Implementation of time integration methods

- Restructuring of sample code using driver & layout
  - Separates scene layout from simulation algorithms
  - Compartmentalized, reusable operations
  - Switching between integration methods is more straightforward
  - Initially demonstrated on our Forward Euler example

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- WARNING: SOURCE CODE AHEAD!!

Implementation of time integration methods

- Issues with flat code organization
  (i.e. everything in main.cpp)
  - Difficult to read (even more so, when we start increasing the complexity)
  - Algorithms and scene setup are not separated

- WARNING: SOURCE CODE AHEAD!!

```
    #include <PhysBAM_Tools/Log/LOG.h>
#include <PhysBAM_Tools/Parsing/STRING_UTILITIES.h>
#include <PhysBAM_Tools/Read_Write/Utilities/FILE_UTILITIES.h>
#include <PhysBAM_Geometry/Geometry_Particles/GEOMETRY_PARTICLES.h>
#include <PhysBAM_Geometry/Geometry_Particles/REGISTER_GEOMETRY_READ_WRITE.h>
#include <PhysBAM_Geometry/Solids_Geometry/DEFORMABLE_GEOMETRY_COLLECTION.h>
#include <PhysBAM_Geometry/Topology_Based_Geometry/SEGMENTED_CURVE.h>
#include <PhysBAM_Geometry/Topology_Based_Geometry/FREE_PARTICLES.h>
using namespace PhysBAM;

int main(int argc,char* argv[])
{
    typedef float T;
    typedef float RW;

    RW rw=RW();STREAM_TYPE stream_type(rw);
    typedef VECTOR<T,3> TV;

    LOG::Initialize_Logging();
    Initialize_Geometry_Particle();Initialize_Read_Write_Structures();

const int n=11;                             // Number of particles in wire mesh
const int number_of_frames=100;             // Total number of frames
const T frame_time=.05;                     // Frame (snapshot) interval
const T youngs_modulus=10.;                 // Elasticity and damping coefficients
const T damping_coefficient=10.;
const T wire_mass=1.;                       // Mass and length for entire wire
const T wire_length=1.;
const T mass=wire_mass/(T)n;                // Mass (per each particle)
const T restlength=wire_length/(T)(n-1); // Restlength (per each spring)

GEOMETRY_PARTICLES<TV> particles;particles.Store_Velocity();
SEGMENTED_CURVE<TV>& wire_curve=*SEGMENTED_CURVE<TV>::Create(particles);
wire_curve.mesh.Initialize_Straight_Mesh(n);particles.array_collection->Add_Elements(n);
for(int p=1;p<=n;p++) particles.X(p)=TV(0,(T)(1-p)/(T)(n-1),.5);
FREE_PARTICLES<TV>& wire_particles=*FREE_PARTICLES<TV>::Create(particles);
for(int p=1;p<=n;p++) wire_particles.nodes.Append(p);

DEFORMABLE_GEOMETRY_COLLECTION<TV> collection(particles);
collection.Add_Structure(&wire_curve);collection.Add_Structure(&wire_particles);
```

```
DEFORMABLE_GEOMETRY_COLLECTION<TV> collection(particles);
collection.Add_Structure(&wire_curve);collection.Add_Structure(&wire_particles);

ARRAY<TV> force(n),dX(n),dV(n);

T dt_damping=mass*restlength/damping_coefficient;
T dt_elastic=damping_coefficient*restlength/youngs_modulus;
T CFL_number=0.5;
T dt_max=CFL_number*std::min(dt_damping,dt_elastic),dt;
T time=0.;

LOG::cout<<"dt_damping="<<dt_damping<<std::endl;
LOG::cout<<"dt_elastic="<<dt_elastic<<std::endl;
LOG::cout<<"Maximum dt="<<dt_max<<std::endl;

FILE_UTILITIES::Create_Directory("output/0");collection.Write(stream_type,"output",0,0,true);

for(int frame=1;frame<=number_of_frames;frame++){
    T frame_end_time=frame_time*(T)frame;
for(;time<frame_end_time;time+=dt){
    dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

    // Set upper endpoint position and velocity
    T angular_velocity=two_pi/(frame_time*(T)number_of_frames);
    particles.X(1)=TV(.5*sin(time*angular_velocity),0,.5*cos(time*angular_velocity));
    particles.V(1)=TV(.5*angular_velocity*cos(time*angular_velocity),0,
                      -.5*angular_velocity*sin(time*angular_velocity));

   force.Fill(TV()); // Clear all forces from previous iterations

    // Add spring force
    for(int s=1;s<=wire_curve.mesh.elements.m;s++){
        int p1,p2;wire_curve.mesh.elements(s).Get(p1,p2);
        TV X1=particles.X(p1),X2=particles.X(p2);
        TV normal=(X1-X2).Normalized();
        T length=(X1-X2).Magnitude();
        TV f=-normal*youngs_modulus*(length/restlength-1.);
        force(p1)+=f;force(p2)-=f;}
```

```
force.Fill(TV()); // Clear all forces from previous iterations

// Add spring force
for(int s=1;s<=wire_curve.mesh.elements.m;s++){
    int p1,p2;wire_curve.mesh.elements(s).Get(p1,p2);
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    TV normal=(X1-X2).Normalized();
    T length=(X1-X2).Magnitude();
    TV f=-normal*youngs_modulus*(length/restlength-1.);
    force(p1)+=f;force(p2)-=f;}

// Add damping force
for(int s=1;s<=wire_curve.mesh.elements.m;s++){
    int p1,p2;wire_curve.mesh.elements(s).Get(p1,p2);
    TV X1=particles.X(p1),X2=particles.X(p2);
    TV V1=particles.V(p1),V2=particles.V(p2);
    TV normal=(X1-X2).Normalized();
    T vrel=TV::Dot_Product(normal,V1-V2);
    TV f=-damping_coefficient*vrel*normal;
    force(p1)+=f;force(p2)-=f;}

        // Add gravity
        force+=-TV::Axis_Vector(2)*mass*9.81;

        // Apply the Forward Euler method
        dX=dt*particles.V;  // Compute position change
        dV=(dt/mass)*force; // Compute velocity change
        dX(1)=dV(1)=TV();   // First particle has externally prescribed motion; do not alter
        particles.X+=dX;    // Update particle positions and velocities
        particles.V+=dV;

        FILE_UTILITIES::Create_Directory("output/"+STRING_UTILITIES::Value_To_String(frame));
        collection.Write(stream_type,"output",frame,0,true);
    }
}

LOG::Finish_Logging();
}
```

