DIRECTED ENERGY PROFESSIONAL SOCIETY

SECURITY THROUGH DIRECTED ENERGY

Short Course

Introduction to tempus

MZA Associates Corporation

Bob Praus & Steve Coy
praus@mza.com

2021 Girard Blvd. SE, Suite 150
Albuquerque, NM 87106
voice: (505)245-9970, ext. 111

Certain features of tempus are Patent Pending
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Course Abstract

Computer simulation has become an important tool in many fields of endeavor, from science and engineering to computer based training and computer animation. Over the years considerable progress has been made in tools and methodologies for simulation, but much of this progress has come in the form of improvements to a variety of relatively specialized tools, for modeling control systems, flexible structures, fluid dynamics, communication networks, and so forth. By comparison, relatively little progress had been made in tools designed to support interdisciplinary simulation, involving interactions among subsystems with qualitatively dissimilar behaviors and requiring differing modeling approaches.

tempus is a simulation executive that uses a powerful and flexible block diagram-based architecture designed to meet the demands of interdisciplinary simulation. Combining ideas from object-oriented programming and hybrid simulation, tempus can be used to model just about anything. It has an open architecture, which makes it easy to integrate other software into tempus, and vice versa. This course provides an introduction to the application of tempus to the development of large, complex, and interdisciplinary models.

Course Objectives

- **Explain the motivation for the existence and design of tempus.**
- **Explain how to use tempus.**
- **Explain how to develop models with tempus, including developing new source code capabilities.**

The terminologies of computer programming and simulation are not always standardized. The terms and concepts used throughout this lesson may have broader meanings than that which is used here.

Authors

Bob Praus	praus@mza.com
Steve Coy	coy@mza.com
MZA Associates Corporation	www.mza.com

Acknowledgments

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References

- Modeling and Simulation
  - http://en.wikipedia.org/wiki/Simulation#Computer_simulation
  - http://www.dmem.strath.ac.uk/~pball/simulation/simulate.html
  - http://www.ecs.umass.edu/ece/labs/codes/bktoc.html
  - http://www.imaginethatinc.com/sols_simoverview.html
  - http://www.ici.ro/ici/revista/sic2002_1/art05.htm

- Object-oriented Programming
  - http://en.wikipedia.org/wiki/Object-oriented_programming

- The C++ Programming Language
  - http://www.pcai.com/web/ai_info/pcai_cpp.html
  - http://public.research.att.com/~bs/
  - http://www.cppforlife.tk/

Agenda

Modeling and simulation concepts	**1300**
Time-domain and discrete event modeling	
Composition-based modeling	
Isomorphic modeling	
Multi-modeling	
Simulation executives	
Object-oriented modeling in C++	
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Overview	
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tempus concepts	
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Modeling and Simulation Concepts

- Time-domain and discrete event modeling
- Composition-based modeling
- Isomorphic modeling
- Multi-modeling
- Simulation executives
- Object-oriented modeling in C++

Modeling and Simulation Concepts
(1 of 2)

- **Simulation: the technique of imitating the behavior of some situation or system (economic, mechanical, etc.) by means of an analogous model, situation, or apparatus, either to gain information more conveniently or to train personnel. (Oxford Eng. Dictionary)**

- **Time-domain modeling: a technique in which the performance of a system is simulated by predicting the state of the system as a function of time.**

- **Discrete event-driven modeling: a time-domain simulation technique in which the logic of the simulation is primarily governed by specific events which occur within the modeled system.**

Modeling and Simulation Concepts
(2 of 2)

- **Composition-based modeling: the process of building software models by combining smaller, more fundamental, software components.**

- **Multi-modeling: the use of composition-based modeling in interdisciplinary physical modeling problems.**

- **Variable fidelity modeling: the process of building and employing a model which has multiple levels of fidelity.**

- **Isomorphic: exactly corresponding in form and relations. (Oxford Eng. Dictionary)**

- **Isomorphic modeling: the design and implementation of a model using isomorphism as a prevailing guiding principle.**

Simulation Executives

- **Software tools meant to assist in the development and use of simulations.**
- **Usually specific to a particular domain.**
- **One would rarely use the simulation executive if one were not interested in the particular domain to which the simulation executive applies.**
- **Generally not appropriate for large simulations.**
- **Usually composition-based.**
- **Methods to expand the library of models is limited.**
- **Component behavior is usually limited to a particular fundamental modeling approach.**
- **Examples: Simulink, Easy5, acslXtreme, Systembuild, SPICE**

Modeling and Simulation Concepts

- Time-domain and discrete event modeling
- Composition-based modeling
- Isomorphic modeling
- Multi-modeling
- Simulation executives
- Object-oriented modeling in C++

Object-Oriented Programming

- **A computer programming paradigm in which a program is based on a collection of individual units, or objects, that act on each other, as opposed to a traditional (procedural) paradigm in which a program may be seen as a collection of functions or procedures, or simply as a list of instructions to the computer. Each object is capable of receiving messages, processing data, and sending messages to other objects. (Wikipedia)**

Object Oriented Programming
The Benefits

- Benefits of OOP
  - Facilitates the application of isomorphism - the programming practice of implementing a one-to-one correspondence between segments of code and modeled entities.
  - Facilitates modularity of both code and data.
  - Facilitates the application of polymorphism - the programming practice of using the same code for different objects which have common characteristics.
  - High-level (executive) code is highly readable.

- Benefits of C++
  - Both widespread and highly supported.
  - Very efficient (largely because it is based on C).
  - Supports the implementation of both high-level (executive) and low-level (math and bit-twiddling) code.

There are a lot of advantages to OOP. See Object-Oriented Analysis and Design by Grady Booch for more complete information.

Object Oriented Programming

The Perils (because you can)

- Perils of OOP
  - OOP codes are <u>susceptible to over-design</u> -- churning over the design of a particular feature without any real benefit (because you can).
  - OOP codes are <u>susceptible to over-implementation</u> -- coding an object such that it can do any conceivable operation (because you can) when all that is really necessary is meeting current requirements. This results in wasted effort and a legacy of untested code because many routines are never used.
  - As a result of the two previous susceptablities, <u>OOP codes can become spaghetti codes</u> of a new sort. This particular form of tangularity results in practically every line of code being a reference to code in some other compilation unit. Finding bugs then involves a lot of unnecessary hopping around between source files.
  - Programmers can <u>mistakenly rely on the OOP model</u> as a substitute for true innovation (because you can) .
- Perils of C++
  - <u>C++ arrays are inflexible</u> (especially multi-dimensional arrays). For mathematical codes, this results in having to implement a substitute.
  - <u>C++ pointers are dangerous</u>. Memory leaks and dangling pointers are common.
  - <u>C++ templates can be bad</u>. Don’t use them unless you know what you are doing.
  - <u>C++ has obtuse syntax</u>. Low-level code can be difficult to read.

Despite these dangers, using OOP within C++ is probably the most flexible and powerful contemporary approach to developing a complex application which is both portable and efficient.

Base Classes and Virtual Methods

***Classes*, *base classes* and *virtual methods* are all standard terms used in *object-oriented programming*.**

A *class* is language-level construct which can be used to encapsulate a well-defined software representation of a specific category of objects, including both its *data members* and its *behavior*.

A class can *inherit* attributes (data and/or behavior) from one or more other classes, called its *base classes*. Some classes, like *System* in tempus, are specifically designed to be used as base classes.

***Virtual methods* are "stub" functions defined in a base class which can be re-defined by derived classes. Virtual methods are used to define standardized interfaces for customizable behaviors.**

C++ Templates

- Templates are a way of implementing C++ functions and classes in a type-neutral kind of way.
- The Type of interest is specified to the Template code at compile time and the appropriate code is generated taking into account fairly generic aspects of the underlying type.
- This is how one might implement a vector of integers with essentially the same code as they might implement a vector of floats.
- Templates can also be used to specify other compile-time attributes.

C++ Code

Base class:

```
class TRect {
public:
   // data members
   short fTop;
   short fLeft;
   short fBottom;
   short fRight;
   // member functions
   virtual short Area(void);
   Boolean PointInRect(Point thePt);
};
```

Class which uses inheritance:

```
class TRoundRect : public TRect {
protected:
   // added data members
   short fHOval;
   short fVOval;
   // override the area member function
   virtual short Area(void);
};
```

Template class:

```
template<class T> class vector {
   T* v;
   int sz;
public:
   vector (int);
   T& operator[] (int);
   T& elem(int i) { return v[i]; }
   // ...
};
```

Using Classes:

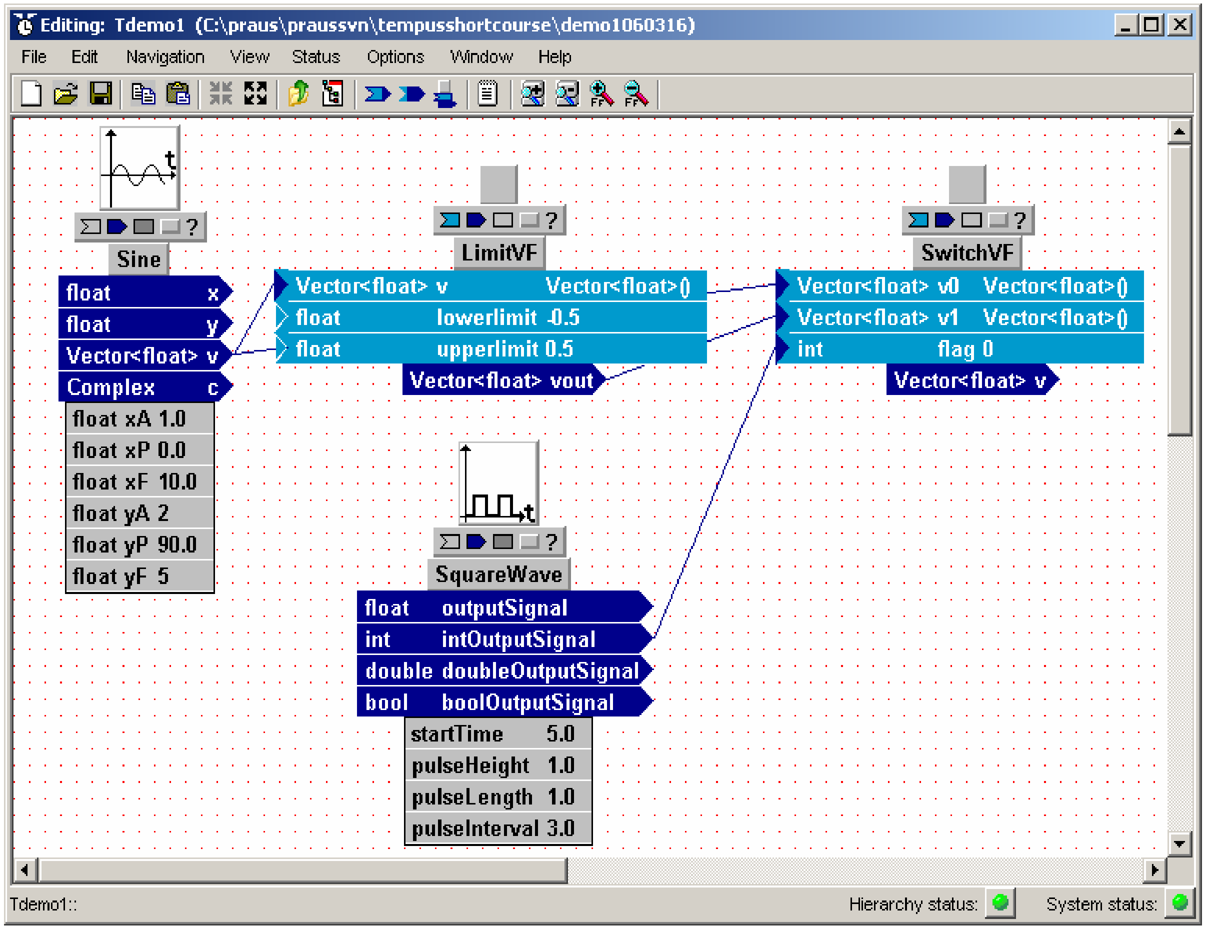
```
int top, left, bottom, right;
...
TRect r(top, left, bottom, right);
TRoundRect rr(top, left, bottom, right);

vector<float> vf(5);
vf[0] = (r.area() + rr.area())/2.0;

vector<int> vi(4);
vi[0] = top;
vi[1] = left;
vi[2] = bottom;
vi[3] = right;
```

