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1. Introduction

Visualizations in Pavane consist of three concurrent components. The underlying computation is a program whose behavior is to be visualized; we assume that the computation can be characterized by a state which undergoes a series of atomic transformations. The visualization computation examines the state of the underlying computation and, through application of a collection of rules, produces a set of tuples called the animation space. The rendering computation transforms the animation space into visual form.

This paper describes the use of CtoVis, a package of functions which allows a C (or C++) program to act as the underlying computation of a Pavane visualization. Through the use of CtoVis, the animator (the constructor of the visualization) initiates the visualization and rendering computations, selects which portions of the C program state are to be examined, and identifies those points in the code where the state information is to be transmitted to the visualization computation.

The remainder of this paper is divided into five parts. The first three cover respectively the specification of the part of the state that is monitored, the initialization of the visualization and rendering computations, and the transmission of state information. The fourth section describes how to compile programs that use the CtoVis package. The final section contains several complete sample uses of the package.

2. Selection of monitored data

Monitoring refers to the selection of one or more C variables whose contents are to be examined and transmitted to the visualization computation. The main operation involved in monitoring is the conversion of C data types into Pavane data types. We will first discuss the various data types, then return to the routine that handles monitoring of the variables.

CtoVis permits monitoring of the following C data types:

- Numeric data types (char, short, int, long, float, and double)
- Strings (null-terminated arrays of characters) represented either by pointers to character arrays (char *) or as arrays of characters (char [])
- Arrays ([] ) of any monitorable type; the dimension of the array must be fixed.
- Structures (struct) whose components are any monitorable type.

This is, of course, a recursive definition, so it is possible to monitor a variable which is an array of structures, each containing a short, a double, and a char *; examples of such conversions are provided below. Pointer data types (other than char * as a string) are not supported at this time. Each C variable that is monitored must be transformed into one of the following Pavane data types:

- Integer (a fixed-point number with range equivalent to that of a C long).
- Real (a floating-point number with range equivalent to a C double).
- Boolean (either true or false).
- Strings (sequences of up to 100 characters).
- Arrays of any Pavane data type.
- Structures of any Pavane data type.

The conversion between these types must be indicated. The following conversions are permitted:

- Any C numeric type may be converted to a Pavane integer, real, or boolean data type, with conversion rules the same as in C. Thus, converting a C double to a Pavane integer is equivalent to assigning a double to a long, with the associated problems of loss of precision, while assigning any type to a Pavane boolean uses the C "zero is false, non-zero is true" test.
- C strings (char * and char []) may be converted into a Pavane string; of course, the latter type can also be considered as an array of character and converted into a Pavane array of
integer, real, or boolean. During the conversion to a Pavane string, Pavane's 100-character limit is silently enforced by the truncation of the input strings.

- C arrays may be converted into Pavane arrays.
- C structures may be converted into Pavane structures

This is again recursive, the conversions for the elements of arrays and components of structures must also be given.

Each separate monitored variable is transformed into a single Pavane tuple with a type-name selected by the user. The C data is also transformed into Pavane's internal representation. Thus, four things must be specified when a variable is selected for monitoring: the Pavane type name, the location of the variable, the Pavane data type, and the C data type. These form the arguments of the VisualMonitor function, a variadic function declared as:

```
VisualMonitor(char *typename, void *data, ...);
```