Implementation of time integration methods

- Improvement : Factor out a “Layout” class
  - Includes : Description of simulated geometry
  - Includes : Definition of forces
  - Includes : Definition of kinematic constraints
  - Includes : User-specified simulation parameters
    - Frame rate, # of frames, CFL number, etc.
  - Includes : (Almost) all the state in our virtual world
  - Does NOT include : Time integration algorithms

```
    namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient      // Elasticity and damping coefficients
    const T wire_mass,wire_restlength;              // Mass and length for entire wire
    ARRAY<T> mass,restlength;                       // Mass (per each particle), restlength (per each spring)

    GEOMETRY_PARTICLES<TV> particles;
    DEFORMABLE_GEOMETRY_COLLECTION<TV> collection;

    const int number_of_frames;  // Total number of frames
    const T frame_time;          // Frame (snapshot) interval
    const T CFL_number;          // CFL number (not to exceed 1)

    SEGMENTED_CURVE<TV>* wire_curve;
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
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    GEOMETRY_PARTICLES<TV> particles;
    DEFORMABLE_GEOMETRY_COLLECTION<TV> collection;

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    const T wire_mass,wire_restlength;              // Mass and length for entire wire
    ARRAY<T> mass,restlength;                       // Mass (per each particle), restlength (per each spring)

    GEOMETRY_PARTICLES<TV> particles;
    DEFORMABLE_GEOMETRY_COLLECTION<TV> collection;

    const int number_of_frames;  // Total number of frames
    const T frame_time;          // Frame (snapshot) interval
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    SEGMENTED_CURVE<TV>* wire_curve;
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public:
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    cor
    SEGMENTED_CURVE<TV>* wire_curve;
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
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};
}
```

```
template<class T>
SIMULATION_LAYOUT<T>::SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input)
    :stream_type(stream_type_input),
     n(11),youngs_modulus(100.),damping_coefficient(100.),
     wire_mass(1.),wire_restlength(1.),
     collection(particles),
     number_of_frames(100),frame_time(.05),CFL_number(.5)
{
    Initialize_Geometry_Particle();Initialize_Read_Write_Structures();
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

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    cor
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    ARF

    GEC
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    cor
    cor
    cor

    SEGMENTED_CURVE<TV>* wire_curve;
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```
namespace PhysBAM{
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c
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```

```
template<class T>
void SIMULATION_LAYOUT<T>::Initialize()
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    wire_curve=SEGMENTED_CURVE<TV>::Create(particles);
    wire_curve->mesh.Initialize_Straight_Mesh(n);particles.array_collection->Add_Elements(n);
    for(int p=1;p<=n;p++) particles.X(p)=TV(0,(T)(1-p)/(T)(n-1),.5);

    wire_particles=FREE_PARTICLES<TV>::Create(particles);
    for(int p=1;p<=n;p++) wire_particles->nodes.Append(p);

    collection.Add_Structure(wire_curve);collection.Add_Structure(wire_particles);

    mass.Resize(n);mass.Fill(wire_mass/(T)n);
    restlength.Resize(n-1);restlength.Fill(wire_restlength/(T)(n-1));
}
```

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namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
```

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template<class T>
void SIMULATION_LAYOUT<T>::Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force)
{
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        TV X1=X(p1),X2=X(p2);
        TV normal=(X1-X2).Normalized();
        T length=(X1-X2).Magnitude();
        TV f=-normal*youngs_modulus*(length/restlength(s)-1.);
        force(p1)+=f;force(p2)-=f;
    }
}
```

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    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force)
{
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        TV X1=X(p1),X2=X(p2);
        TV normal=(X1-X2).Normalized();
        T length=(X1-X2).Magnitude();
        TV f=-normal*youngs_modulus*(length/restlength(s)-1.);
        force(p1)+=f;force(p2)-=f;
    }
}
```

$$f_1 = -k\left(\frac{l}{l_0} - 1\right)\frac{x1 - x2}{\|x1 - x2\|}$$

```
    SEGMENTED_CURVE<TV>* wire_curve;
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
    ARRAY<TV>& force)
{
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        TV X1=X(p1),X2=X(p2);
        TV V1=V(p1),V2=V(p2);
        TV normal=(X1-X2).Normalized();
        T vrel=TV::Dot_Product(normal,V1-V2);
        TV f=-damping_coefficient*vrel*normal;
        force(p1)+=f;force(p2)-=f;
    }
}
```

```
    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
    ARRAY<TV>& force)
{
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        TV X1=X(p1),X2=X(p2);
        TV V1=V(p1),V2=V(p2);
        TV normal=(X1-X2).Normalized();
        T vrel=TV::Dot_Product(normal,V1-V2);
        TV f=-damping_coefficient*vrel*normal;
        force(p1)+=f;force(p2)-=f;
    }
}
```