The tempus Paradigm

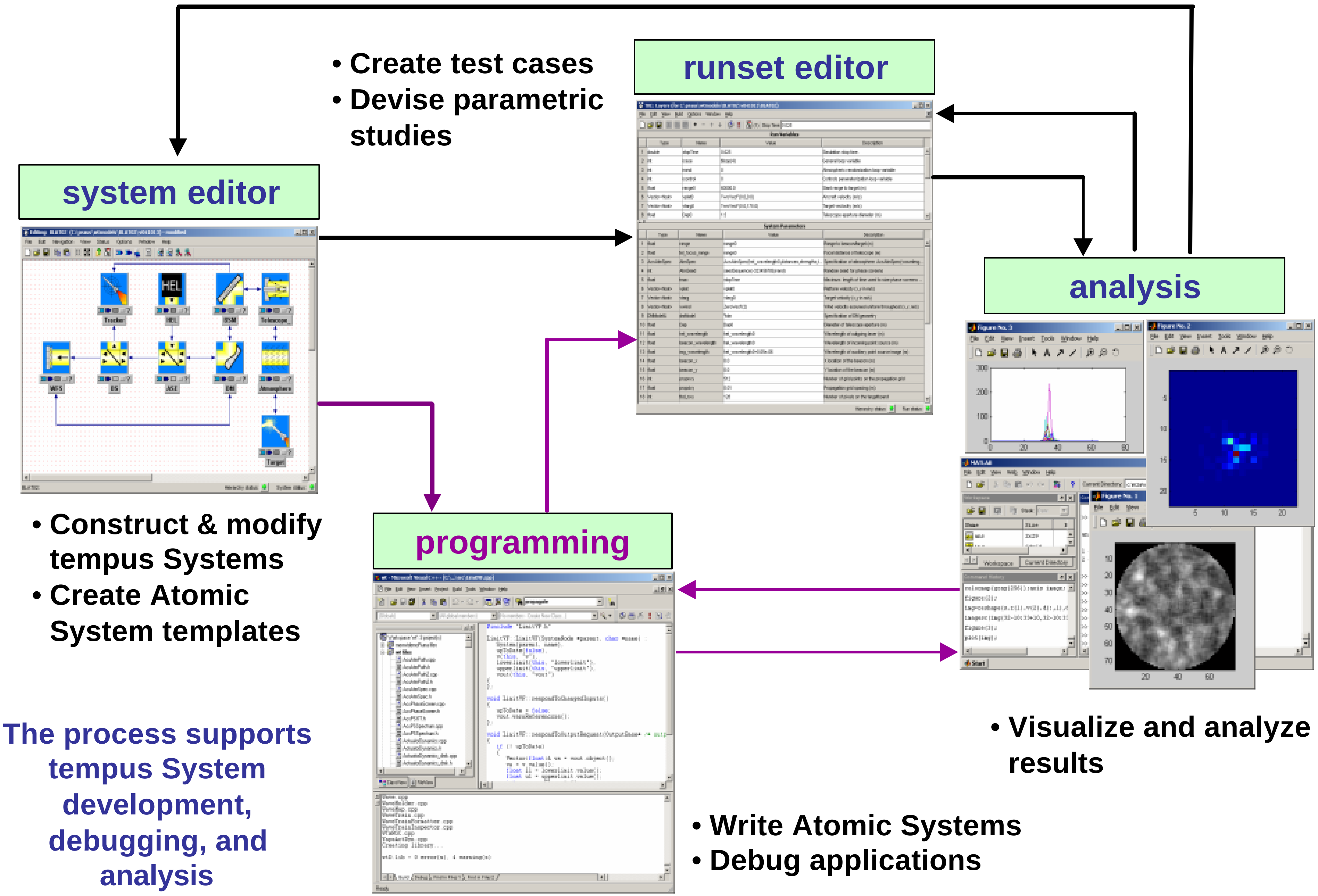
- Overview
- tempus visual editor
- tempus concepts
- Connection-driven execution
- tempus source form

tdemo1 Example

- To provide context, we'll go to a short demonstration the creation, execution, examination, and manipulation of a simple tempus user application.



tempus Process Flow

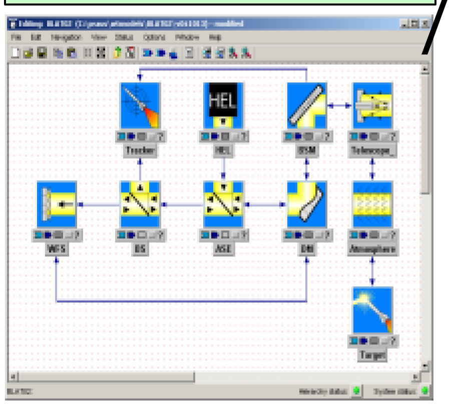


The process supports tempus System development, debugging, and analysis

tempus User Applications

runset editor

system editor



Notional Generated Code

```
#include "tempus.h"
#include "TopLevel.h"

int main(int argc, char* argv[])
{
   Universe u(NULL, "u");
   int p1 = 2;
   double p2 = 3.1415;
   for (iloop=0; iloop<nloop; iloop++)
   {
      double p3 = iloop * p1 * p2;
      TopLevel t(u, "t", p1, p2, p3);
      Recorder r(u, "r");
      r.i <== t.ss.o;
      u.advanceTime(stopTime);
   }
}
```

```
class TopLevel : public System {
public:
   int p1;
   double p2;
   double p3;
   Subsystem ss;
   TopLevel(System* p, char* n, int _p1,...) :
      System(p, n),
      p1(_p1), p2(_p2), p3(_p3), ss(p1, p2, p3)
   {
   ...
   }; ...
}
```

User Code

tempus kernel Classes

Universe

System
Input<T>
Output<T>

tempus Utilities

Recording

Numerical Library

User Libraries

Libraries of Systems

Utility Code

The tempus Paradigm

Overview

tempus visual editor

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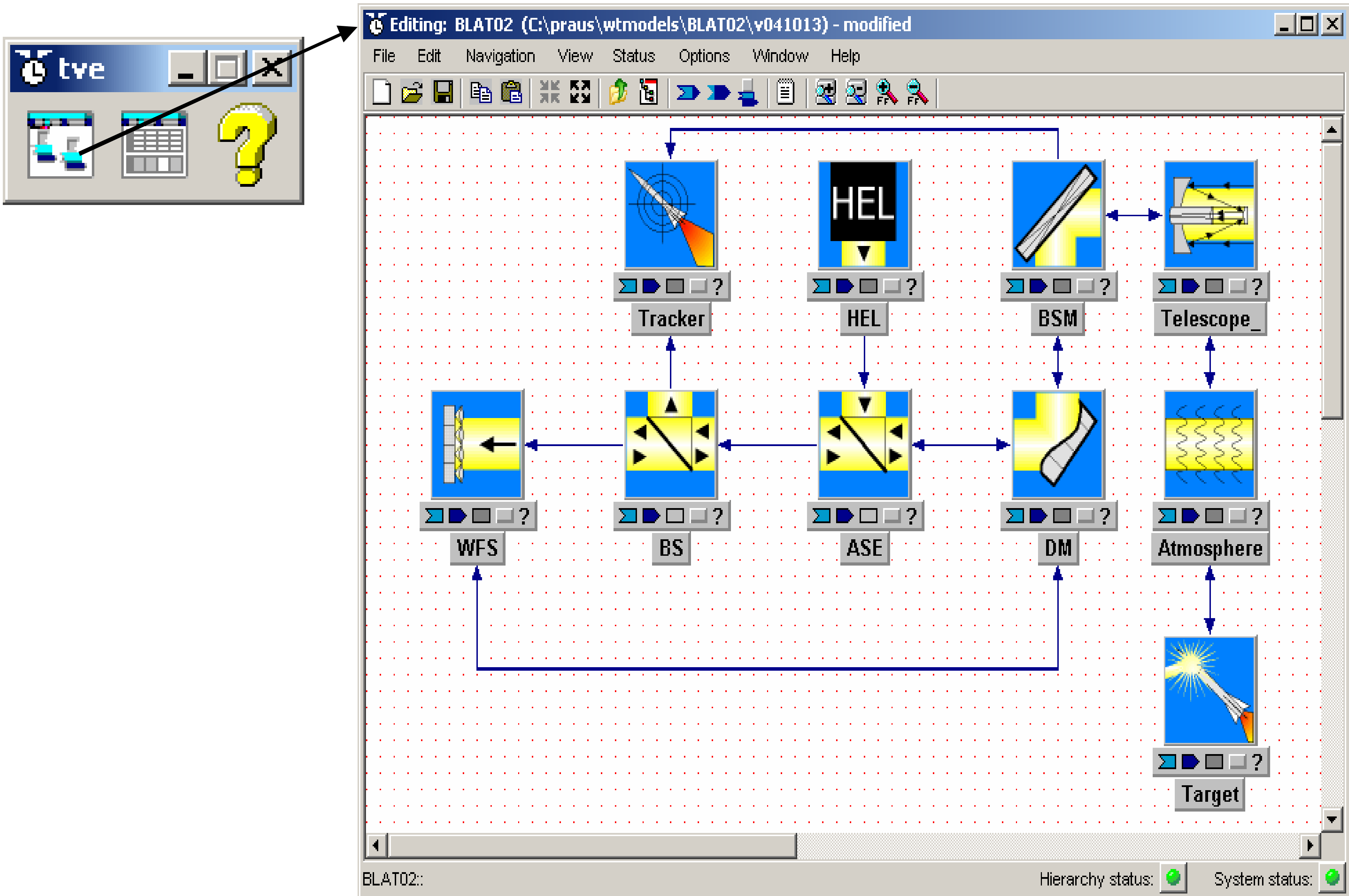
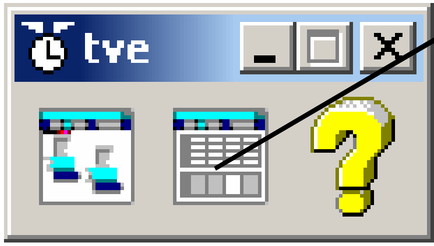
tempus Visual Editor

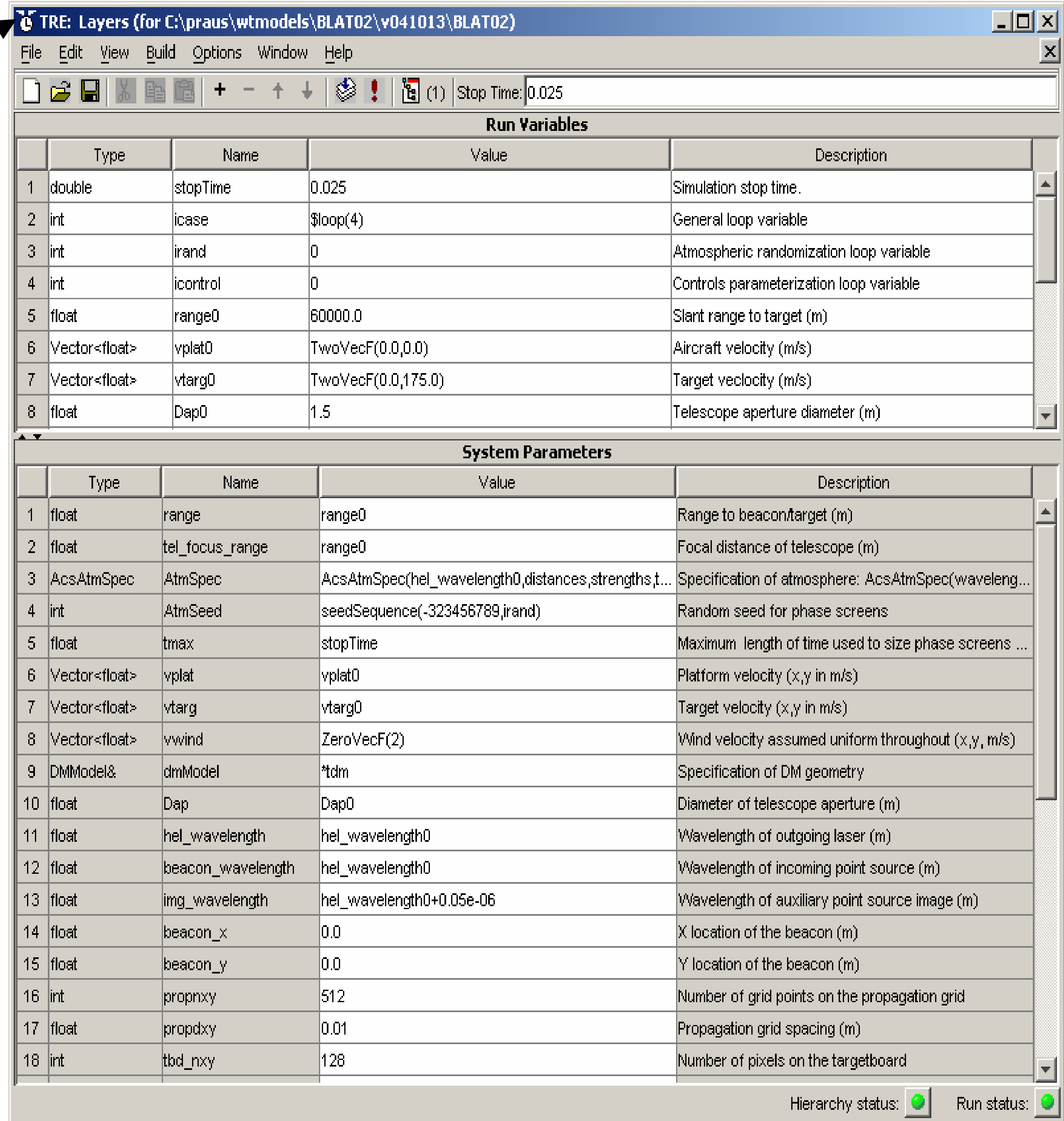
Concept	Description
tve – tempus visual editor	The graphical user interface (GUI) through which the user constructs tempus models and sets up and executes tempus simulations. Given user inputs, the tve generates code which is compiled and linked with user-written code to create and execute user applications.
tse – tempus system editor	The tve window used to create, configure, and edit tempus Systems.
tre – tempus runset editor	The tve window used to set up and execute tempus simulations.

