Detector construction

Mihaly Novak (CERN, EP-SFT)

Getting Started with **`Geant4`** at CERN, Geneva (Switzerland), 21-23 January 2020

Detector construction

- Material definition
  - The **Geant4** material model
  - Material definition
  - The **NIST** material data base
- Geometry definition
  - The **Geant4** geometry description
  - Solid, Logical - , Physical - volume

Material definition

THE GEANT4 MATERIAL MODEL

The `Geant4` material model

- The **`Geant4` material** model follows the natural one: materials are made of **elements** and elements are made of **isotopes**
- The 3 main classes to describe these objects are
  - `G4Isotope`*:* describes the properties of atoms (`Z` - atomic number, `N` - number of nucleons and `A` - molar mass) with unique `name` and `index`
  - `G4Element`*:* describes the properties of elements (`Z` - effective atomic number, `N` - effective number of nucleons and `A` - effective molar mass, number of isotopes, etc.) with unique `name, symbol` and `index`
  - `G4Material`*:* describes the macroscopic properties of matter (**density**, **state**, **temperature**, **pressure**, etc.) with unique `name` and `index`
- Unique index: a pointer to the created object is automatically stored in global table (isotope, element and material tables)

The **`Geant4`** material model

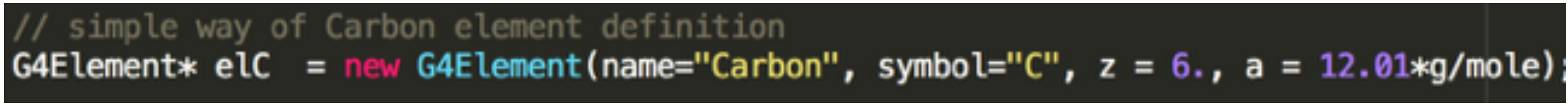
- The **material density** must be set (> zero) by the user at definition (except NIST materials) !
- The **material temperature** and **pressure** can optionally be set:
  - default: Normal Temperature and Pressure(NTP) 293.15 [k], 1 [atm] = 101.325 [kPascal]
- The **material state** can be **solid**, **liquid** or **gas**:
  - default is either solid or gas depending on the density (`kGasThreshold` = 10 [mg/cm^3])
  - non-crystalline (i.e. amorphous) solid by default (special extension for incorporating some information on the crystal structure)
- Special set of pre-defined materials: **`NIST`** material composition data base with some frequently used HEP materials
- **Geant4 material documentation:** **Material Documentation**

Material definition

MATERIAL DEFINITION

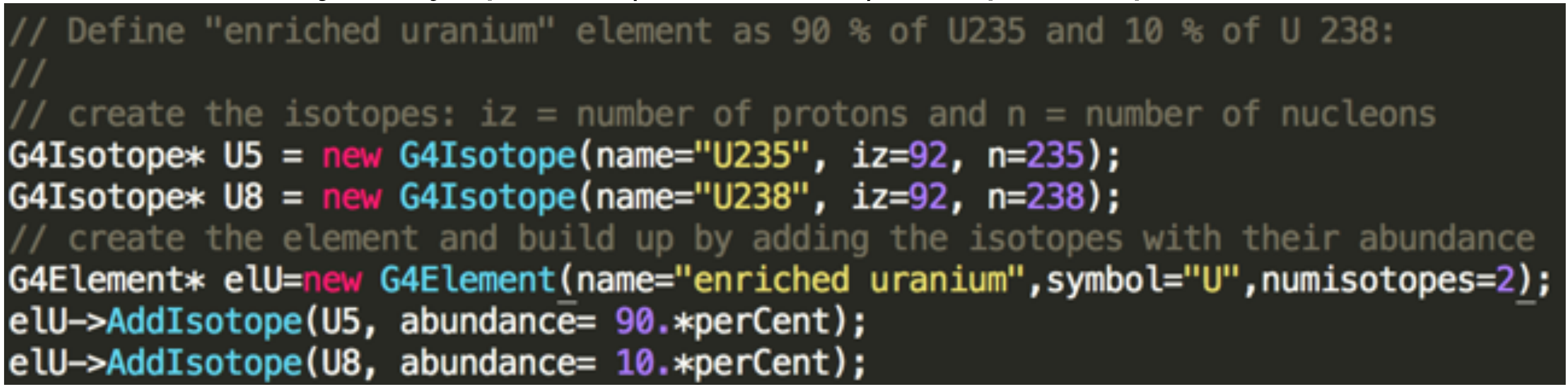
Material definition: elements and isotopes