$$f_1^d = -bnn^T(v1 - v2)$$

```
    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int
    const T y
    const T w
    ARRAY<T> m                                                    (per each spring)

    GEOMETRY_
    DEFORMABL

    const int
    const T frame_time;             // frame (snapshot) interval
    const T CFL_number;             // CFL number (not to exceed 1)

    SEGMENTED_CURVE<TV>* wire_curve;
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Add_External_Forces(ARRAY<TV>& force)
{
    for(int p=1;p<=n;p++)
        force(p)-=TV::Axis_Vector(2)*mass(p)*9.81;
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;
```

```
template<class T>
T SIMULATION_LAYOUT<T>::Maximum_Dt()
{
    T maximum_dt=frame_time;
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){                    ng)
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        T spring_mass=1./(1./mass(p1)+1./mass(p2));
        maximum_dt=std::min(maximum_dt,spring_mass*restlength(s)/damping_coefficient);
        maximum_dt=std::min(maximum_dt,damping_coefficient*restlength(s)/youngs_modulus);
    }

    return CFL_number*maximum_dt;
}
```

```
    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;
```

```
template<class T>
T SIMULATION_LAYOUT<T>::Maximum_Dt()
{
    T maximum_dt=frame_time;
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        T spring_mass=1./(1./mass(p1)+1./mass(p2));
        maximum_dt=std::min(maximum_dt,spring_mass*restlength(s)/damping_coefficient);
        maximum_dt=std::min(maximum_dt,damping_coefficient*restlength(s)/youngs_modulus);
    }

    return CFL_number*maximum_dt;
}
```

$$dt < \frac{ml_0}{b} \quad \text{AND} \quad dt < \frac{bl_0}{k}$$

```
    SIMULATION_LAYOUT(const STREAM_TYPE stream_
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient // Elasticity and damping coefficients
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Write_Output(const int frame)
{
    FILE_UTILITIES::Create_Directory("output/"+STRING_UTILITIES::Value_To_String(frame));
    collection.Write(stream_type,"output",frame,0,true);
}
```

```
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient // Elasticity and damping coefficients
    const T wire_mass,wire_restlength;          // Mass and length for entire wire
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X)
{
    // Set upper endpoint position
    T angular_velocity=two_pi/(frame_time*(T)number_of_frames);
    particles.X(1)=TV(.5*sin(time*angular_velocity),0,.5*cos(time*angular_velocity));
}
```

```
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient // Elasticity and damping coefficients
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V)
{
    // Set upper endpoint position
    T angular_velocity=two_pi/(frame_time*(T)number_of_frames);
    particles.V(1)=TV(.5*angular_velocity*cos(time*angular_velocity),0,
        -.5*angular_velocity*sin(time*angular_velocity));
}
```

```
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient      // Elasticity and damping coefficients
    const T wire_mass,wire_restlength;              // Mass and length for entire wire
    ARRAY<T> mass,restlength;                       // Mass (per each particle), restlength (per each spring)

    GEOMETRY_PARTICLES<TV> particles;
    DEFORMABLE_GEOMETRY_COLLECTION<TV> collection;

    c
    c
    c

    S
    F

    S
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
template<class T>
void SIMULATION_LAYOUT<T>::Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array)
{
    // Only the first particle is constrained
    array(1)=TV();
}
```

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;

    const STREAM_TYPE stream_type;

    const int n;                                    // Number of particles in wire mesh
    const T youngs_modulus,damping_coefficient      // Elasticity and damping coefficients
    const T wire_mass,wire_restlength;              // Mass and length for entire wire
    ARRAY<T> mass,restlength;                       // Mass (per each particle), restlength (per each spring)

    GEOMETRY_PARTICLES<TV> particles;
    DEFORMABLE_GEOMETRY_COLLECTION<TV> collection;

    const int number_of_frames;  // Total number of frames
    const T frame_time;          // Frame (snapshot) interval
    const T CFL_number;          // CFL number (not to exceed 1)

    SEGMENTED_CURVE<TV>* wire_curve;
    FREE_PARTICLES<TV>* wire_particles;

    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

Implementation of time integration methods

- Improvement : Factor out a “Layout” class
  - main.cpp now only calls the LAYOUT class
  - main.cpp retains the time integration algorithm (for now)

```
    #include "SIMULATION_LAYOUT.h"
using namespace PhysBAM;

int main(int argc,char* argv[])
{
    typedef float T;typedef float RW;typedef VECTOR<T,3> TV;
    RW rw=RW();STREAM_TYPE stream_type(rw);

    LOG::Initialize_Logging();

    SIMULATION_LAYOUT<T> layout(stream_type);
    layout.Initialize();layout.Write_Output(0);

    T dt_max=layout.Maximum_Dt(),dt,time=0.;

    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

 [...]
        }

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
    #include "SIMULATION_LAYOUT.h"
using namespace PhysBAM;

int main(int argc,char* argv[])
{
    typedef float T;typedef float RW;typedef VECTOR<T,3> TV;
    RW rw=RW();STREAM_TYPE stream_type(rw);

    LOG::Initialize_Logging();

    SIMULATION_LAYOUT<T> layout(stream_type);
    layout.Initialize();layout.Write_Output(0);

    T dt_max=layout.Maximum_Dt(),dt,time=0.;

    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

 [...]
        }

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
    #include "SIMULATION_LAYOUT.h"
using namespace PhysBAM;

int main(int argc,char* argv[])
{
    typedef float T;typedef float RW;typedef VECTOR<T,3> TV;
    RW rw=RW();STREAM_TYPE stream_type(rw);

    LOG::Initialize_Logging();

    SIMULATION_LAYOUT<T> layout(stream_type);
    layout.Initialize();layout.Write_Output(0);

    T dt_max=layout.Maximum_Dt(),dt,time=0.;

    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

 [...]
        }

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