tve & tse


tve
Editing: BLAT02 (C:\praus\wtmodels\BLAT02\v041013) - modified
File Edit Navigation View Status Options Window Help
Tracker
HEL
BSM
Telescope_
WFS
BS
ASE
DM
Atmosphere
Target
BLAT02::
Hierarchy status:
System status:

tve & tre





Run Variables

	Type	Name	Value	Description
1	double	stopTime	0.025	Simulation stop time.
2	int	icase	$loop(4)	General loop variable
3	int	irand	0	Atmospheric randomization loop variable
4	int	icontrol	0	Controls parameterization loop variable
5	float	range0	60000.0	Slant range to target (m)
6	Vector<float>	vplat0	TwoVecF(0.0,0.0)	Aircraft velocity (m/s)
7	Vector<float>	vtarg0	TwoVecF(0.0,175.0)	Target veclocity (m/s)
8	float	Dap0	1.5	Telescope aperture diameter (m)

System Parameters

	Type	Name	Value	Description
1	float	range	range0	Range to beacon/target (m)
2	float	tel_focus_range	range0	Focal distance of telescope (m)
3	AcsAtmSpec	AtmSpec	AcsAtmSpec(hel_wavelength0,distances,strengths,t...	Specification of atmosphere: AcsAtmSpec(waveleng...
4	int	AtmSeed	seedSequence(-323456789,irand)	Random seed for phase screens
5	float	tmax	stopTime	Maximum length of time used to size phase screens ...
6	Vector<float>	vplat	vplat0	Platform velocity (x,y in m/s)
7	Vector<float>	vtarg	vtarg0	Target velocity (x,y in m/s)
8	Vector<float>	vwind	ZeroVecF(2)	Wind velocity assumed uniform throughout (x,y, m/s)
9	DMModel&	dmModel	*tdm	Specification of DM geometry
10	float	Dap	Dap0	Diameter of telescope aperture (m)
11	float	hel_wavelength	hel_wavelength0	Wavelength of outgoing laser (m)
12	float	beacon_wavelength	hel_wavelength0	Wavelength of incoming point source (m)
13	float	img_wavelength	hel_wavelength0+0.05e-06	Wavelength of auxiliary point source image (m)
14	float	beacon_x	0.0	X location of the beacon (m)
15	float	beacon_y	0.0	Y location of the beacon (m)
16	int	propnxy	512	Number of grid points on the propagation grid
17	float	propdxy	0.01	Propagation grid spacing (m)
18	int	tbd_nxy	128	Number of pixels on the targetboard

The tempus Paradigm

Overview

tempus visual editor

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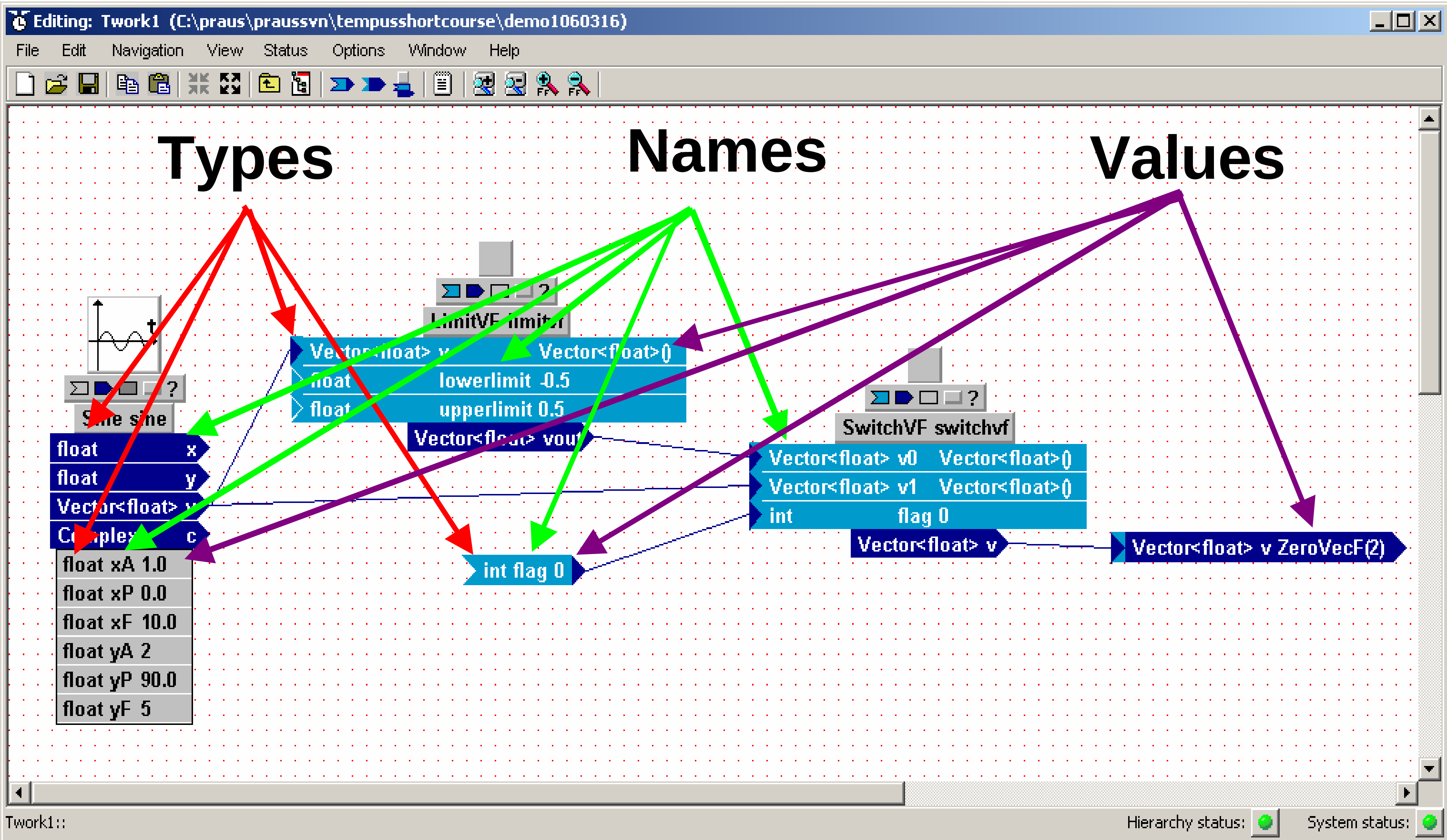
Variables, Types, and Names

- **Systems, Inputs, Outputs, and Parameters are implemented as programming variables and all have types and names.**
- **Type refers to the particular data type of the entity. In this usage, type and class are nearly synonymous.**
  - **All Systems are of some Type which must be derived from class System. So all Systems are classes.**
  - **All Inputs and Outputs have a type, but not through inheritance. Rather, Inputs and Outputs get their type through a template argument. The type can be just about any valid C++ type, but it must support a few standard operations. The GUI hides the details concerning the use of templates.**
  - **Parameters are simple variables of a user-specified type. The type which can be simple, such as float or int or more complex, such as an arbitrary class. The type can be just about any valid C++ type, but it must support a few standard operations.**
- **Name refers to the name of the particular variable within the context that it resides.**

Types and names in the tve



tempus Classes

Class	Description
System	The base class for the fundamental building block of tempus applications. Specific Systems can be automatically generated or user-written. Systems are configured by their Parameters and contain Inputs and Outputs in facilitate time-domain interfaces with other Systems.
Input<T>	The primary mechanism through which a System is affected by other Systems.
Output<T>	The primary mechanism through which a System can effect other Systems.
Universe	A top-level executive object which controls the order of System execution and the passage of time.

Categories of Systems

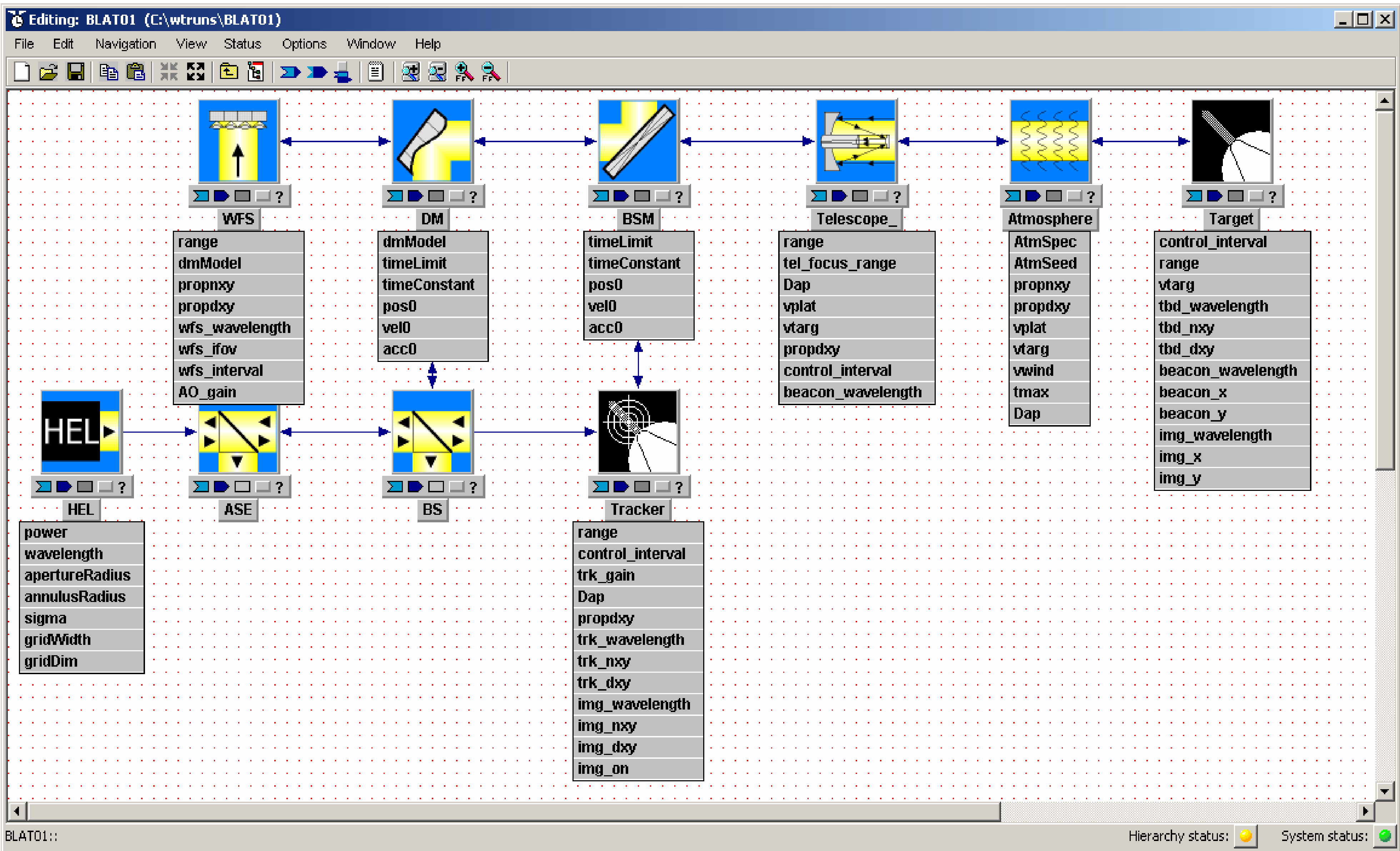
Concept	Description
Subsystem	A System contained in another System. Almost all Systems are Subsystems because all Systems, except the very top-level System, is contained by another.
Composite System	A System composed of one or more Systems. Composite Systems are typically (but don't have to be) generated by the tempus system editor.
Atomic System	A System written to carry-out computations of specific interest. Ultimately, all of the meaningful computation of a tempus user application is done by an Atomic System.
Top-level System	A System which contains all other Systems in a particular tempus user application.

tempus Parametric Concepts

Concept	Description
Parameter	The mechanism through which Systems are configured. The values of Parameters are provided to Systems through constructor arguments, so they are only effective in specifying static initialization inputs. Parameters of Subsystems are often specified by expressions involving Parameters of the System that contains them.
Runset	The collection of information which specifies the Parameter values for a set of user application executions. The Runset specifies the Parameter values for the Top-Level System which Outputs are to be recorded.