The first argument, typename, is the name of the Pavane tuple type. data is the address of the C data that is to be monitored. The remaining, variadic arguments, all of type long, specify the type-conversions between the output (Pavane) data types and the corresponding input (C) data types. The following predefined constants are to be used in this section:

```
VISMONITOR_PAVANE_INTEGER — The output data type is to be a Pavane integer. This constant must be followed by a C numeric type, specified by one of the following constants: VISMONITOR_C_CHAR, VISMONITOR_C_SHORT, VISMONITOR_C_INT, VISMONITOR_C_LONG, VISMONITOR_C_FLOAT, or VISMONITOR_C_DOUBLE.

VISMONITOR_PAVANE_REAL — The output data type is to be a Pavane real. This constant must be followed by a C numeric type, using the constants listed above.

VISMONITOR_PAVANE_BOOLEAN — The output data type is to be a Pavane boolean. This constant must be followed by a C numeric type, using the constants listed above.

VISMONITOR_PAVANE_STRING — The output data type is to be a Pavane string. This must be followed by a C string type, using the constant VISMONITOR_C_CHAR_PTR (for a char * data type) or VISMONITOR_C_CHAR_ARRAY (N) (for a char [N] data type). In the latter case, N must be fixed and between 1 and 16384.

VISMONITOR_PAVANE_ARRAY — The output data type is to be a Pavane array. This constant must be followed by the size of the array, cast as a long, which in turn must be followed by the type-conversion of the elements of the array. For example, an array of 10 C long's that is to be represented by a Pavane array of 10 integers would be specified by the conversion VISMONITOR_PAVANE_ARRAY, (long)10, VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG.

Note the recursion, with the type-conversion of the array elements specified in the same manner as the type-conversion for a single variable of that type.

VISMONITOR_PAVANE_STRUCT — The output data type is to be a Pavane structure. This constant must be followed by the number of components in the structure, cast as a long, which in turn must be followed by the type-conversions of the components in the order that they appear in the C structure. For example, a C structure containing a long, a long, and a two-dimensional array of 10 by 10 of double's that is to be converted into a similar Pavane structure using integers for long's and reals for double's would be specified by the conversion