```
[...]
int main(int argc,char* argv[])
{
[...]
    for(int frame=1;frame<=layout.number_of_frames;frame++){
        T frame_end_time=layout.frame_time*(T)frame;

        for(;time<frame_end_time;time+=dt){
            dt=std::min(dt_max,(T)1.001*(frame_end_time-time));

            layout.Set_Kinematic_Positions(time,layout.particles.X);
            layout.Set_Kinematic_Velocities(time,layout.particles.V);

            ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
            layout.Add_Elastic_Forces(layout.particles.X,force);
            layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
            layout.Add_External_Forces(force);

            // Apply the Forward Euler method
            dX=dt*layout.particles.V;                    // Compute position change
            for(int p=1;p<=layout.n;p++)
                dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

            layout.Clear_Values_Of_Kinematic_Particles(dX);
            layout.Clear_Values_Of_Kinematic_Particles(dV);

            layout.particles.X+=dX;                      // Update particle positions and velocities
            layout.particles.V+=dV;

            layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
            layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);}

        layout.Write_Output(frame);}

    LOG::Finish_Logging();
}
```

Implementation of time integration methods

- Improvement : Factor out a “Driver” class
  - DRIVER contains all the functionality for advancing the simulation forward in time
  - DRIVER does NOT contain the state of the system
  - DRIVER is reusable, and scene-independent

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

template<class T>
class SIMULATION_DRIVER
{
public:
    typedef VECTOR<T,3> TV;

    SIMULATION_LAYOUT<T>& layout;
    T time;

    SIMULATION_DRIVER(SIMULATION_LAYOUT<T>& layout_input)
        :layout(layout_input) {}

    void Run()
    {
        layout.Initialize();layout.Write_Output(0);time=0;

        for(int frame=1;frame<=layout.number_of_frames;frame++){
            Simulate_Frame(frame);layout.Write_Output(frame);}
    }

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

template<class T>
class SIMULATION_DRIVER
{
public:
    typedef VECTOR<T,3> TV;

    SIMULATION_LAYOUT<T>& layout;
    T time;

    SIMULATION_DRIVER(SIMULATION_LAYOUT<T>& layout_input)
        :layout(layout_input) {}

    void Run()
    {
        layout.Initialize();layout.Write_Output(0);time=0;

        for(int frame=1;frame<=layout.number_of_frames;frame++){
            Simulate_Frame(frame);layout.Write_Output(frame);}
    }

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

template<class T>
class SIMULATION_DRIVER
{
public:
    typedef VECTOR<T,3> TV;

    SIMULATION_LAYOUT<T>& layout;
    T time;

    SIMULATION_DRIVER(SIMULATION_LAYOUT<T>& layout_input)
        :layout(layout_input) {}

    void Run()
    {
        layout.Initialize();layout.Write_Output(0);time=0;

        for(int frame=1;frame<=layout.number_of_frames;frame++){
            Simulate_Frame(frame);layout.Write_Output(frame);}
    }

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

template<class T>
class SIMULATION_DRIVER
{
public:
    typedef VECTOR<T,3> TV;

    SIMULATION_LAYOUT<T>& layout;
    T time;

    SIMULATION_DRIVER(SIMULATION_LAYOUT<T>& layout_input)
        :layout(layout_input) {}

    void Run()
    {
        layout.Initialize();layout.Write_Output(0);time=0;

        for(int frame=1;frame<=layout.number_of_frames;frame++){
            Simulate_Frame(frame);layout.Write_Output(frame);}
    }

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

templ
clas
{
publ
```

```
template<class T>
void SIMULATION_DRIVER<T>::Simulate_Frame(const int frame)
{
    T frame_end_time=layout.frame_time*(T)frame,dt_max,dt;

    for(;time<frame_end_time;time+=dt){
        dt_max=layout.Maximum_Dt();
        dt=std::min(dt_max,(T)1.001*(frame_end_time-time));
        Simulate_Time_Step(time,dt);}
}
```

```
    layout.Initialize();layout.Write_Output(0);time=0;

    for(int frame=1;frame<=layout.number_of_frames;frame++){
        Simulate_Frame(frame);layout.Write_Output(frame);}
}

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

```
    namespace

template<cla

template<cla
class SIMULA
{
public:
    typedef

    SIMULATI
    T time;

    SIMULATI
        :lay

    void Run
    {
        layo

        for(

    }

    void Sim
    void Sim

};

}
```

```
template<class T>
void SIMULATION_DRIVER<T>::Simulate_Time_Step(const T time,const T dt)
{
    layout.Set_Kinematic_Positions(time,layout.particles.X);
    layout.Set_Kinematic_Velocities(time,layout.particles.V);

    ARRAY<TV> force(layout.n),dX(layout.n),dV(layout.n);
    layout.Add_Elastic_Forces(layout.particles.X,force);
    layout.Add_Damping_Forces(layout.particles.X,layout.particles.V,force);
    layout.Add_External_Forces(force);