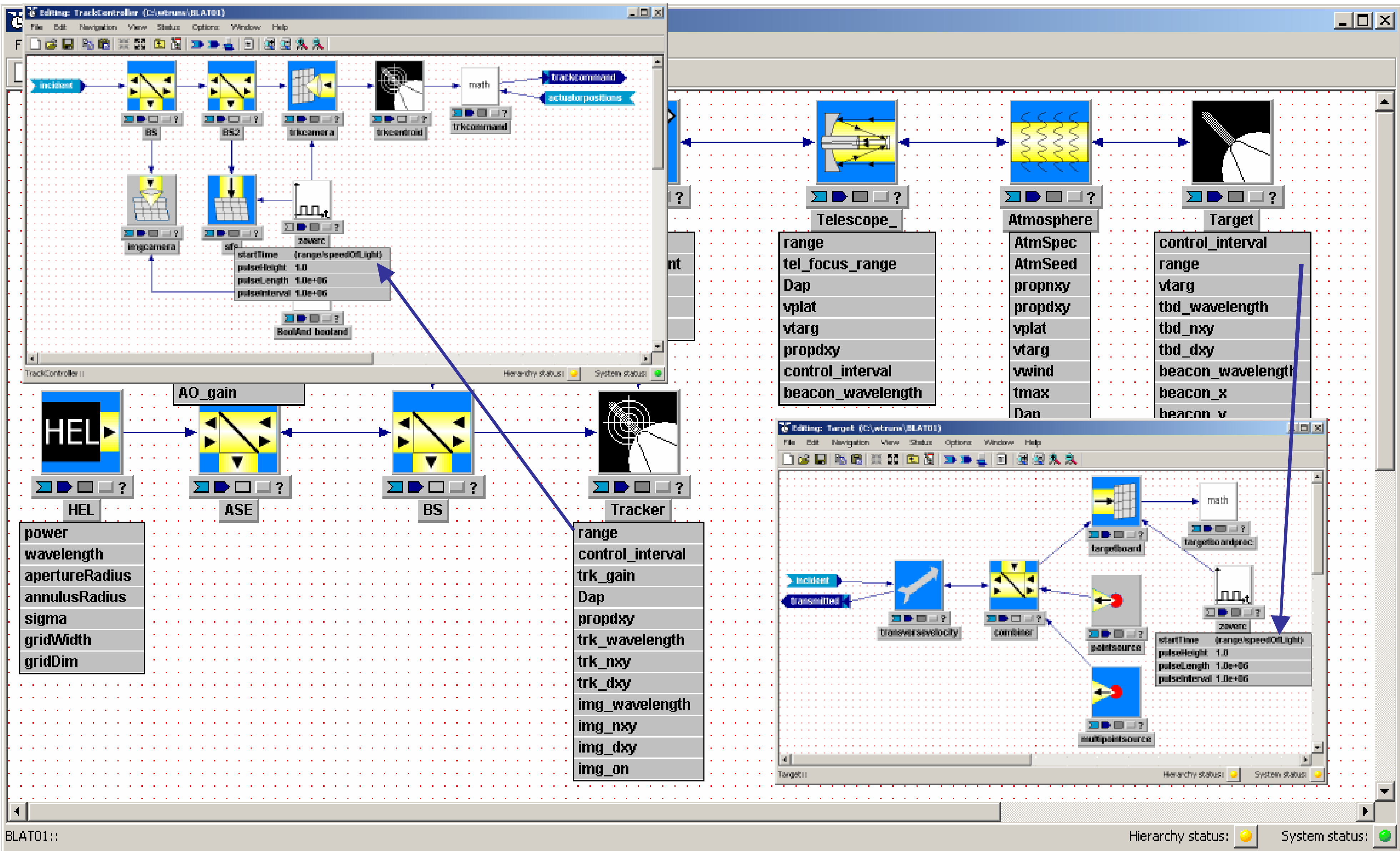
tempus Concepts

System Parameters



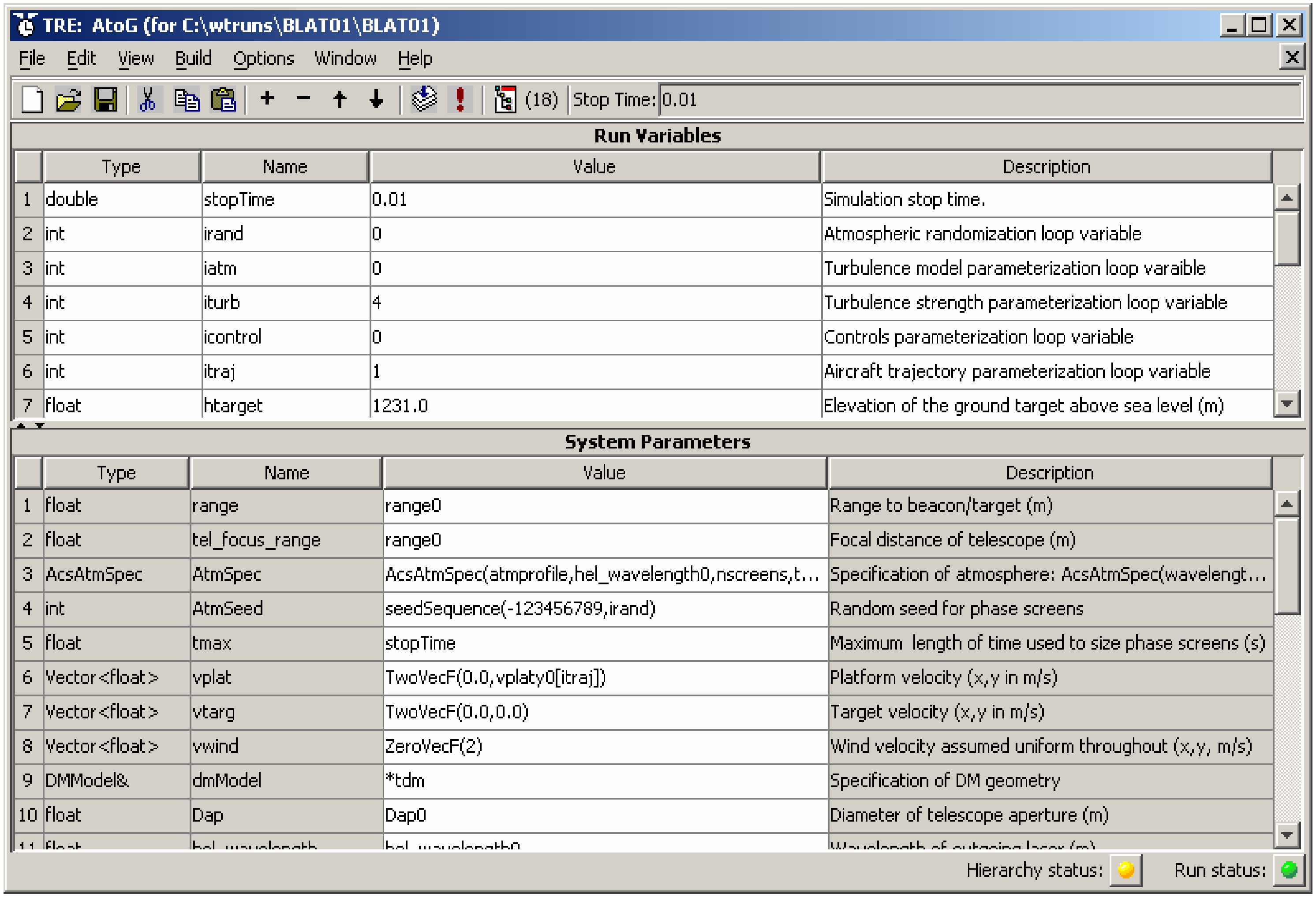
tempus Concepts

System Parameters Flow Down from Containing Systems



tempus Concepts

Runsets



TRE: AtoG (for C:\wtruns\BLAT01\BLAT01)

File Edit View Build Options Window Help

(18) Stop Time: 0.01

Run Variables

	Type	Name	Value	Description
1	double	stopTime	0.01	Simulation stop time.
2	int	irand	0	Atmospheric randomization loop variable
3	int	iatm	0	Turbulence model parameterization loop varaible
4	int	iturb	4	Turbulence strength parameterization loop variable
5	int	icontrol	0	Controls parameterization loop variable
6	int	itraj	1	Aircraft trajectory parameterization loop variable
7	float	htarget	1231.0	Elevation of the ground target above sea level (m)

System Parameters

	Type	Name	Value	Description
1	float	range	range0	Range to beacon/target (m)
2	float	tel_focus_range	range0	Focal distance of telescope (m)
3	AcsAtmSpec	AtmSpec	AcsAtmSpec(atmprofile,hel_wavelength0,nscreens,t...	Specification of atmosphere: AcsAtmSpec(wavelengt...
4	int	AtmSeed	seedSequence(-123456789,irand)	Random seed for phase screens
5	float	tmax	stopTime	Maximum length of time used to size phase screens (s)
6	Vector<float>	vplat	TwoVecF(0.0,vplaty0[itraj])	Platform velocity (x,y in m/s)
7	Vector<float>	vtarg	TwoVecF(0.0,0.0)	Target velocity (x,y in m/s)
8	Vector<float>	vwind	ZeroVecF(2)	Wind velocity assumed uniform throughout (x,y, m/s)
9	DMModel&	dmModel	*tdm	Specification of DM geometry
10	float	Dap	Dap0	Diameter of telescope aperture (m)
11	float	hel_wavelength	hel_wavelength0	Wavelength of outgoing laser (m)

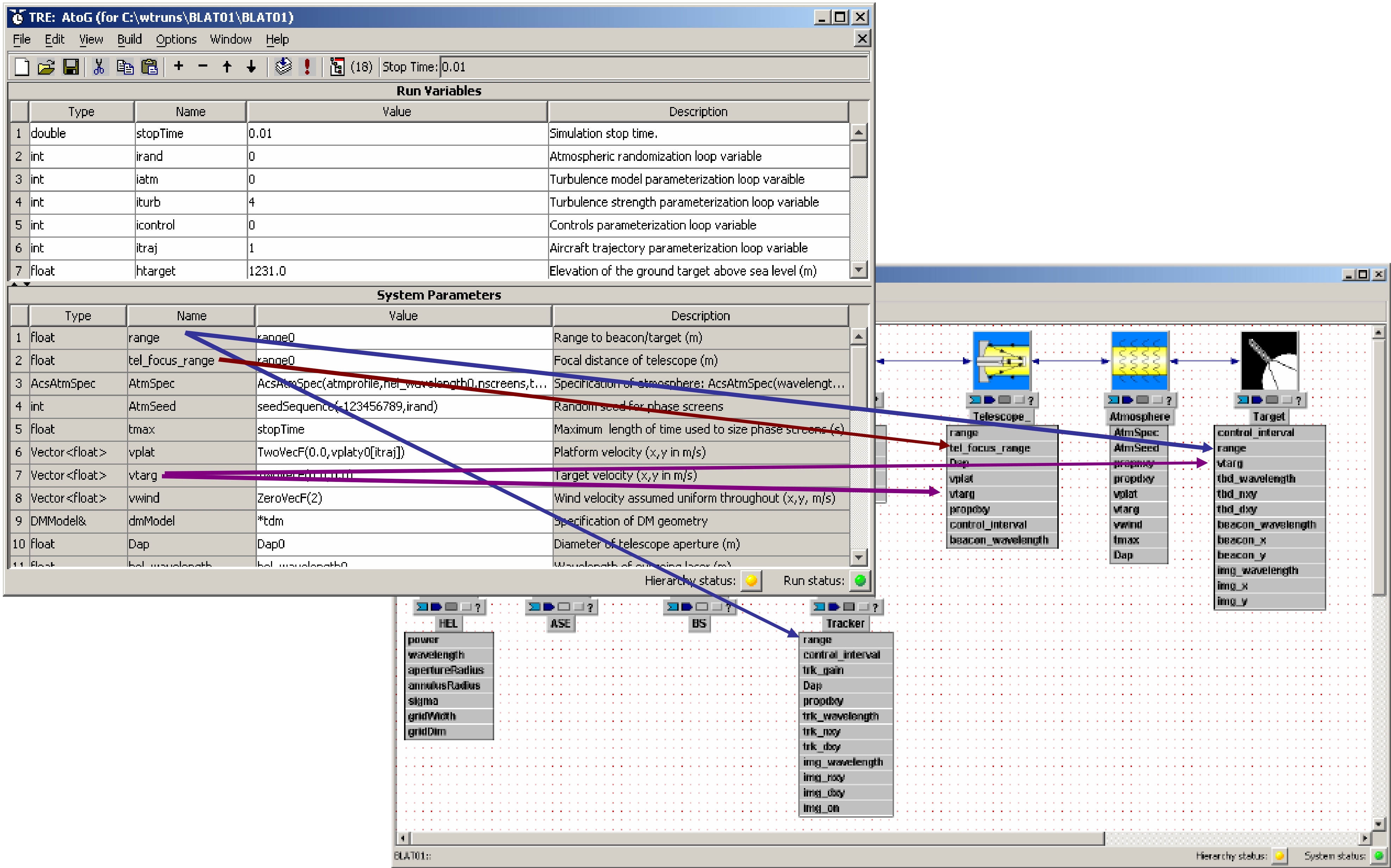
Hierarchy status: Run status:

Runsets…

- define the values of all parameters which the model-builder has “flowed-up” to the user.
- provide a configuration management tool for defining the inputs of a run.
- are used to set up parametric studies, allowing parameters to be changed systematically.
- definitions help to define how work is distributed across multiple processors.

tempus concepts

Block Parameters Flow Down from Runset



Concepts Not Detailed in This Course

Concept	Description
Recallability	The mechanism through which Systems can request the values of their input for some time in the past.
Recallable<T>	The class through which Recallability is implemented.
SaveVariable<T>	Another class which helps implement Recallability.

