaction 2
      CpuWrite(CpuRec, DMA_ADDR_LO, DmaAddrLoIn);
      Wt2 := 0 ;                 -- remove from randomization

    when others =>   report "DistInt" severity failure ;

  end case ;
end loop ;

CpuWrite(CpuRec, DMA_CTRL, START_DMA or DmaCycle);
```

The following code segment uses an exclude list to keep from repeating the last value. Note when passing an integer value to an integer_vector parameter, an aggregate using named association "(0=> LastDataInt)" is used to denote a single element array. Note that during the first execution of this process, LastDataInt has the value integer'left (a very small number), which is outside the range 0 to 255, and as a result, has no impact on the randomization.

```
RandomGenProc : process
  variable RV : RandomPType ;
  variable DataInt, LastDataInt : integer ;
begin
  . . .
  DataInt := RV.RandInt(0, 255, (0 => LastDataInt)) ;

  LastDataInt := DataInt;
  . . .
```

The following code segment uses an exclude list to keep from repeating the four previous values.

```
RandProc : process
  variable RV : RandomPtype ;
  variable DataInt : integer ;
  variable Prev4DataInt : integer_vector(3 downto 0) := (others => integer'low) ;
begin
  . . .
  DataInt := RV.RandInt(0, 100, Prev4DataInt) ;

  Prev4DataInt := Prev4DataInt(2 downto 0) & DataInt ;
  . . .
```

10 Creating a Test

Creating tests is all about methodology. SynthWorks' methodology marries randomization subprograms (from RandomPkg) and functional coverage subprograms (from CoveragePkg - also freely available at http://www.synthworks.com/downloads) with VHDL programming constructs. Each test sequence is derived by randomly selecting either branches of code or values for operations. Randomization constraints are created using normal sequential coding techniques (such as nesting of case, if, loop, and assignment statements). This approach is simple yet powerful. Since all of the code is sequential, randomized sequences are readily mixed with directed and algorithmic sequences.

A simple demonstration of randomizing is the following test which uses heuristics (guesses) at length of bursts of data and delays between bursts of data to randomization traffic being sent to a FIFO.

```
variable RV : RandomPType ;
. . .
TxStimGen : while TestActive loop
  -- Burst between 1 and 10 values
  BurstLen := RV.RandInt(Min => 1, Max => 10);
  for i in 1 to BurstLen loop
    DataSent := DataSent + 1 ;
    WriteToFifo(DataSent) ;
  end loop ;
   --  Delay between bursts: (BurstLen <=3: 1-6, >3: 3-10)
  if BurstLen <= 3 then
    BurstDelay := RV.RandInt(1, 6) ;  -- small burst, small delay
  else
    BurstDelay := RV.RandInt(3, 10) ; -- bigger burst, bugger delay
  end if ;
  wait for BurstDelay * tperiod_Clk - tpd ;
  wait until Clk = '1' ;
end loop TxStimGen ;
```

Functional coverage counts which test cases have been generated and give engineers an indication of when testing is done. This is essential when using randomization to create a test as otherwise there is no way to know what the test actually did. Functional coverage can be implemented using subprogram calls (either custom or from the CoveragePkg) or VHDL code. Functional coverage is stored in signals and can be used to change the randomization (either directly as a constraint or indirectly as something that contributes to changing a constraint) to generate missing coverage items.

With a FIFO, we need to see lots of write attempts while full and read attempts while empty. One thing we can do to improve the previous test is to increase or decrease the burst length and delay based on the number of write attempts while full or read attempts while empty we have seen. To explore how to generate the coverage, see the CoveragePkg documentation.

For a design for which has numerous conditions we need to generate, we can do coverage on the input stimulus and then randomly select one of the uncovered conditions as the next transaction to be generated.

Solutions for the two previous coverage driven randomization problems are provided in SynthWorks' VHDL Testbenches and Verification class.

11 Random Stability

A protected type is always used with a variable object. If the object is declared in a process, it is a regular variable. If the object is declared in an architecture, then it is declared as a shared variable.

All of the examples in this document show RandomPType being defined in a process as a regular variable. This is done to ensure random stability. Random stability is the ability to re-run a test and get exactly the same sequence. Random stability is required for verification since if we find a failure and then fix it, if the same sequence is not generated, we will not know the fix actually worked.

Random stability is lost when a randomization variable is declared as a shared variable in an architecture and shared among multiple processes. When a randomization variable is shared, the seed is shared. Each randomization reads and updates the seed. If the processes accessing the shared variable run during the same delta cycle, then the randomization of the test depends on the order of which RandomPType is accessed. This order can change anytime the design is optimized - which will happen after fixing bugs. As a result, the test is unstable.

To ensure stability, create a separate variable for randomization in each process.

12 Other Distributions

By default, all randomizations use a uniform distribution. In addition to uniform distributions, RandomPType also provides distributions for FavorSmall, FavorBig, normal, and poisson. The following is the overloading for these functions.