- Elements and isotopes:
  - **G4Element** object without specifying the isotope composition:



```
// simple way of Carbon element definition
G4Element* elC  = new G4Element(name="Carbon", symbol="C", z = 6., a = 12.01*g/mole);
```

    - need to give: `name, symbol, Z` and `A` (effective atomic number and molar mass)
    - isotopes will be automatically added with natural abundances (`A` won't be updated)
  - **G4Element** object by specific (non-natural) isotope composition:

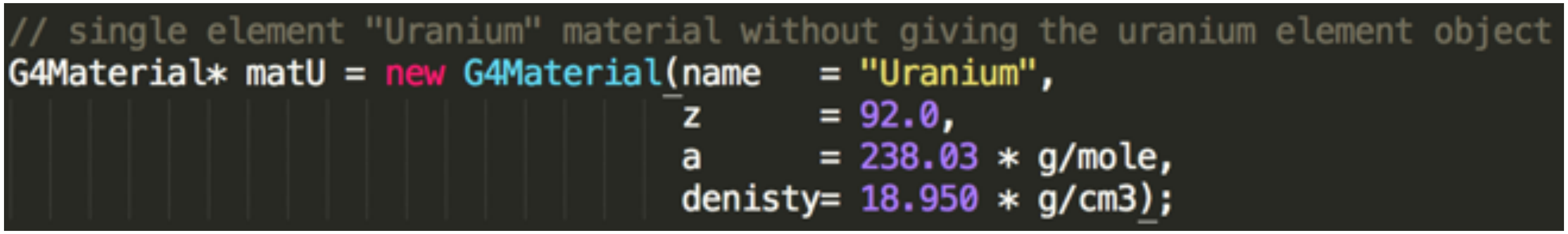


```
// Define "enriched uranium" element as 90 % of U235 and 10 % of U 238:
//
// create the isotopes: iz = number of protons and n = number of nucleons
G4Isotope* U5 = new G4Isotope(name="U235", iz=92, n=235);
G4Isotope* U8 = new G4Isotope(name="U238", iz=92, n=238);
// create the element and build up by adding the isotopes with their abundance
G4Element* elU=new G4Element(name="enriched uranium",symbol="U",numisotopes=2);
elU->AddIsotope(U5, abundance= 90.*perCent);
elU->AddIsotope(U8, abundance= 10.*perCent);
```

    - element object must be created: `name, symbol, number of isotopes`
    - isotope objects must be created: `name, number of protons` and `nucleons`
    - isotopes need to be added by their relative abundance

Material definition: simple material definition

- Simple `G4Material` object definition:
  - “simple”: the material contains only one element and the corresponding `G4Element` object is not provided:

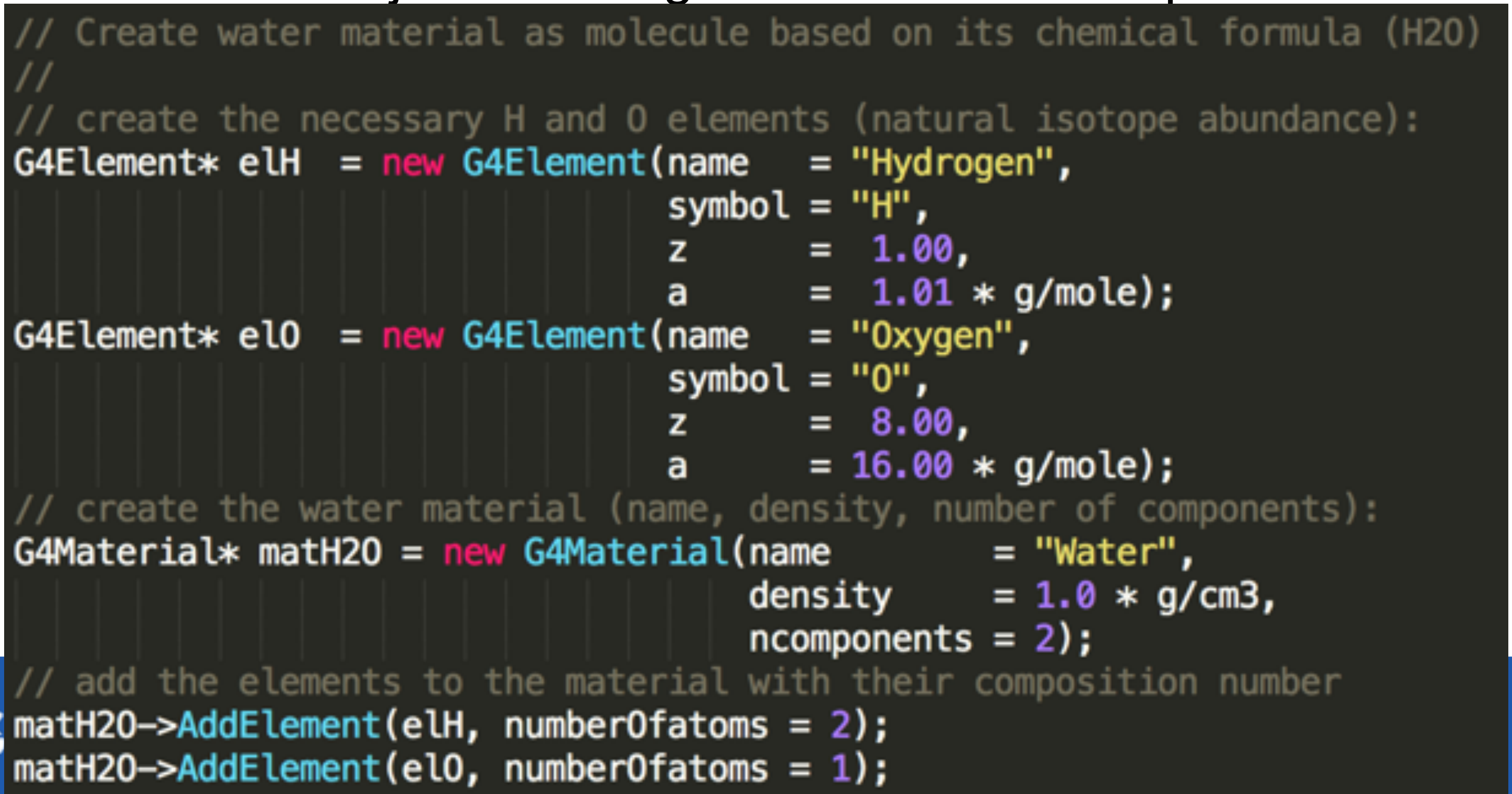


```
// single element "Uranium" material without giving the uranium element object
G4Material* matU = new G4Material(name    = "Uranium",
                                  z       = 92.0,
                                  a       = 238.03 * g/mole,
                                  denisty= 18.950 * g/cm3);
```