The tempus Paradigm

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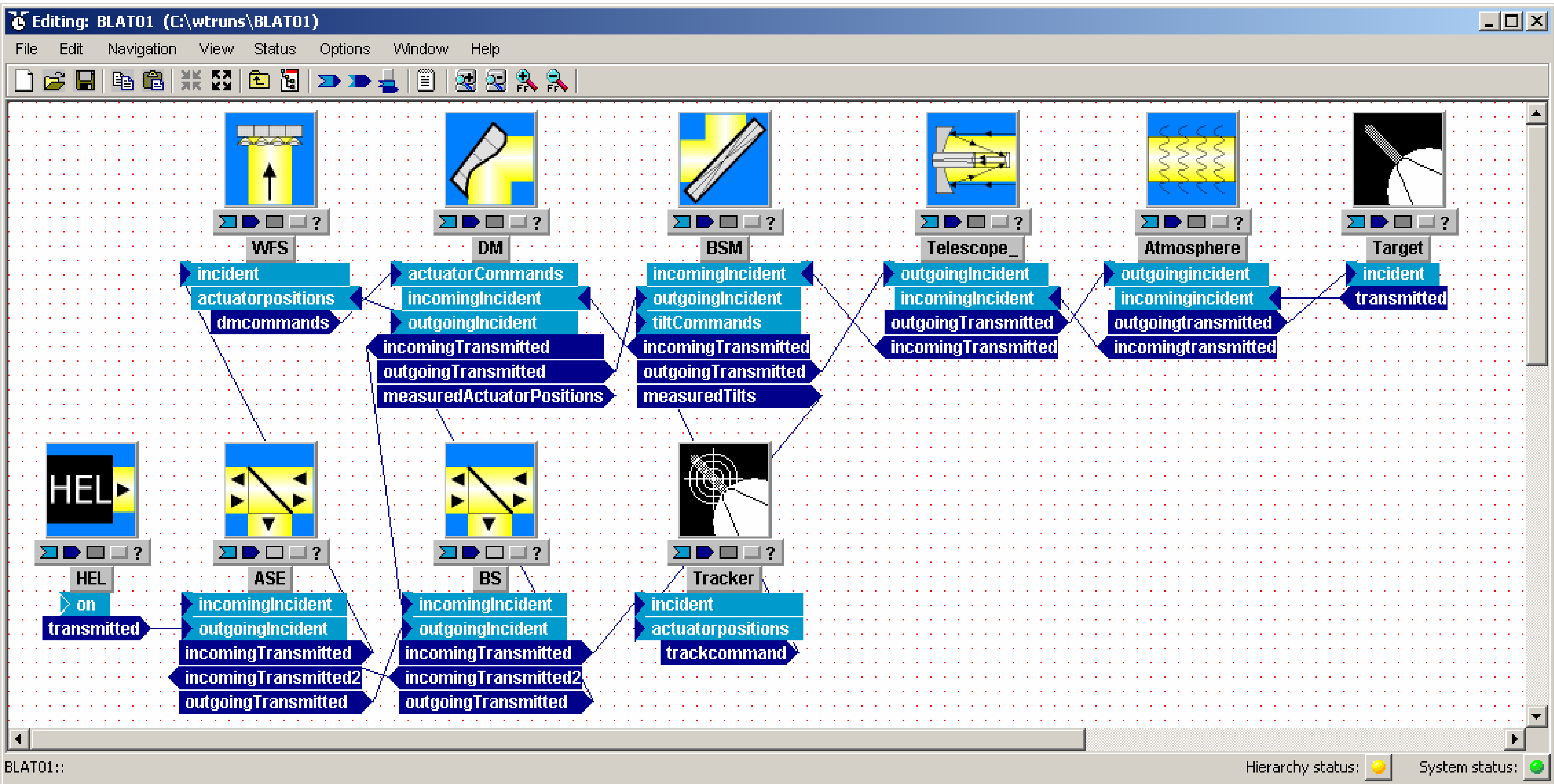
tempus Concepts
Inputs, Outputs, and Connectivity



Input and Output Types

- Inputs and Outputs are template-typed classes.
- Inputs and Outputs can be of nearly any valid C++ type.
- Connections are only made between two entities of the same type.
- Provisions have been made to provide automatic conversions between types which are nearly compatible.

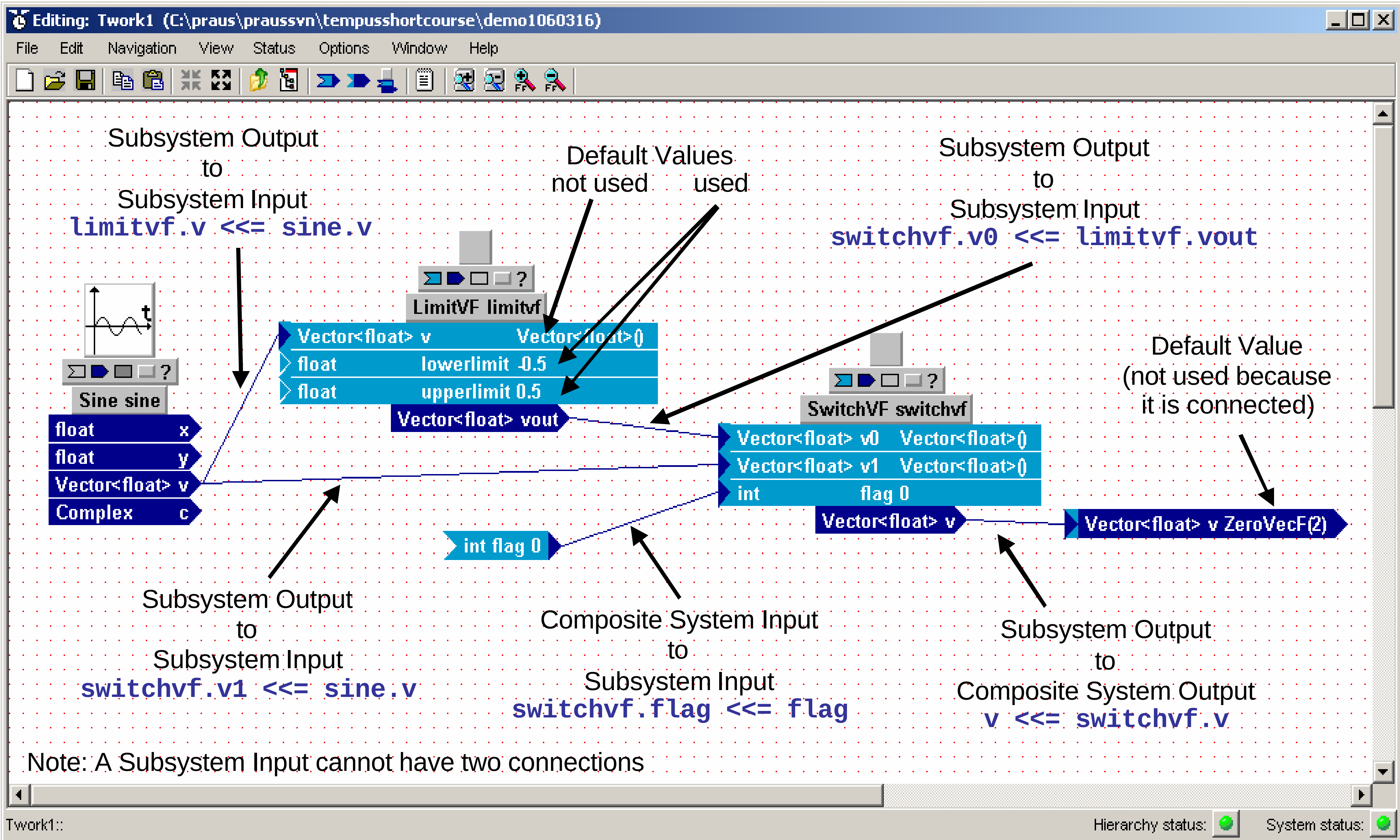
Three Types of Connections

Connection	Description
Subsystem Output to Subsystem Input **`ss1.i <<= ss2.o`**	The most intuitive type of connection feeds a Subsystem's Output to a Subsystem's Input.
Composite System Input to Subsystem Input **`ss.i <<= i`**	Composite System Inputs are routed to its Subsystem Inputs.
Subsystem Output to Composite System Output **`o <<= ss.o`**	Subsystem Outputs can become Outputs of the containing Composite System.

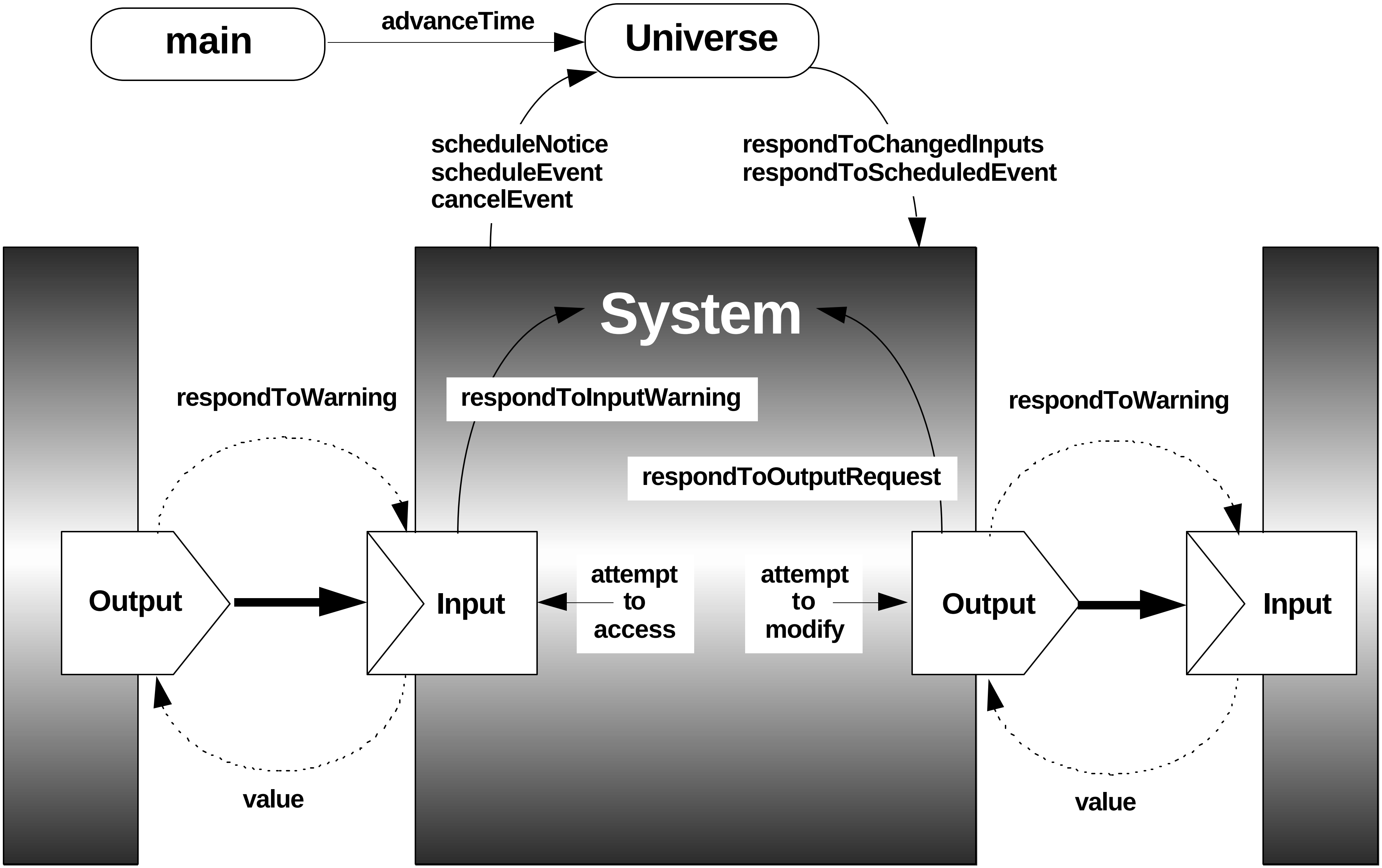
Default Behaviors

Concept	Description
Default Value assigned to Input	Default values for an Input can be specified so that the Input does not have to be externally connected.
Default Value assigned to System Output	Default values for System Outputs can be specified to provide an output value in the situation that a Subsystem Output is not eventually connected to it.