    // Apply the Forward Euler method
    dX=dt*layout.particles.V;                   // Compute position change
    for(int p=1;p<=layout.n;p++)
        dV(p)=(dt/layout.mass(p))*force(p); // Compute velocity change

    layout.Clear_Values_Of_Kinematic_Particles(dX);
    layout.Clear_Values_Of_Kinematic_Particles(dV);

    layout.particles.X+=dX;     // Update particle positions and velocities
    layout.particles.V+=dV;

    layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
    layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);
}
```

```
    namespace PhysBAM{

template<class T> class SIMULATION_LAYOUT;

template<class T>
class SIMULATION_DRIVER
{
public:
    typedef VECTOR<T,3> TV;

    SIMULATION_LAYOUT<T>& layout;
    T time;

    SIMULATION_DRIVER(SIMULATION_LAYOUT<T>& layout_input)
        :layout(layout_input) {}

    void Run()
    {
        layout.Initialize();layout.Write_Output(0);time=0;

        for(int frame=1;frame<=layout.number_of_frames;frame++){
            Simulate_Frame(frame);layout.Write_Output(frame);}
    }

    void Simulate_Frame(const int frame);
    void Simulate_Time_Step(const T time,const T dt);

};

}
```

Implementation of time integration methods

- Improvement : Factor out a “Driver” class
  - DRIVER contains all the functionality for advancing the simulation forward in time
  - DRIVER does NOT contain the state of the system
  - DRIVER is reusable, and scene-independent
  - main() effectively becomes a stub function

```
    #include <PhysBAM_Geometry/Geometry_Particles/REGISTER_GEOMETRY_READ_WRITE.h>
#include <PhysBAM_Geometry/Solids_Geometry/DEFORMABLE_GEOMETRY_COLLECTION.h>
#include <PhysBAM_Geometry/Topology_Based_Geometry/SEGMENTED_CURVE.h>
#include <PhysBAM_Geometry/Topology_Based_Geometry/FREE_PARTICLES.h>

#include "SIMULATION_LAYOUT.h"
#include "SIMULATION_DRIVER.h"

using namespace PhysBAM;

int main(int argc,char* argv[])
{
    typedef float T;typedef float RW;typedef VECTOR<T,3> TV;
    RW rw=RW();STREAM_TYPE stream_type(rw);

    LOG::Initialize_Logging();

    SIMULATION_LAYOUT<T> layout(stream_type);
    SIMULATION_DRIVER<T> driver(layout);
    driver.Run();

    LOG::Finish_Logging();
}
```

Implementation of time integration methods

- Swapping out Forward Euler for a different integration method
  - e.g.

$$\begin{aligned} x^{n+1} &= x^n + \frac{dt}{2}(v^n + v^{n+1}) \\ v^{n+1} &= v^n + \frac{dt}{m} f(x^n, v^{n+1}) \end{aligned}$$

- or, for a mass spring system

$$\begin{aligned} x^{n+1} &= x^n + \frac{dt}{2}(v^n + v^{n+1}) \\ v^{n+1} &= v^n + \frac{dt}{m}\left\{f^{el}(x^n) + G(x^n)v^{n+1}\right\} \end{aligned}$$

- which leads to:

$$\left(I - \frac{dt}{m}G(x^n)\right) v^{n+1} = v^n + \frac{dt}{m} f(x^n)$$

```
namespace PhysBAM{
template<class T>
class SIMULATION_LAYOUT
{
public:
    typedef VECTOR<T,3> TV;
```

```
template<class T>
T SIMULATION_LAYOUT<T>::Maximum_Dt()
{
    T maximum_dt=frame_time;
    for(int s=1;s<=wire_curve->mesh.elements.m;s++){
        int p1,p2;wire_curve->mesh.elements(s).Get(p1,p2);
        T spring_mass=1./(1./mass(p1)+1./mass(p2));
        maximum_dt=std::min(maximum_dt,2*damping_coefficient*restlength(s)/youngs_modulus);
    }

    return CFL_number*maximum_dt;
}
```

$$dt < \frac{2bl_0}{k}$$

```
    SIMULATION_LAYOUT(const STREAM_TYPE stream_type_input);
    void Initialize();
    void Add_Elastic_Forces(const ARRAY_VIEW<TV>& X,ARRAY<TV>& force);
    void Add_Damping_Forces(const ARRAY_VIEW<TV>& X,const ARRAY_VIEW<TV>& V,
        ARRAY<TV>& force);
    void Add_External_Forces(ARRAY<TV>& force);
    T Maximum_Dt();
    void Write_Output(const int frame);
    void Set_Kinematic_Positions(const T time,ARRAY_VIEW<TV>& X);
    void Set_Kinematic_Velocities(const T time,ARRAY_VIEW<TV>& V);
    void Clear_Values_Of_Kinematic_Particles(ARRAY<TV>& array);
};
}
```

```
    namespace

template<cla

template<cla
class SIMULA
{
public:
    typedef

    SIMULATI
    T time;

    SIMULATI
        :lay

    void Run
    {
        layo

        for(

    }

    void Sim
    void Sim

};

}
```

```
template<class T>
void SIMULATION_DRIVER<T>::Simulate_Time_Step(const T time,const T dt)
{
    layout.Set_Kinematic_Positions(time,layout.particles.X);
    layout.Set_Kinematic_Velocities(time,layout.particles.V);