    - the corresponding `G4Element` object will be automatically created (with natural isotope abundance)
    - need to give: `name`, `density` of the material, `Z` and `A` (effective atomic number and molar mass) of the single `G4Element`
    - what happens if we want the single element to have non-natural isotope abundance e.g. the previously created `enriched uranium` (see later)

Material definition: chemical molecule

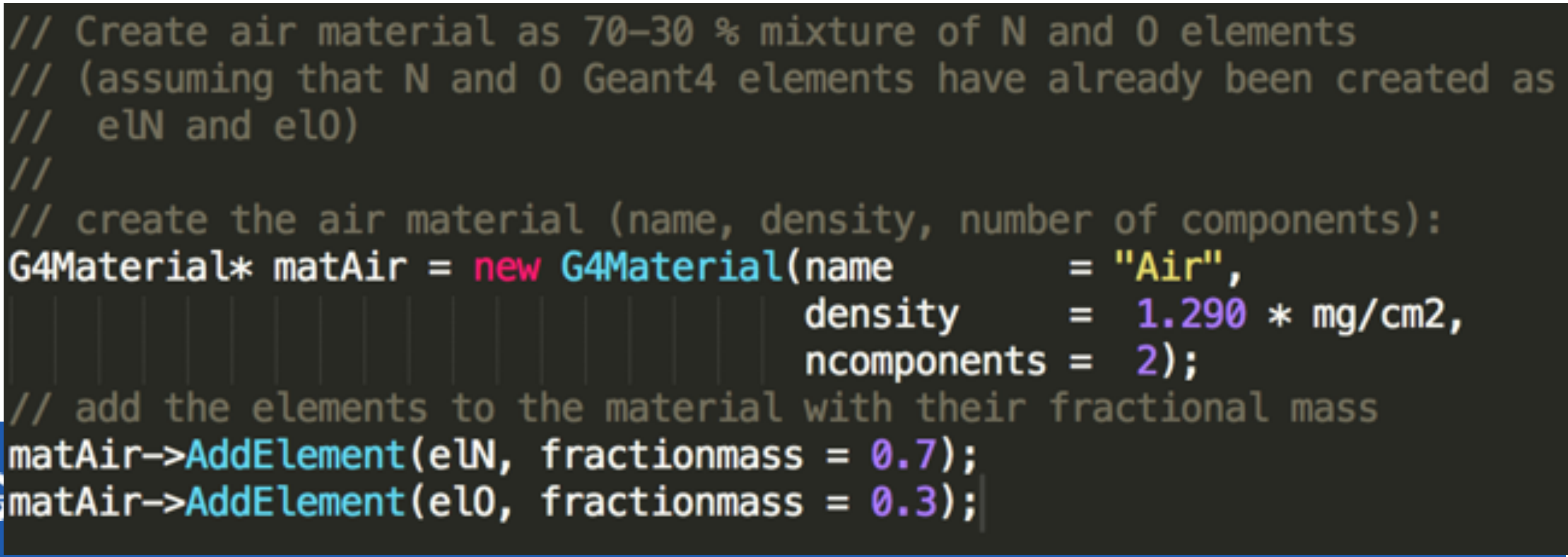
- `G4Material` object definition as chemical molecule:
  - molecules build up from (several) elements with composition specified by the number of element (e.g. water = H_2O)
  - accordingly, `G4Material` object can be created by adding `G4Element` objects to it together with their composition number:



```
// Create water material as molecule based on its chemical formula (H2O)
//
// create the necessary H and O elements (natural isotope abundance):
G4Element* elH  = new G4Element(name   = "Hydrogen",
                                symbol = "H",
                                z      =  1.00,
                                a      =  1.01 * g/mole);
G4Element* elO  = new G4Element(name   = "Oxygen",
                                symbol = "O",
                                z      =  8.00,
                                a      = 16.00 * g/mole);
// create the water material (name, density, number of components):
G4Material* matH2O = new G4Material(name        = "Water",
                                    density     = 1.0 * g/cm3,
                                    ncomponents = 2);
// add the elements to the material with their composition number
matH2O->AddElement(elH, numberOfatoms = 2);
matH2O->AddElement(elO, numberOfatoms = 1);
```