Connections in the tve



Connection-driven Execution



System Virtual Methods

```
class System : public SystemNode
{
   protected:
      virtual void respondToInputWarning(InputBase* input);
      virtual void respondToChangedInputs();
      virtual void respondToOutputRequest(const OutputBase* /*output*/);
      virtual void respondToScheduledEvent(const Event& /*event*/);
   ...
}
```

- Depending on the desired system behavior, the Atomic System coder writes a System-specific implementation of one or more virtual methods.
- Composite Systems do not implement the virtual methods because the behavior of Composite Systems is governed by the behavior its Subsystems.
- Each of the virtual methods have default logic so that Atomic Systems do not have to overload methods unrelated to its desired execution behavior.

Input-Driven Logic

```
class System : public SystemNode
{
   protected:
      virtual void respondToInputWarning(InputBase* input);
      virtual void respondToChangedInputs();
      virtual void respondToOutputRequest(const OutputBase* /*output*/);
      virtual void respondToScheduledEvent(const Event& /*event*/);
   ...
}
```

- **`respondtoInputWarning(InputBase*)`** warns a System that one of its Inputs is about to be changed.
- Before any System changes an Output which is connected to another System's Input, the Input's System's **`respondtoInputWarning(InputBase*)`** is called.
- **`respondtoChangedInputs()`** notifies a System that one or more of it's inputs has been changed.

Output-Driven Logic (Lazy Evaluation)

```
class System : public SystemNode
{
   protected:
      virtual void respondToInputWarning(InputBase* input);
      virtual void respondToChangedInputs();
      virtual void respondToOutputRequest(const OutputBase* /*output*/);
      virtual void respondToScheduledEvent(const Event& /*event*/);
   ...
}
```

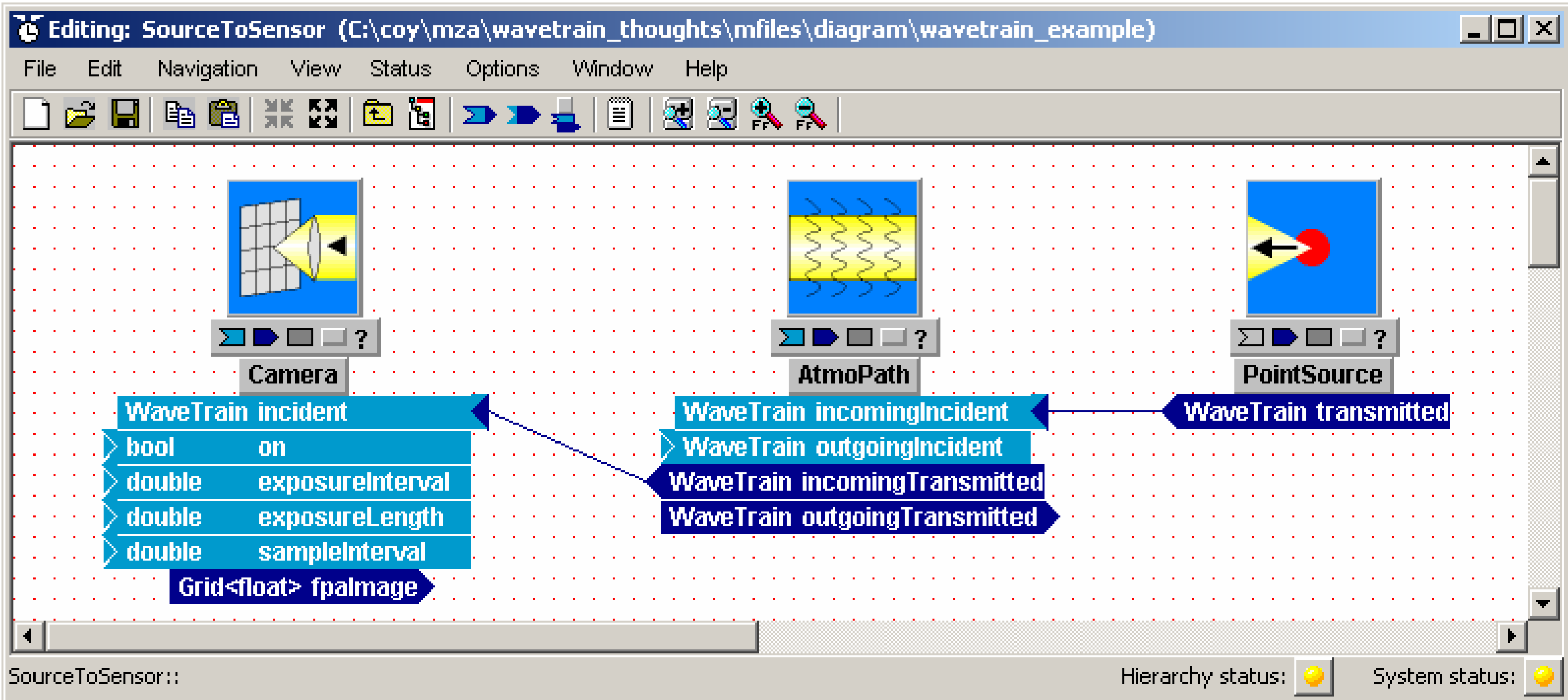
- When a System accesses the value of an Input which is connected to another System's Output, that Output's System's **`respondtoOutputRequest(OutputBase)`** is called.

Event Driven Logic

```
class System : public SystemNode
{
   protected:
      virtual void respondToInputWarning(InputBase* input);
      virtual void respondToChangedInputs();
      virtual void respondToOutputRequest(const OutputBase* /*output*/);
      virtual void respondToScheduledEvent(const Event& /*event*/);
   private:
      EventId scheduleEvent(double delay, char* descriptor="", void* info=NULL)
   ...
}
```

- A System can exercise strong control over it's execution by scheduling Events for itself by invoking the **`scheduleEvent(...)`** method.
- After the specified amount of time has passed, the scheduler called the System's **`respondToScheduledEvent(const Event&)`** method.

Complex Producer-Consumer Models



Inputs and Outputs can be of nearly any valid C++ type. The extreme flexibility of connection-driven execution combined with sophisticated Input-Output types, can provide extremely complex System interactions. MZA's wave-optics code is named after its fundamental interface type, WaveTrain, which provides a two-way dialog between optical components.

The tempus Paradigm

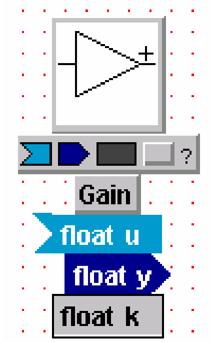
- Overview
- tempus visual editor
- tempus concepts
- Connection-driven execution
- tempus source form

Code Generation Strategy

- Atomic Systems are built by the tve as System class stubs.
  - The programmer is expected to implement virtual methods which define the System's behavior.
  - Because many systems have common features, inheritance and polymorphism is used a lot.
- Composite Systems are coded as complete Systems
  - Parameters are constructor arguments.
  - Inputs and Outputs are member objects.
  - Subsystems are declared and initialized using expressions involving the parameters of the system.
  - Subsystems are connected using the simple overloaded operator <<=.
  - Miscellaneous code handles default unconnected inputs.
- Runsets are coded as the main program.
  - The code contains explicit loops for loop variable.
  - The run variables and top-level system parameters are declared and set. Run variables and system parameters which are dependent on loop variables inside the appropriate loops.
  - The top-level system is constructed using the system parameters.
  - Recording systems are constructed and connected.
  - Each run is executed with a call to advanceTime(…).
  - There is miscellaneous code which takes care of runset monitoring and setting up the output trf file.

tempus System Examples

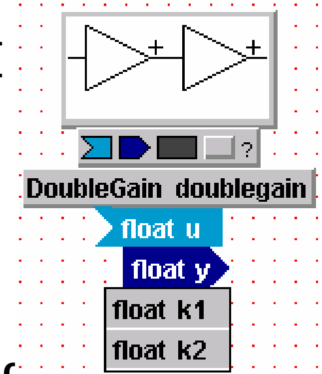
Gain : An Atomic System




```
class Gain : public System
{
private:
    float k;
public:
   Input<float>     u;
   Output<float>    y;
   Gain(SystemNode* parent,
        char* name,
        float _k) :
      System(this, name),
      k(_k), u(this, "u"), y(this, "y") {}
private:
    void respondToInputWarning(InputBase* input)
    {
         y.warnReferencors();
    }
    void respondToOutputRequest()
    {
         y=k*u;
    }
};
```

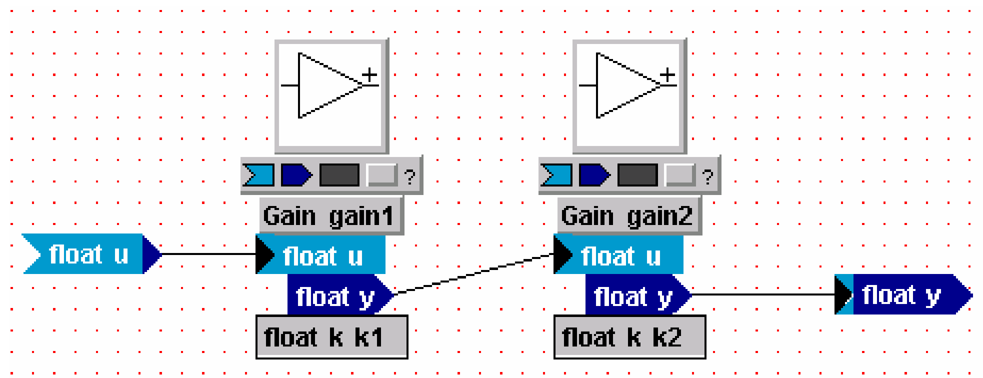
Atomic Systems' code is written by hand. In this case, the code in blue is all the logic that was added. The GUI provided the rest in the form of a template.

DoubleGain : A Composite System




```
class DoubleGain : public System {
private:
   Gain gain1;
   Gain gain2;
public:
   Input<float> u;
   Output<float> y;
   DoubleGain(SystemNode* parent, char* name,
                float _k1, float _k2) :
      System(this,name),
      gain1(this,"gain1",_k1),
      gain2(this,"gain2",_k2),
      u(this,"u"),y(this,"y")
   {
      gain1.u <<=  u;
      gain2.u <<=  gain1.y;
      y <<= gain2.y;
   }
};
```

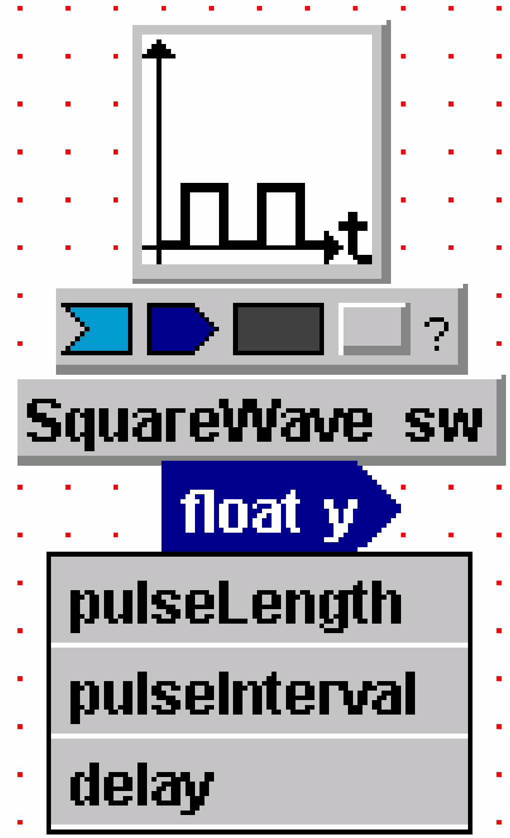
Composite Systems' code is usually generated by the GUI.



tempus SquareWave Example

Atomic system SquareWave uses event-driven logic.

```
class SquareWave : public System {
private:
   float pulseLength;
   float pulseInterval;
public:
   Output<float> y;
   SquareWave(SystemNode parent, char* name,
              float _pulseLength,
              float _pulseInterval,
              float _delay) :
      SystemNode(parent, name),
      pulseLength(_pulseLength),
      pulseInterval(_pulseInterval),
      y(this, "y")
   {
      scheduleEvent(_delay,“begin pulse”);
   }
private:
   void respondToScheduledEvent(const Event& event)
   {
      if (event == "beginPulse")
      {
         y = 1.0;
         scheduleEvent(pulseLength, “end pulse”);
         scheduleEvent(pulseInterval, “begin pulse”);
      }
      else if (event == ”end pulse”))
      {
         y = 0.0;
      }
   }
};
```