    << Somehow solve for dV=V^{n+1}-V^n >>

    // Trapezoidal position
    dX=(dt/2)*layout.particles.V;
    layout.particles.V+=dV;
    dX+=(dt/2)*layout.particles.V;

    layout.Clear_Values_Of_Kinematic_Particles(dX);
    layout.Clear_Values_Of_Kinematic_Particles(dV);

    layout.particles.X+=dX;     // Update particle positions and velocities
    layout.particles.V+=dV;

    layout.Set_Kinematic_Positions(time+dt,layout.particles.X);
    layout.Set_Kinematic_Velocities(time+dt,layout.particles.V);
}
```

Implementation of time integration methods

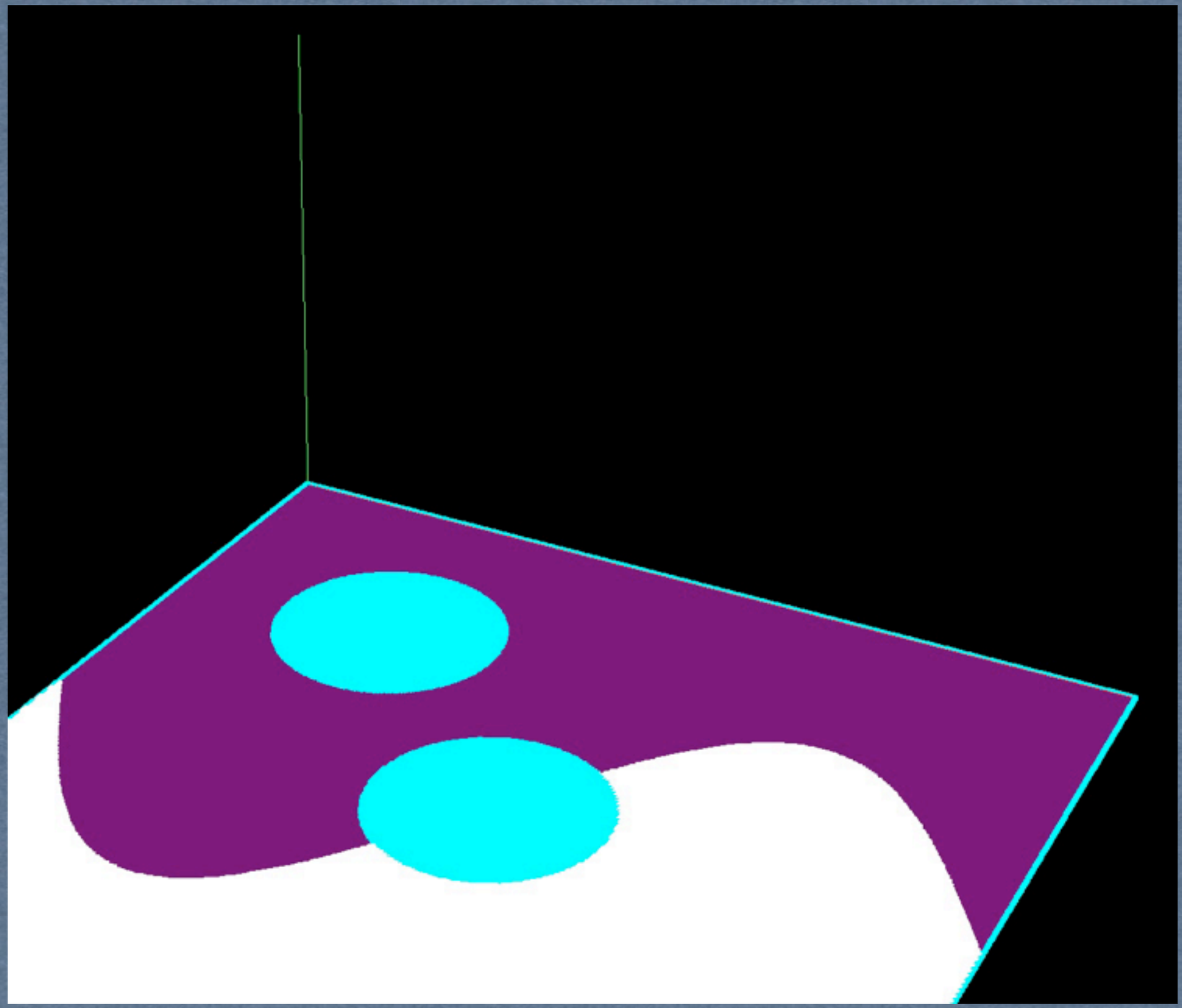