Material definition: mixture

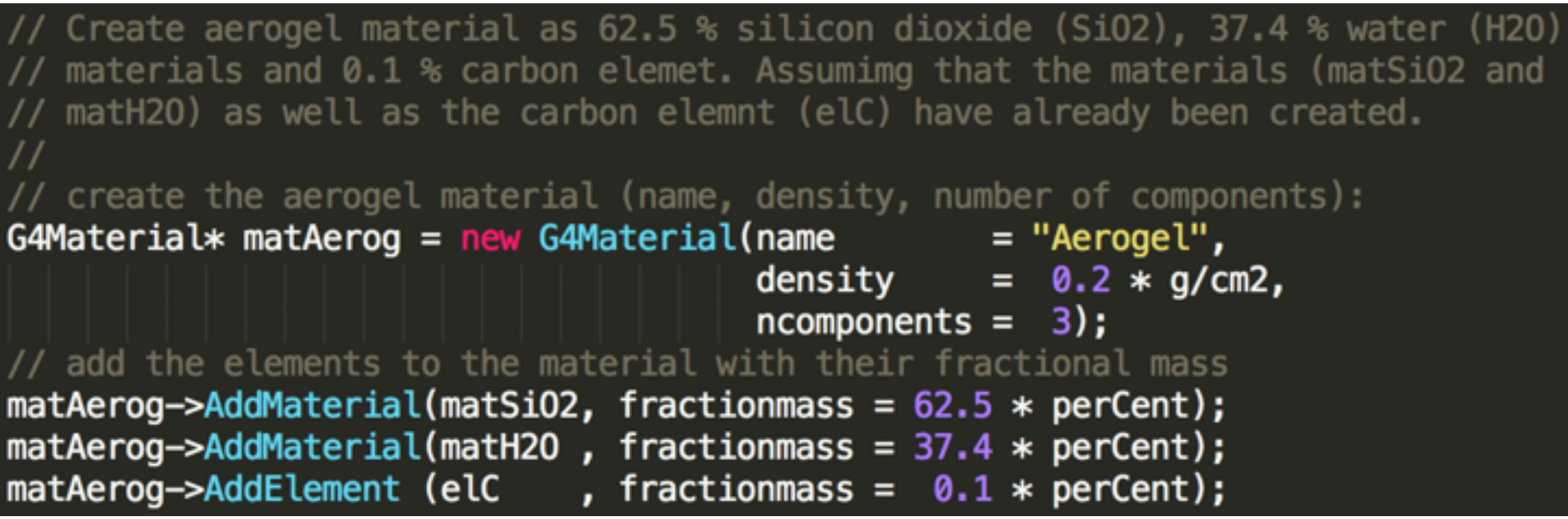
- `G4Material` object definition as mixture:
  - mixture of elements (`G4Element`), mixture of other materials (`G4Material`) or even mixture of elements and materials
  - similar to molecules with the differences:
    - components can be other materials not only elements
    - the ratio of the components must be given as "**`fractional mass`**" not as "**`number of atoms`**"
  - **mixture of elements** example: using the `AddElement` method



```
// Create air material as 70-30 % mixture of N and O elements
// (assuming that N and O Geant4 elements have already been created as
//   elN and elO)
//
// create the air material (name, density, number of components):
G4Material* matAir = new G4Material(name         = "Air",
                                    density      =  1.290 * mg/cm2,
                                    ncomponents =  2);
// add the elements to the material with their fractional mass
matAir->AddElement(elN, fractionmass = 0.7);
matAir->AddElement(elO, fractionmass = 0.3);
```