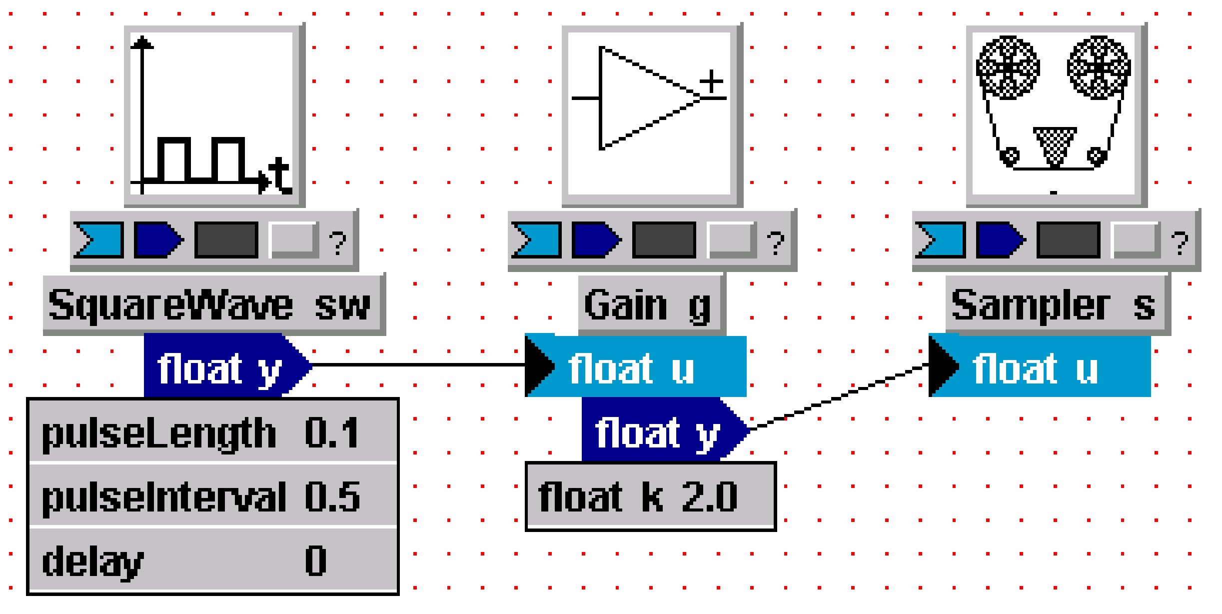


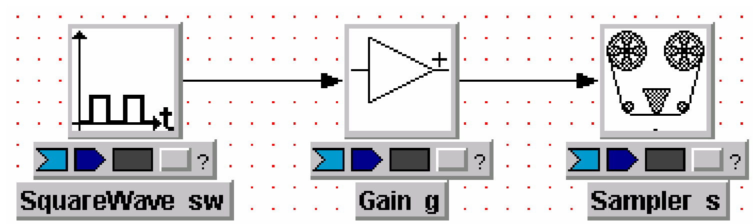
The code in blue was written by the System implementer. The rest of the code was provided by the GUI as a template.

tempus Main Program Example

```
main()
{
      SquareWave sw(0.1,0.5,0);       // construct a Square Wave.
      Gain g(2.0);                    // construct a Gain
      Sampler<float> s();             // construct a Sampler.
      g.u << = sw.y;                  // connect Gain's input to the SquareWave's output
      s.u <<= g.y;                    // connect the Sampler's input to the Gain's output
      advanceTime(100.0);             // advance virtual time 100 seconds
}
```

- The main program is usually generated by the GUI, but it can be written by hand just as well.





tempus Code is Readable

- **Each composite system declares and initializes its subsystems:**

```
pointsource(this, "pointsource", wavelength, 1.0e6, 0.0, 0.0),
transversevelocity1(this, "transversevelocity1", -wind, 0.0, 0.0, 0.0),
transversevelocity3(this, "transversevelocity3", wind, 0.0, 0.0, 0.0),
atmosphericpath1(this, "atmosphericpath1",
           AcsAtmSpec(wavelength,nscreen,clear1Factor,hPlatform,hTarget,range),
           atmoSeed, propnxy, propdxy, 1.8, 0.05,
           -propnxy*propdxy/2.0, propnxy*propdxy/2.0, -propnxy*propdxy/2.0, propnxy*propdxy/2.0,
           -propnxy*propdxy/2.0, propnxy*propdxy/2.0, -propnxy*propdxy/2.0, propnxy*propdxy/2.0,
           propdxy, 0.0, 0.0, 0),
camera1(this, "camera1", 1.0, wavelength, wavelength, apdiam/propdxy,
           propdxy, 64, wavelength/apdiam, 0.0),
simplefieldsensor1(this, "simplefieldsensor1", wavelength, apdiam/propdxy, propdxy),
telescope1(this, "telescope1", range, apdiam/2.0, 0.0),
incomingsplitter1(this, "incomingsplitter1"),
```

- **Then the subsystems inputs and outputs are connected:**

```
simplefieldsensor1.incident <<= incomingsplitter1.incomingTransmitted2;
camera1.incident <<= incomingsplitter1.incomingTransmitted;
incomingsplitter1.incomingIncident <<= telescope1.incomingTransmitted;
telescope1.incomingIncident <<= transversevelocity3.incomingTransmitted;
transversevelocity3.incomingIncident <<= atmosphericpath1.incomingTransmitted;
atmosphericpath1.incomingIncident <<= transversevelocity1.incomingTransmitted;
transversevelocity1.incomingIncident <<= pointsource.transmitted;
```

- **Then the simulation is run:**

```
advanceTime(stopTime);
```

blue names are systems
green names are inputs
red names are outputs
cyan names are regular variables

A Complete tempus Run

```
#include "tempus.h"
#include "Recorders.h"
#include "FileSys.h"

#include "PointSource.h"
#include "AtmoPath.h"
#include "Telescope.h"
#include "Camera.h"

#ifndef NO_TEMPUS_SMF_MONITOR
  #include "TempusStatusSMF.h"
#endif

main(int argc, char* argv[])
{
//
// Decoration related to monitoring the system during the run.
//
#ifndef NO_TEMPUS_SMF_MONITOR
  double stopTime = 0.0050;
  char *___outfile = "WtDemoRunHand.trf";
  char *___trfname;
  char *___smfname;
  parseName(argc, argv, ___outfile, &___smfname, &___trfname, stopTime);
  TempusStatusSMFWriter ___smfWriter(___smfname, ___trfname, "", 1);
  setCurrentSMF(&___smfWriter);
#endif
Universe ut1("Hand");
//
// Construction of all the systems. Variables could be used in the parameters
// below rather than the constants.
//
  PointSource pointsource(NULL, "ps", 1.0e-06, 1.0e+06, 0.0, 0.0);
  AtmoPath atmosphericpath(NULL, "ap",
                  AcsAtmSpec(1.0e-06,10,2.0,2413.0,2728.0,52600.0),
                  -765432189, 256, 0.02, 1.8, 0.05,
                  -256*0.02/2.0, 256*0.02/2.0, -256*0.02/2.0, 256*0.02/2.0,
                  -256*0.02/2.0, 256*0.02/2.0, -256*0.02/2.0, 256*0.02/2.0,
                  0.02, 0.0, 0.0, 0);
  Telescope telescope(NULL, "tel", 52600.0, 1.5/2.0, 0.0);
  Camera camera(NULL, "cam", 1.0, 1.0e-06, 1.0e-06, 1.5/0.02, 0.02, 64,
                 1.0e-06/1.5, 0.0);
//
// Connection of the systems.
//
  atmosphericpath.incomingIncident <<= pointsource.transmitted;
  telescope.incomingIncident <<= atmosphericpath.incomingTransmitted;
  camera.incident <<= telescope.incomingTransmitted;
//
// Construction and connection of non-connected inputs.
//
  Output<bool> camera_on(&camera, "cam_on", true);
  Output<double> camera_ei(&camera, "cam_ei", 1.0e-3);
  Output<double> camera_el(&camera, "cam_el", 1.0e-6);
  Output<double> camera_si(&camera, "cam_si", -1.0);
  camera.on <<= camera_on;
  camera.exposureInterval <<= camera_ei;
  camera.exposureLength <<= camera_el;
  camera.sampleInterval <<= camera_si;
//
// Decoration related to recording the outputs.
//
  ParamSet pst1;
  RecorderFile rft1(NULL, "rft1", ___trfname, ParamSet_stringify(pst1),
       pst1);
  GridRecorder<float> rft11(NULL, "rft11", "camera.fpaImage",
       "Grid<float>", "image", true, (float)0.0, 0.0);
  rft11.dr <<= rft1.dr;
  rft11.i <<= camera.fpaImage;
//
// Run the simulation.
//
  advanceTime(stopTime);
}

// Black code is always the same.
// Blue code is dependent on the problem.
// Green code is administrative in nature.
// Gray code supports optional functionality.

// To run:
//      setupwt
//      mktr WtDemoRunHand
//      WtDemoRunHand
```

The Future of tempus

Continuous Time Dynamics Solver

Dynamic System Composition

Multi-Inputs and Multi-Outputs

Heavy use of stl

Runtime inspection & modification

New GUI

Continuous Time Dynamics Solver

- tempus 2006 has been upgraded to include a powerful DAE solver to provide for the solution of continuous time dynamics.
- The following pages show a planar seven body problem called "The Pleiades" as implemented and tested in tempus 2006.
- The Pleiades problem is specified on pages 245-6 of E. Hairer, S. P. Norsett, and G. Wanner. <u>Solving Ordinary Differential Equations I, Nonstiff Problems</u>. Springer-Verlag, Berlin, 1993. ISBN 3–540–56670–8.
- Zane Dodson, a consultant to MZA, implemented the tempus continuous time solver and The Pleiades solution which follows.

Pleiades -- GravitationalForce

```
class GravitationalForce : public tSystem
{
public:
     GravitationalForce(const string& name = "", double G = 0.0)
          : tSystem(name), G(G), body1("body1"), body2("body2"),
          force_on_1_by_2("force_on_1_by_2"), force_on_2_by_1("force_on_2_by_1")
     {
          add(&body1);
          add(&body2);
          add(&force_on_1_by_2);
          add(&force_on_2_by_1);
     }
     virtual void respondToOutputRequest(const tOutput*)
     {
          tV2 displacement = body2.get().position - body1.get().position;
          const double distance = norm(displacement);
          const tV2 f = (G * body1.get().mass * body2.get().mass * displacement
                    / (distance * distance * distance));
          force_on_1_by_2.set(f);
          force_on_2_by_1.set(-1.0 * f);
     }
     tInputT<BodyDynamics> body1;
     tInputT<BodyDynamics> body2;
     tOutputT<tV2> force_on_1_by_2;
     tOutputT<tV2> force_on_2_by_1;
private:
     double G;
};
```

Pleiades – Body (1 of 2)

```
class Body : public tSystem
{
public:
     Body(const string& name = "", double mass = 0.0, const tV2& r0 = tV2(),
               const tV2& rdot0 = tV2())
          :
          tSystem(name), force("force", true), dynamics("dynamics"), mass(mass),
          r0(r0), rdot0(rdot0)
     {
          add(&force);
          add(&dynamics);
          r.setContainer(this); // FIXME
          rdot.setContainer(this); // FIXME

          const double nan = numeric_limits<double>::quiet_NaN();
          const tV2 rddot0 = tV2(nan, nan);
          r.set(r0, rdot0);
          rdot.set(rdot0, rddot0);

          tVariable::addDependency(&force, &rdot.residual());
          tVariable::addDependency(&r, &dynamics);
          tVariable::addDependency(&rdot, &dynamics);
          tVariable::addDependency(&rdot.derivative(), &dynamics);
     }

     ...
```

Pleiades – Body (2 of 2)

```
    ...
    void init() // FIXME
    {
        tV2 cummulative_force(0.0, 0.0);
        for (tInputT<tV2>::iterator i = force.begin(); i != force.end(); ++i)
            cummulative_force += *i;
        rdot.set(rdot0, cummulative_force / mass);
    }
    virtual void respondToComputeOde(const tContinuousState* state)
    {
        if (state == &r)
            r.residual().set(rdot.get() - r.derivative().get());
        else
        {
            tV2 cummulative_force(0.0, 0.0);
            for (tInputT<tV2>::iterator i = force.begin(); i != force.end(); ++i)
                cummulative_force += *i;
            rdot.residual().set(cummulative_force - mass * rdot.derivative().get());
        }
    }
    virtual void respondToOutputRequest(const tOutput*)
    {
        dynamics.set(BodyDynamics(r.get(), rdot.get(), rdot.derivative().get(), mass));
    }
    tInputT<tV2> force;
    tOutputT<BodyDynamics> dynamics;
private:
    double mass;
    tV2 r0, rdot0;
    tContinuousStateT<tV2> r, rdot;
};
```

Pleiades – main (1 of 2)