```
-- Generate values, each with an equal probability
impure function Uniform (Min, Max : in real) return real ;
impure function Uniform (Min, Max : integer) return integer ;
```

```
impure function Uniform (Min, Max : integer ; Exclude: integer_vector) return
integer ;

-- Generate more small numbers than big
impure function FavorSmall (Min, Max : real) return real ;
impure function FavorSmall (Min, Max : integer) return integer ;
impure function FavorSmall(Min, Max: integer; Exclude: integer_vector) return
integer ;

-- Generate more big numbers than small
impure function FavorBig (Min, Max : real) return real ;
impure function FavorBig (Min, Max : integer) return integer ;
impure function FavorBig (Min, Max : integer ; Exclude: integer_vector) return
integer ;

-- Generate normal = gaussian distribution
impure function Normal (Mean, StdDeviation : real) return real ;
impure function Normal (Mean, StdDeviation, Min, Max : real) return real ;
impure function Normal (
      Mean          : real ;
      StdDeviation  : real ;
      Min           : integer ;
      Max           : integer ;
      Exclude       : integer_vector := NULL_INTV
) return integer ;

-- Generate poisson distribution
impure function Poisson (Mean : real) return real ;
impure function Poisson (Mean, Min, Max : real) return real ;
impure function Poisson (
      Mean          : real ;
      Min           : integer ;
      Max           : integer ;
      Exclude       : integer_vector := NULL_INTV
) return integer ;
```

The package also provides experimental mechanisms for changing the distributions used with functions RandInt, RandSlv, RandUnsigned, and RandSigned.

13 Sorting integer_vector

The package SortListPkg_int provides a Sort and RevSort functions for sorting type integer_vector. The following example uses RandIntV and Sort to create a random set of 10 integer values between 0 and 255 that increase in value and do not repeat.

```
IntV := Sort(RV.RandIntV(0, 255, 10, 10)) ;
```

The overloading for Sort and RevSort are as follows.

```
impure function Sort (A : integer_vector) return integer_vector;
impure function RevSort (A : integer_vector) return integer_vector ;
```

14 Compiling RandomPkg and Friends

See OSVVM_release_notes.pdf for the current compilation directions. Rather than referencing individual packages, we recommend using the context declaration:

```
library OSVVM ;
  context osvvm.OsvvmContext ;
```

15 About RandomPkg

RandomPkg was developed and is maintained by Jim Lewis of SynthWorks VHDL Training. It evolved from methodology and packages developed for SynthWorks' VHDL Testbenches and verification class. It is part of the Open Source VHDL Verification Methodology (OSVVM), which brings leading edge verification techniques to the VHDL community.

Please support our effort in supporting RandomPkg and OSVVM by purchasing your VHDL training from SynthWorks.

RandomPkg is released under the Apache open source license. It is free (both to download and use - there are no license fees). You can download it from https://github.com/OSVVM/OSVVM. It will be updated from time to time. Currently there are numerous planned revisions.

If you add features to the package, please donate them back under the same license as candidates to be added to the standard version of the package. If you need features, be sure to contact us. I blog about the packages at http://www.synthworks.com/blog. We also support a user community and blogs through http://www.osvvm.org.

If you find any innovative usage for the package, let us know - we can set you up to

16 Future Work

RandomPkg.vhd is a work in progress and will be updated from time to time.

Things not documented in this document, such as type RandomParmType and method SetRandomParm, are experimental and may be removed in a future revision of the package (to reduce the overhead to basic randomization). Note that the current version of this package gives direct access to this capability via methods FavorSmall, FavorBig, normal, and poisson.

17 About the Author - Jim Lewis

Jim Lewis, the founder of SynthWorks, has thirty plus years of design, teaching, and problem solving experience. In addition to working as a Principal Trainer for SynthWorks, Mr Lewis has done ASIC and FPGA design, custom model development, and consulting.

Mr. Lewis is chair of the IEEE 1076 VHDL Working Group (VASG) and is the primary developer of the Open Source VHDL Verification Methodology (OSVVM.org) packages. Neither of these activities generate revenue. Please support our volunteer efforts by buying your VHDL training from SynthWorks.

If you find bugs these packages or would like to request enhancements, you can reach me at jim@synthworks.com.