Material definition: mixture

- `G4Material` object definition as mixture:
  - **mixture of element(s) and material(s)** example: using the `AddElement` and `AddMaterial` methods



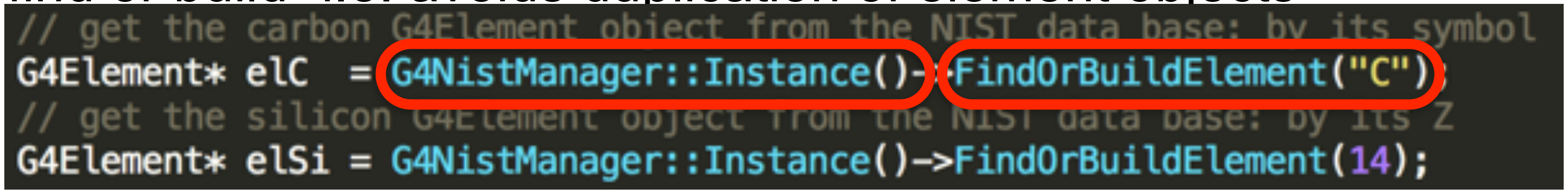
```
// Create aerogel material as 62.5 % silicon dioxide (SiO2), 37.4 % water (H2O)
// materials and 0.1 % carbon elemet. Assumimg that the materials (matSiO2 and
// matH2O) as well as the carbon elemnt (elC) have already been created.
//
// create the aerogel material (name, density, number of components):
G4Material* matAerog = new G4Material(name        = "Aerogel",
                                      density     =  0.2 * g/cm2,
                                      ncomponents =  3);
// add the elements to the material with their fractional mass
matAerog->AddMaterial(matSiO2, fractionmass = 62.5 * perCent);
matAerog->AddMaterial(matH2O , fractionmass = 37.4 * perCent);
matAerog->AddElement (elC    , fractionmass =  0.1 * perCent);
```

Material definition

THE NIST MATERIAL DATA BASE

The **`NIST`** material data base

- The data base includes more than 3000 **isotopes**
- Isotopic composition of **elements** (Z = [1-108]) with their **natural isotopic abundance**: using the **NIST Atomic Weights and Isotopic Compositions** data base
- **NIST elements** can be obtained easily from the **`Geant4 NIST`** data base **by** using **their** `symbol` or `Z - atomic number:`
  - the corresponding **`G4Isotope`** objects will be automatically built
  - "find or build" i.e. avoids duplication of element objects



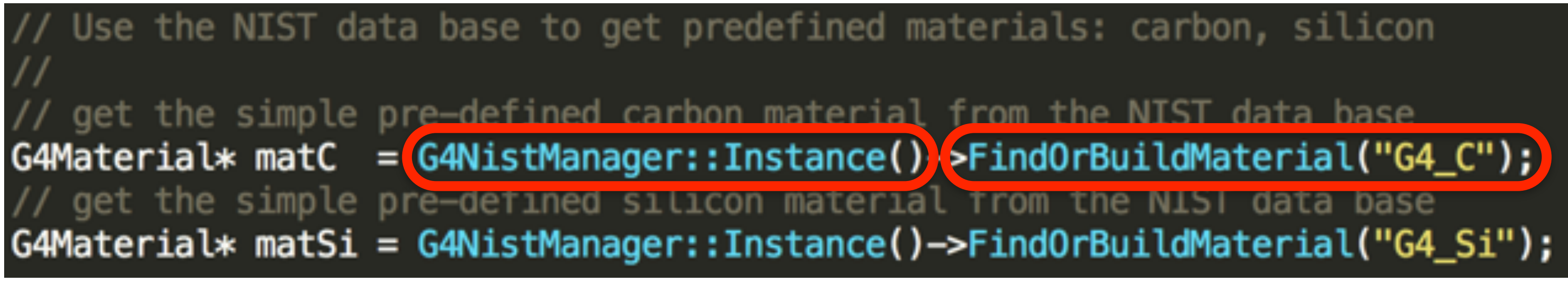
```
// get the carbon G4Element object from the NIST data base: by its symbol
G4Element* elC  = G4NistManager::Instance()->FindOrBuildElement("C");
// get the silicon G4Element object from the NIST data base: by its Z
G4Element* elSi = G4NistManager::Instance()->FindOrBuildElement(14);
```

- Large collection of **pre-defined materials**:
  - pre-defined: density, elemental composition (with the pre-defined natural isotopic composition), mean ionization energy, density effect parameters, etc.