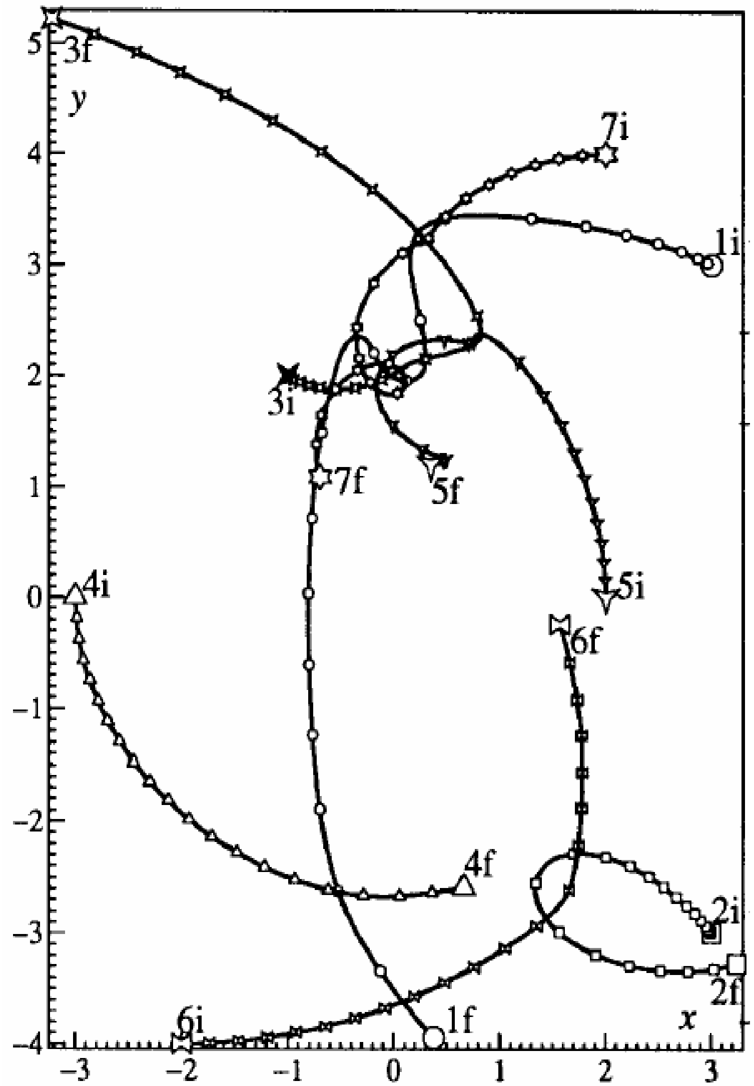
```
int main()
{
     const double G = 1.0;
     tUniverse U("U");

     std::vector<Body*> bodies;
     bodies.push_back(new Body("body1", 1.0, tV2( 3.0,  3.0), tV2( 0.0,  0.0)));
     bodies.push_back(new Body("body2", 2.0, tV2( 3.0, -3.0), tV2( 0.0,  0.0)));
     bodies.push_back(new Body("body3", 3.0, tV2(-1.0,  2.0), tV2( 0.0,  0.0)));
     bodies.push_back(new Body("body4", 4.0, tV2(-3.0,  0.0), tV2( 0.0, -1.25)));
     bodies.push_back(new Body("body5", 5.0, tV2( 2.0,  0.0), tV2( 0.0,  1.0)));
     bodies.push_back(new Body("body6", 6.0, tV2(-2.0, -4.0), tV2( 1.75, 0.0)));
     bodies.push_back(new Body("body7", 7.0, tV2( 2.0,  4.0), tV2(-1.50, 0.0)));

     for (int i = 0; i < bodies.size(); ++i)
          U.add(bodies[i]);

     std::vector< std::vector<GravitationalForce*> > gf(bodies.size(),
               std::vector<GravitationalForce*>(bodies.size()));

     for (int i = 0; i < bodies.size(); ++i)
          for (int j = i+1; j < bodies.size(); ++j)
          {
               gf[i][j] = new GravitationalForce("", G);
               U.add(gf[i][j]);
               gf[i][j]->body1.connect(&bodies[i]->dynamics);
               gf[i][j]->body2.connect(&bodies[j]->dynamics);
               bodies[i]->force.connect(&gf[i][j]->force_on_1_by_2);
               bodies[j]->force.connect(&gf[i][j]->force_on_2_by_1);
          }
     ...
```

Pleiades – main (2 of 2)

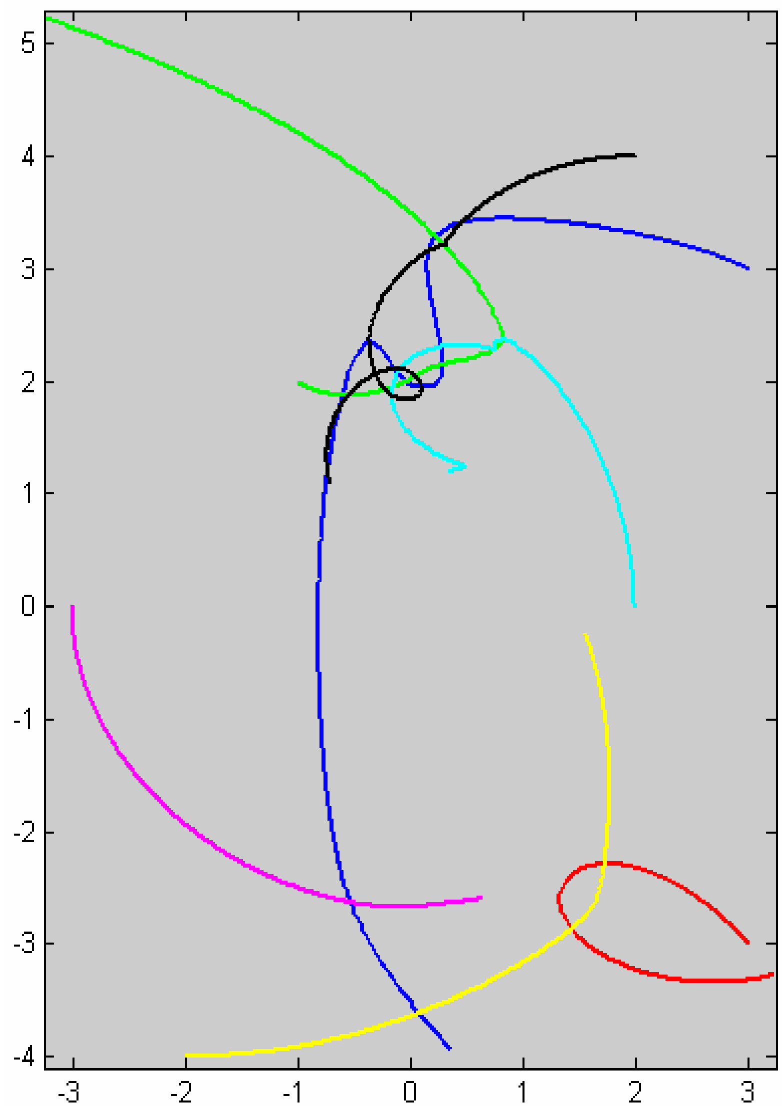
```
...

     for (int i = 0; i < bodies.size(); ++i)
          bodies[i]->init();

     for (int k = 0; k <= 300; ++k)
     {
          cout << U.now();
          for (int i = 0; i < bodies.size(); ++i)
               cout << "\t" << bodies[i]->dynamics.get().position;
          for (int i = 0; i < bodies.size(); ++i)
               cout << "\t" << bodies[i]->dynamics.get().velocity;
          for (int i = 0; i < bodies.size(); ++i)
               cout << "\t" << bodies[i]->dynamics.get().acceleration;
          cout << endl;
          U.tick(0.01);
     }
}
```

Pleiades Solution

The positions of 7 stars traced in a plane

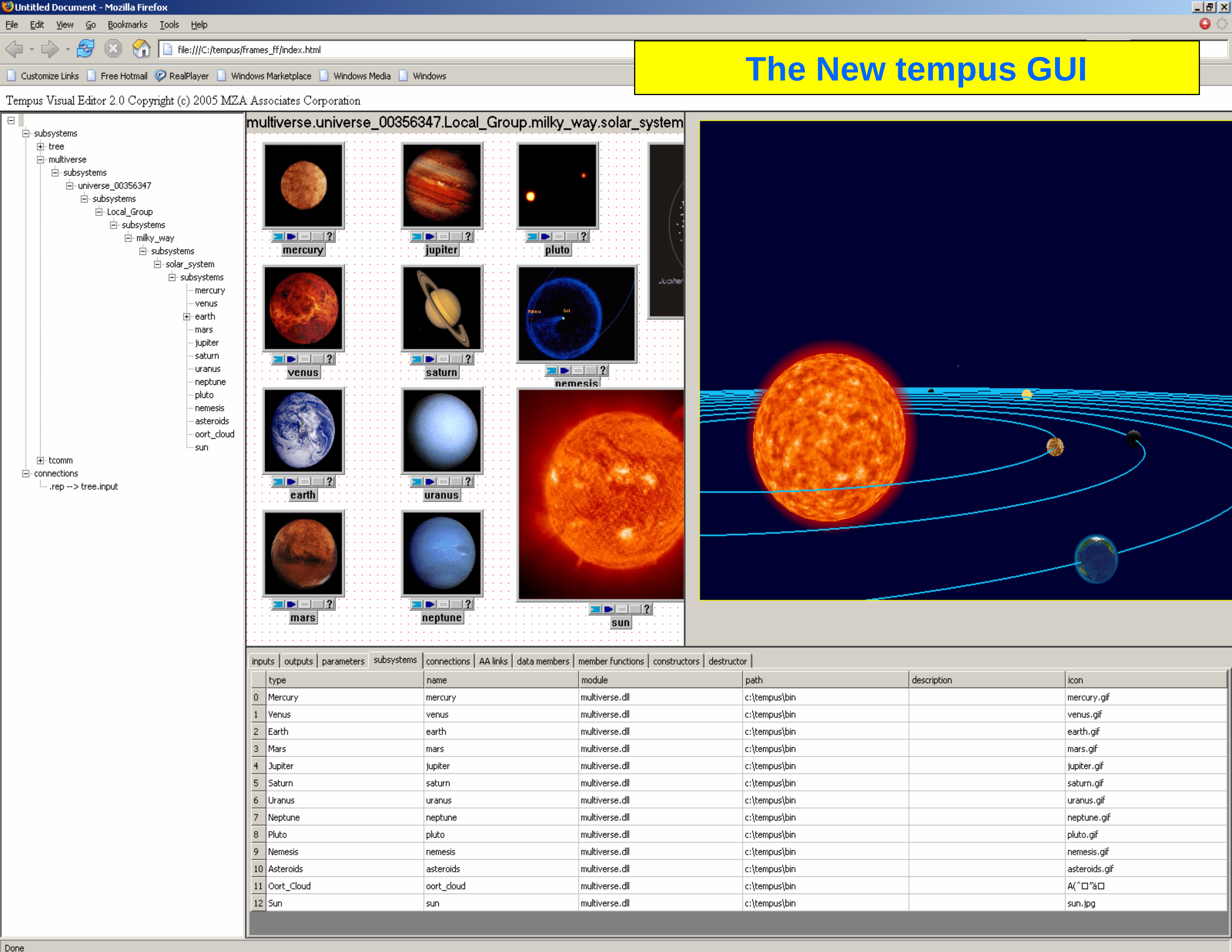


Solution from E. Hairer, S. P. Norsett, and G. Wanner. Solving Ordinary Differential Equations I, Nonstiff Problems. Springer-Verlag, Berlin, 1993. ISBN 3–540–56670–8.



Z. Dodson, tempus 2006 – Continous Time DAE Solver

The New tempus GUI



	type	name	module	path	description	icon
0	Mercury	mercury	multiverse.dll	c:\tempus\bin		mercury.gif
1	Venus	venus	multiverse.dll	c:\tempus\bin		venus.gif
2	Earth	earth	multiverse.dll	c:\tempus\bin		earth.gif
3	Mars	mars	multiverse.dll	c:\tempus\bin		mars.gif
4	Jupiter	jupiter	multiverse.dll	c:\tempus\bin		jupiter.gif
5	Saturn	saturn	multiverse.dll	c:\tempus\bin		saturn.gif
6	Uranus	uranus	multiverse.dll	c:\tempus\bin		uranus.gif
7	Neptune	neptune	multiverse.dll	c:\tempus\bin		neptune.gif
8	Pluto	pluto	multiverse.dll	c:\tempus\bin		pluto.gif
9	Nemesis	nemesis	multiverse.dll	c:\tempus\bin		nemesis.gif
10	Asteroids	asteroids	multiverse.dll	c:\tempus\bin		asteroids.gif
11	Oort_Cloud	oort_cloud	multiverse.dll	c:\tempus\bin		A(^□"ä□
12	Sun	sun	multiverse.dll	c:\tempus\bin		sun.jpg