```
VISMONITOR_PAVANE_STRUCT, (long)3,
VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
VISMONITOR_PAVANE_ARRAY, (long)10,
VISMONITOR_PAVANE_ARRAY, (long)10,
VISMONITOR_PAVANE_REAL, VISMONITOR_C_DOUBLE
```
Again note the recursion, with a separate type-conversion for each of the three components of the structure.

Three rules apply to the use of the VisualMonitor function. First, all monitored variables must be selected and initialized before the visualization is started using VisualOpen. Next, all type names must be distinct and are limited to 63 characters. Finally, the data must exist from the time VisualMonitor is called until the visualization process is halted (using VisualClose). This means that some care must be used when monitoring variables that are declared in a subroutine; since such variables are normally allocated on the C runtime stack, they cease to exist when the subroutine exits. Such variables must be moved outside the subroutine into C's "file scope".

2. Initiating and terminating a visualization

Once all monitored variables have been identified and initialized, the function VisualOpen is used to start the visualization and rendering programs. The visualization program must be the result of compiling a collection of visualization rules (the rendering program is fixed). VisualOpen has the declaration

VisualOpen(char *program, ...);

The first argument is the name of the visualization program that is to be started. The remaining arguments, all of type char *, are a NULL-terminated list of the arguments to be given to the visualization, in the same order as in the visualization's declaration. For example, a visualization which was declared as

visualization AllPairs(integer N, boolean flag)

would require two argument strings and then the NULL. A corresponding use of VisualOpen, assuming that the visualization code had been compiled into the file AllPairsVis, would be

VisualOpen("AllPairsVis", "8", "true", (char *)NULL);

Note that the arguments must be strings; some conversion may be required. If, for example, the value corresponding to N was known only at run-time, a sequence something like the following might be used:

char buf[16];
...
sprintf(buf, "%d", number_of_nodes);
VisualOpen("AllPairsVis", Buf, "true", (char *)NULL);

VisualOpen starts the visualization program and sends the initial state of the computation (the values of all the monitored variables). For this reason, these variables should be initialized before VisualOpen is called.

To terminate a visualization, use VisualClose. When VisualClose is called, the visualization and rendering computations are halted and the CtoVis monitoring package is re-initialized. Another visualization may then be set up and started with calls to VisualMonitor and VisualOpen.

3. Transmitting state information

Once a visualization is started with VisualOpen, three routines may be used to send state information (the values of all the monitored variables) to the visualization. The first of these is VisualUpdate, which simply sends all the state information when it is called.

A second method is provided by the functions VisualBeginAtomic and VisualEndAtomic. As the names imply, this pair of functions is used to delineate the boundaries of logical "atomic transitions" in the C code, i.e., blocks of code that are considered to represent a single state change. Whenever an atomic transition is complete (defined as an equal number of calls to VisualBeginAtomic and VisualEndAtomic) the state is transmitted to the visualization. Internally, these routines modify the value of a counter; VisualBeginAtomic increments the counter, while VisualEndAtomic decrements it and, if the value is zero after decrementing, sends the state
information. The purpose here is a matter of encapsulation. A sorter, for example, could be written using the two
calls to transmit its state information and, if run "stand-alone", would transmit its state at appropriate points. The
same code could be used as a subroutine in a larger program with the call enclosed in a VisualBeginAtomic/
VisualEndAtomic pair; as a result, the state would be transmitted only after the sort was complete, with all the
intermediate VisualEndAtomic calls inside the sorter code having no effect.

VisualUpdate may be used with VisualBeginAtomic and VisualEndAtomic. Calls to
VisualUpdate have no effect on the counter used by the other two routines.

4. Compilation

A program that is to use the CtoVis package must contain the line

#include "/usr/people/pavane/C_INTERFACE/CtoVis.h"

This file contains declarations for the CtoVis functions and definitions of various constants.

When compiling, either the C or C++ CtoVis library must be loaded, depending on which compiler you
use. These libraries are located in the /usr/people/pavane/C_INTERFACE directory, named CtoVis_c.a
and CtoVis.a respectively. A typical C++ compilation line would be

CC -o AllPairs AllPairs.c /usr/people/pavane/C_INTERFACE/CtoVis.a

5. Example programs

We provide the skeletons of two C programs using the CtoVis package. The first is an all-pairs shortest
path algorithm (the Floyd-Warshall algorithm). The second is from an elevator-control simulation and uses
somewhat complex data structures.

5.1. All-pairs algorithm

The all-pairs visualization contains the following code segments:

visualization AllPairs(integer NNodes)
...
input space
<< array of NNodes array of NNodes real D :: d(D) >>;
<< integer K :: scan_counter(K) >>;

This indicates that the visualization program (which is compiled into the file "AllPairsVis") must have one
argument, an integer NNodes. It is also expecting tuples of two types. The type d must contain an NNodes by
NNodes array of real numbers, while the type scan_counter must contain an integer. These conversions are specified
in the following C code.

#include <stdio.h>
#include "CtoVis.h"

/* ARRAYSIZE corresponds to NNodes in the visualization code */
#define ARRAYSIZE 8

static void initgraph(double dist[][ARRAYSIZE]) {