- For efficient solution of the linear system, we use the Conjugate Gradients method
  - Requires : Symmetric matrix
  - Requires : Positive Definite Matrix
  - Iterative procedure : Starts with initial guess, improves as iterations proceed

Problem description

Properties of the resulting discretization

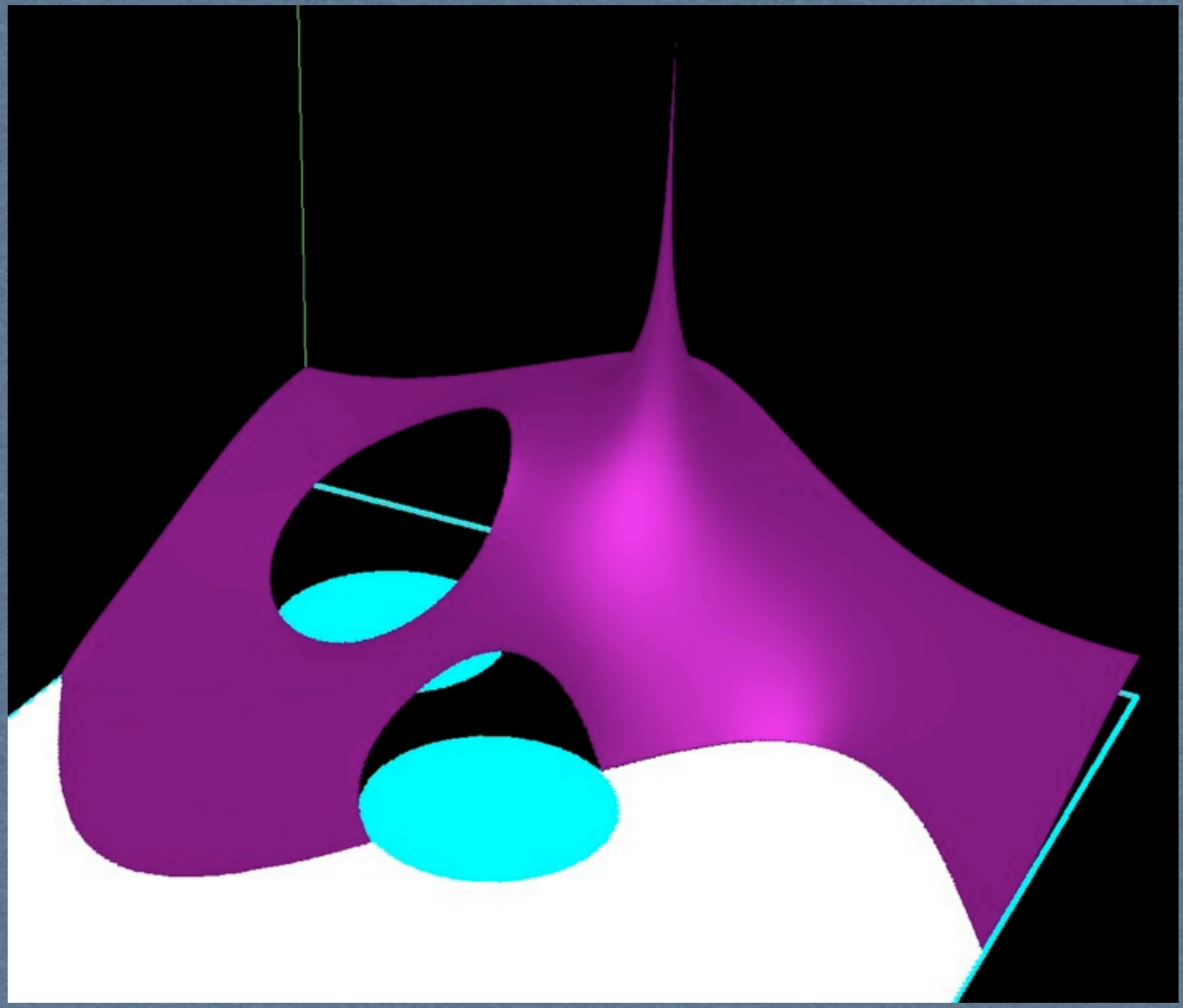
- Symmetric, sparse (banded) system
- Negative semi-definite (strictly definite with any Dirichlet boundary)
- Symmetric Krylov solvers are applicable, i.e. preconditioned CG

Pr



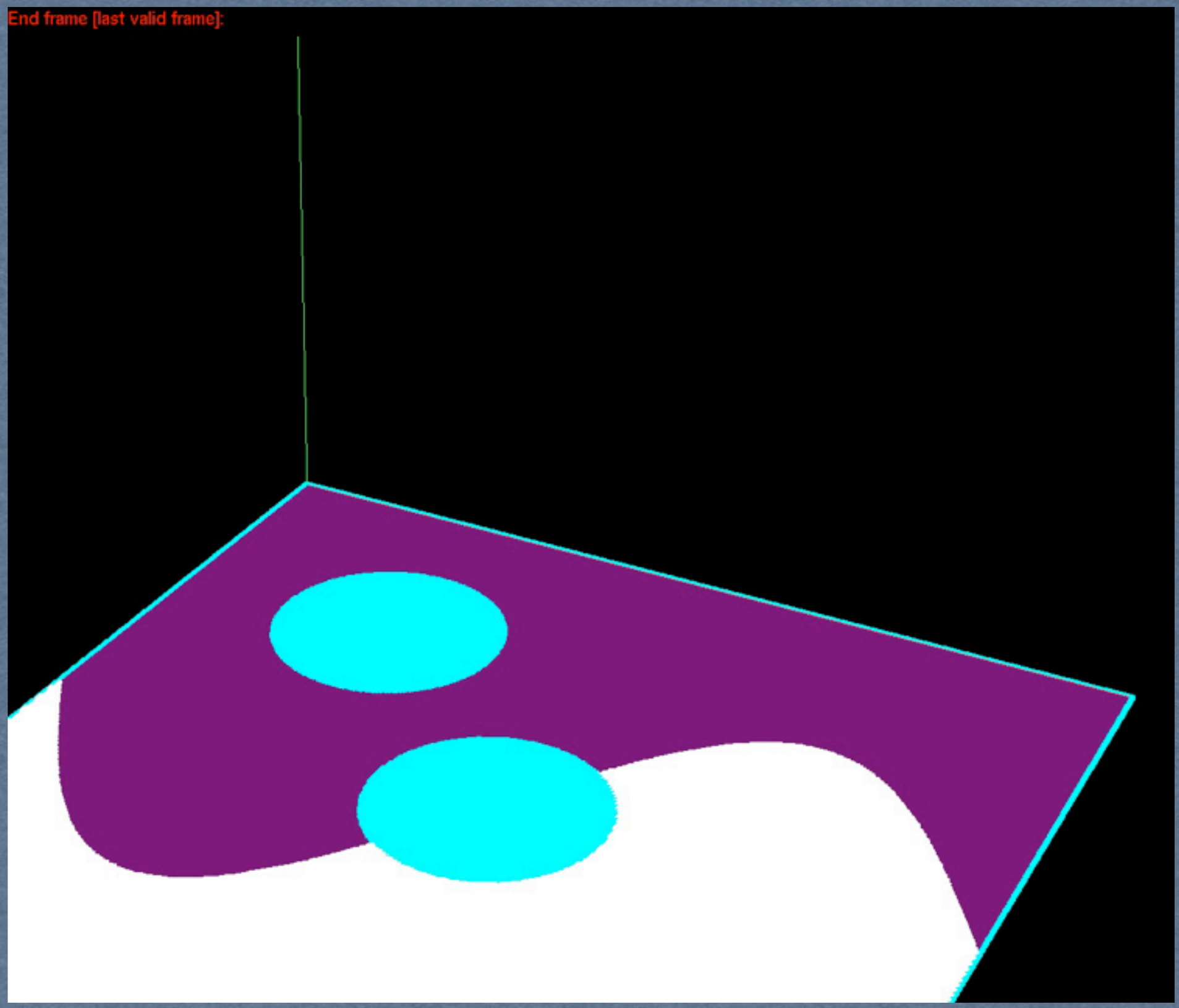