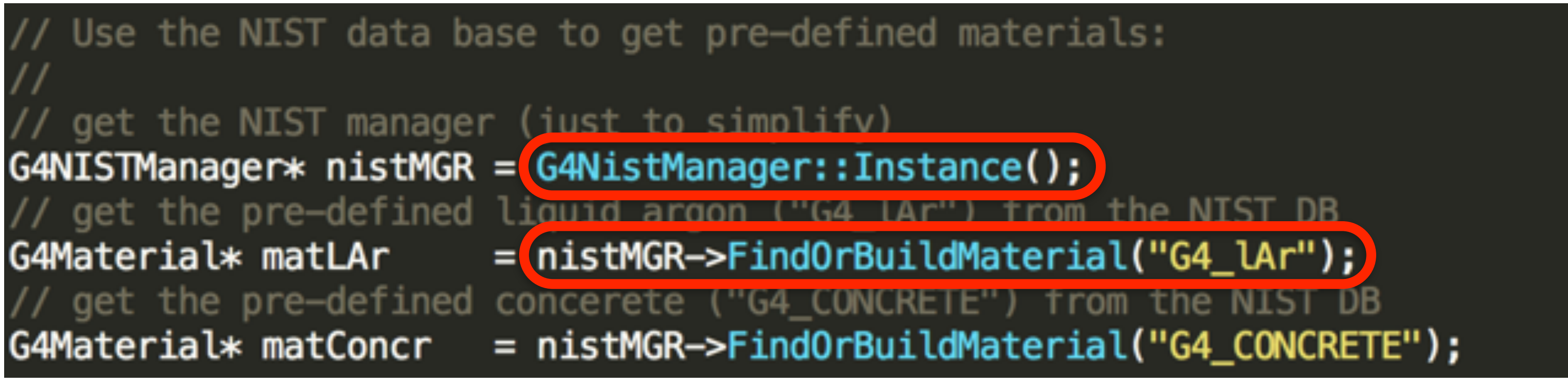
The `NIST` material data base

- **Use these pre-defined materials whenever possible**:
  - guaranties high accuracy for many derived parameters (consistency)
- `NIST` and more pre-defined **materials** (318 at the moment)**:**
  - **single element `NIST`** materials with Z = [1-98] and named after the atomic symbol:
    - aluminum ("`G4_Al`"), silicon ("`G4_Si`"), gold ("`G4_Au`"), etc.
  - **compound NIST** materials:
    - "`G4_AIR`", "`G4_ALUMINUM_OXIDE`", "`G4_MUSCLE_SKELETAL_ICRP`", etc.
  - **HEP** and nuclear materials:
    - liquid argon "`G4_lAr`", lead tungstate "`G4_PbWO4`", "`G4_STAINLESS-STEEL`", etc.
  - **space** materials:
    - "`G4_KEVLAR`", "`G4_NEOPRENE`", etc.
  - **bio-chemical** materials:
    - the DNA bases "`G4_ADENINE`", "`G4_GUANINE`", "`G4_CYTOSINE`", "`G4_THYMINE`", etc.

- How to access these pre-define materials:
  - can be obtained from the **Geant4 NIST** data base **by** using **their name**
  - their name starts with the "**G4_**" **prefix** (see in the previous