    /* code, of no interest to this presentation, which initializes
     * the given graph
     */
}
main()
{
long i,j,k;
char abuf[8];
double d;
double  
dist[ARRAYSIZE][ARRAYSIZE],
        distprime[ARRAYSIZE][ARRAYSIZE];

/* Two variables are of interest here: dist and k. We must
 * indicate that these variables are to be monitored and
 * how they are to be converted from C to Pavane. Note that,
 * although these variables are on the C stack, they will not
 * leave scope until the visualization is completed; we can
 * therefore safely monitor them. */

/* dist will become the tuple "d" (see above). It is an array
 * of ARRAYSIZE arrays of ARRAYSIZE doubles, to be converted
 * into the equivalent two-dimensional Pavane array using
 * Pavane reals. We pass (void *)dist because dist is already
 * the address of the array. */
VisualMonitor("d",(void *)dist,
        VISMONITOR_PAVANE_ARRAY, ARRAYSIZE,
        VISMONITOR_PAVANE_ARRAY, ARRAYSIZE,
        VISMONITOR_PAVANE_REAL, VISMONITOR_C_DOUBLE);

/* k will become the tuple "scan_counter". It is a long, to
 * be represented by a Pavane integer. We have to take the
 * address of the variable k and cast it to void *. */
VisualMonitor("scan_counter",(void *)(&k),
        VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG);

/* Initialize the monitored variables before VisualOpen is
 * called (since that routine will transmit the values of the
 * variables to the visualization) */
initgraph(dist);
k = 0;

/* Start the visualization; this also sends the current state
 * of the monitored variables. */
sprintf(abuf,"%d",ARRAYSIZE);
VisualOpen("AllPairsVis",abuf,(char *)NULL);

/* We now execute the algorithm. The portion between the
 * VisualBeginAtomic and VisualEndAtomic calls form a single
 * "atomic transition" for this algorithm, in which all the
 * array entries are updated at once. The state is sent when
 * VisualEndAtomic is called. */
while (k < ARRAYSIZE) {
    VisualBeginAtomic();
    for (i = 0; i < ARRAYSIZE; i++) {
        for (j = 0; j < ARRAYSIZE; j++) {
d = dist[i][k] + dist[k][j];
if (d < dist[i][j])
    distprime[i][j] = d;
else
    distprime[i][j] = dist[i][j];

for (i = 0; i < ARRAYSIZE; i++)
    for (j = 0; j < ARRAYSIZE; j++)
        dist[i][j] = distprime[i][j];
k++;
VisualEndAtomic();

/* To exit cleanly, we call VisualClose. Simply returning
 * from main() or calling exit() would also terminate the
 * visualization, but not as cleanly.
 */
VisualClose();

5.2. Elevator control simulation

The elevator visualization contains the following code segments:

    visualization ElevatorVis(integer NElevators, integer NFloors)
    ...;
    types
        elevator_type ==
            struct of
                integer floor,
                integer dir,
                integer vel,
                boolean open,
                array of NFloors boolean buttons;
        button_type ==
            struct of
                boolean up,
                boolean down;

    input space
        << array of NElevators elevator_type E :: elevators(E) >>;
        << array of NFloors button_type B :: buttons(B) >>;

The C code (as seen below) has corresponding structures. The main area of interest in this example is the
specification of the conversion between the types.

    #include <stdio.h>
    #include "CtoVis.h"
    #define NELEVATORS 2
    #define NFLOORS 6

    static struct elevator {
        long    floor;
        long    direction;
        long    velocity;
        short   open;
        short   buttons[NFLOORS];
    } elevators[NELEVATORS];
static struct  
   short up;
   short down;
} call_buttons[NFLOORS];

static void InitializeElevators(void) {
    /* some code of no particular interest which initializes
     * the elevators and call_buttons data structures
     */
}

static void InitiateMonitoring(void) {
    char ebuf[16], fbuf[16];

    /* elevators is an array of NELEVATORS structures, so its
    * type-conversion is "VISMONITOR_PAVANE_ARRAY, NELEVATORS"
    * followed by the type-conversion for the structure. The
    * structure has five components (floor, directions, velocity,
    * open, and buttons), so its type-conversion is
    * "VISMONITOR_PAVANE_STRUCT, 5" followed by the
    * type-conversions of the components in the same order that
    * they appear in the structure.
    */
    VisualMonitor("elevators",(void *)elevators,
        VISMONITOR_PAVANE_ARRAY, NELEVATORS,
        VISMONITOR_PAVANE_STRUCT, 5,
        VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
        VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
        VISMONITOR_PAVANE_INTEGER, VISMONITOR_C_LONG,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_C_SHORT,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_PAVANE_BOOLEAN,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_C_SHORT
    );

    /* Similarly, call_buttons is an array of NFLOORS structures,
    * each having two elements.
    */
    VisualMonitor("buttons",(void *)call_buttons,
        VISMONITOR_PAVANE_ARRAY, NFLOORS,
        VISMONITOR_PAVANE_STRUCT, 2,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_C_SHORT,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_PAVANE_BOOLEAN,
        VISMONITOR_PAVANE_BOOLEAN, VISMONITOR_C_SHORT
    );

    sprintf(ebuf,"%d",NELEVATORS);
    sprintf(fbuf,"%d",NFLOORS);
    VisualOpen("ElevatorVis", ebuf, fbuf, (char *)NULL);
}

static void ChangeElevators(void) {
    /* more code of no particular interest which simulates the
    * pressing of buttons and the movement of the elevators
    */
}

main() {
/* initialize the state variables (elevators, buttons) */
InitializeElevators();

/* monitor the two variables and start the visualization */
InitiateMonitoring();

/* this simulation runs forever, with one update after each
 * modification of the state. We could get the same effect
 * by placing ChangeElevators within a VisualBeginAtomic /
 * VisualEndAtomic pair. */

for (; ; ) {
    ChangeElevators();
    VisualUpdate();
}