Sample 2D domain (512x512 resolution)

Pr



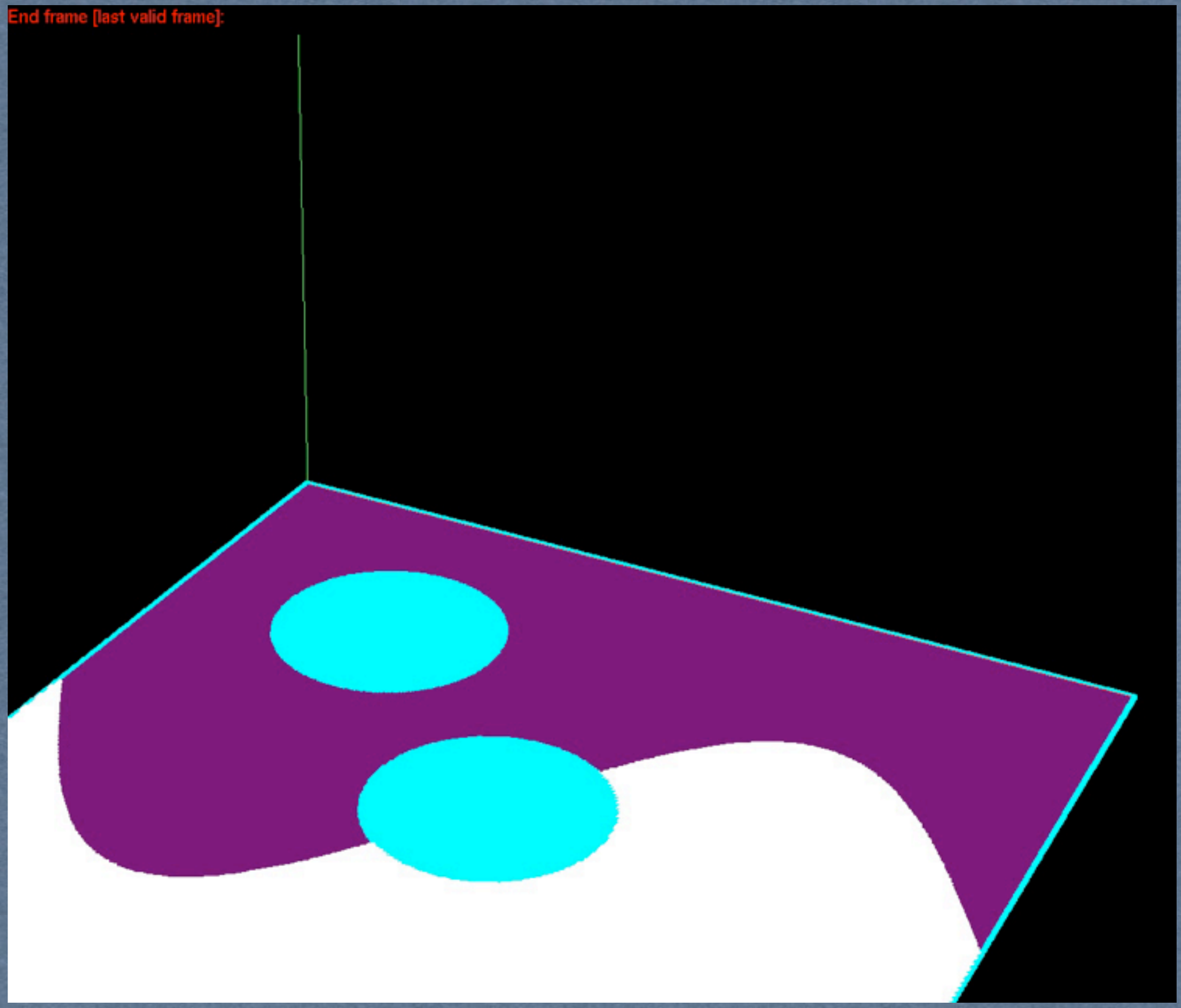
Exact solution (i.e. Green's function; RHS is a delta impulse)

Pr



Convergence of the un-preconditioned CG algorithm

Pr



CG with an Incomplete Cholesky preconditioner

Implementation of time integration methods

- Restructuring of sample code using driver & layout
  - Separates scene layout from simulation algorithms
  - Compartmentalized, reusable operations
  - Switching between integration methods is more straightforward
  - Initially demonstrated on our Forward Euler example