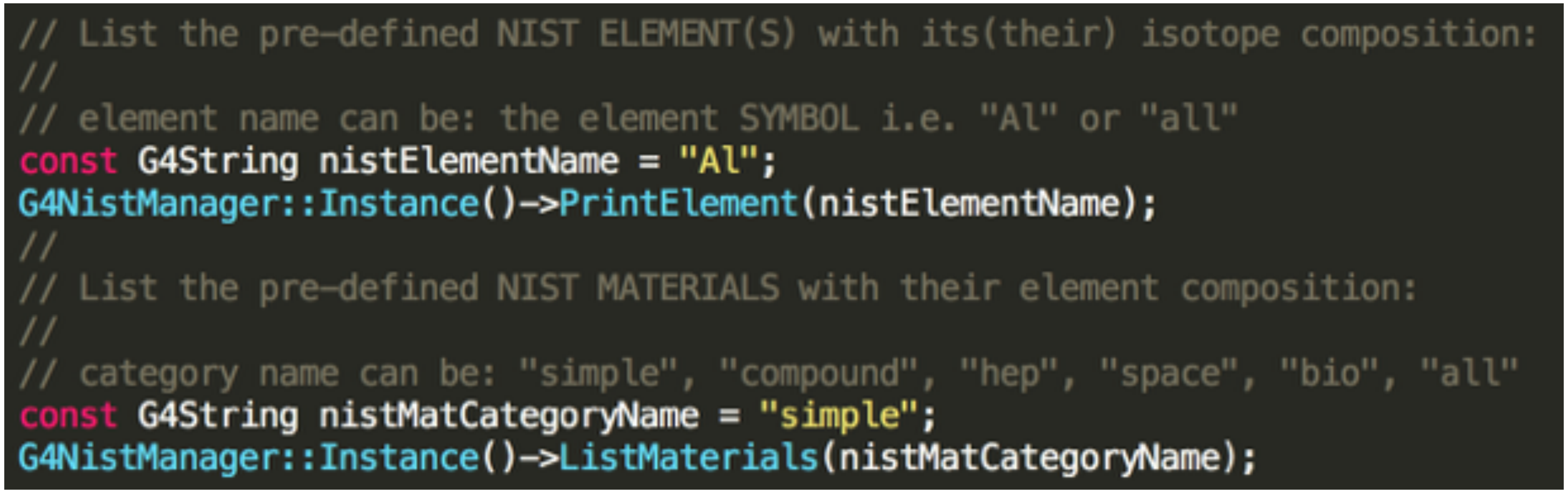
```
// Use the NIST data base to get predefined materials: carbon, silicon
//
// get the simple pre-defined carbon material from the NIST data base
G4Material* matC  = G4NistManager::Instance()->FindOrBuildMaterial("G4_C");
// get the simple pre-defined silicon material from the NIST data base
G4Material* matSi = G4NistManager::Instance()->FindOrBuildMaterial("G4_Si");
```



```
// Use the NIST data base to get pre-defined materials:
//
// get the NIST manager (just to simplify)
G4NISTManager* nistMGR = G4NistManager::Instance();
// get the pre-defined liquid argon ("G4_lAr") from the NIST DB
G4Material* matLAr     = nistMGR->FindOrBuildMaterial("G4_lAr");
// get the pre-defined concerete ("G4_CONCRETE") from the NIST DB
G4Material* matConcr   = nistMGR->FindOrBuildMaterial("G4_CONCRETE");
```

The **NIST** material data base

- List available pre-define **NIST** elements, materials from the data base with their composition:
  - user interface command:
    - `/material/nist/printElement <SYMBOL>`
    - `/material/nist/listMaterials <CATEGORY>`
  - directly from C++ code:



```
// List the pre-defined NIST ELEMENT(S) with its(their) isotope composition:
//
// element name can be: the element SYMBOL i.e. "Al" or "all"
const G4String nistElementName = "Al";
G4NistManager::Instance()->PrintElement(nistElementName);
//
// List the pre-defined NIST MATERIALS with their element composition:
//
// category name can be: "simple", "compound", "hep", "space", "bio", "all"
const G4String nistMatCategoryName = "simple";
G4NistManager::Instance()->ListMaterials(nistMatCategoryName);
```

The **`NIST`** material data base

- List available pre-define **`NIST`** elements, materials from the data base with their composition:
  - user interface command:
    - `/material/nist/printElement <SYMBOL>`

We will keep it simple and use <u>NIST materials</u> in our application Try these out with the simple `main` that we wrote to check the installation!

Geometry definition

THE GEANT4 GEOMETRY DESCRIPTION

The **`Geant4`** geometry description

- **`Geant4`** detector **geometry** description is composed of **three** conceptual **layers**: **Solid**, **Logical-**Volume, **Physical-Volume**
- **users** need to **construct them** directly in their user code (Detector Construction) by "`new`", they get **registered** at construction in the corresponding store (**`G4SolidStore`**, **`G4LogicalVolumeStore, G4PhysicalVolumeStore`**) which will take care of deallocation of the corresponding memory at the end (if needed)
- geometry description can be rather complex but we will keep it simple now and focus only on the parts that we need
- more information on the detector geometry description can be found in the corresponding documentation: **Detector Geometry**

Geometry definition

SOLID

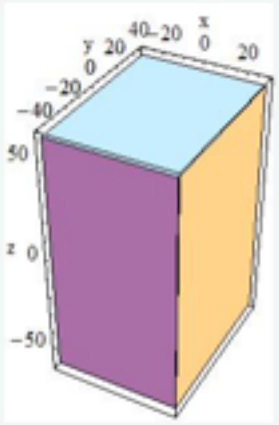
G4VSolid:

- the **shape** of the **Geant4** detector geometry builds up from **geometrical primitives**, all derived from the **G4VSolid** base class that provides interface to:
  - compute distances between the shape and a given point
  - check whether a point is inside the shape
  - compute the extent of the shape
  - compute the surface normal to the shape at a given point
- **Geant4** makes use of **Constructed Solid Geometry** (CSG) to define these geometrical primitives: **G4Box**, **G4Tubes**, **G4Trd**, **G4Para**, **G4Trap**, **G4Torus**, etc.. (special CSG-like solids e.g. **G4Polycone**, **G4Polyhedra**, **G4Ellipsoid**, etc., tessellated and boolean solids are also available. See the **Geometry: Solids** documentation).
- these three-dimensional primitives **described by a minimal set of parameter** to define the dimensions of the corresponding solid e.g. **G4Box**
- these implement the **G4VSolid** base class interface methods

Box:

To create a **box** one can use the constructor:

```
G4Box(const G4String& pName,
            G4double  pX,
            G4double  pY,
            G4double  pZ)
```



In the picture:

`pX = 30, pY = 40, pZ = 60`

by giving the box a name and its half-lengths along the X, Y and Z axis:

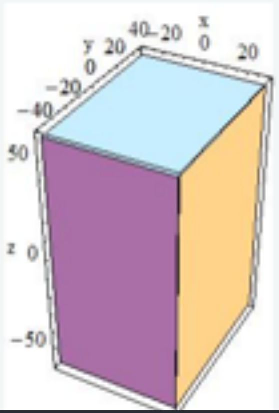
`pX`	half length in X	`pY`	half length in Y	`pZ`	half length in Z

This will create a box that extends from `-pX` to `+pX` in X, from `-pY` to `+pY` in Y, and from `-pZ` to `+pZ` in Z.

Box:

To create a **box** one can use the constructor:

```
G4Box(const G4String& pName,
              G4double  pX,
              G4double  pY,
              G4double  pZ)
```



```
// create solid (box) for the target
G4Box* targetSolid = new G4Box("solid-Target",      // name
                               0.5*targetXSize,    // half x-size
                               0.5*targetYZSize,   // half y-size
                               0.5*targetYZSize); // half z-size
```

by giving the box a name and its half-lengths along the X, Y and Z axis:

pX	half length in X	pY	half length in Y	pZ	half length in Z

This will create a box that extends from -pX to +pX in X, from -pY to +pY in Y, and from -pZ to +pZ in Z.

Geometry definition

LOGICAL VOLUME

Logical volume

`G4LogicalVolumne:`

- encapsulates **all information** of a detector volume element **except** its real physical **position** (position and rotation):
  - the **shape** and dimensions of the volume i.e. a **`G4VSolid`**
  - the **material** of the volume i.e. **`G4Material`** that is the minimally **required** additional information beyond the solid
  - additional, optional information such as magnetic field (**`G4FieldManager`**) or user defined limits (**`G4UserLimits`**), etc.
- its **NOT** a base class! Its constructor:

```
G4LogicalVolume( G4VSolid*              pSolid,       // its Solid
                 G4Material*            pMaterial,    // its Material
                 const G4String&        Name,         // its Name
                 G4FieldManager*        pFieldMgr=0,
                 G4VSensitiveDetector*  pSDetector=0,
                 G4UserLimits*          pULimits=0,
                 G4bool                 Optimise=true )
```

```
G4LogicalVolume*    targetLogical = new G4LogicalVolume(targetSolid,      // solid
                                                        materialTarget,   // material
                                                        "logic-Target"); // name
```

Logical volume

`G4LogicalVolumne:`

- encapsulates **all information** of a detector volume element **expect** its real physical **position** (position and rotation):
  - the **shape** and dimensions of the volume i.e. a **`G4VSolid`**
  - the **material** of the volume i.e. **`G4Material`** that is the minimally **required** additional information beyond the solid
  - additional, optional information such as magnetic field (**`G4FieldManager`**) or user defined limits (**`G4UserLimits`**), etc.
- its **NOT** a base class! Its constructor:

```
G4LogicalVolume( G4VSolid*             pSolid,       // its Solid
                 G4Material*           pMaterial,    // its Material
                 const G4String&       Name,         // its Name
                 G4FieldManager*       pFieldMgr=0,
                 G4VSensitiveDetector* pSDetector=0,
                 G4UserLimits*         pULimits=0,
                 G4bool                Optimise=true )
```

- see the **Geometry: Logical Volumes** documentation

Geometry definition

PHYSICAL VOLUME

Physical volume

`G4VPhysicalVolume`:

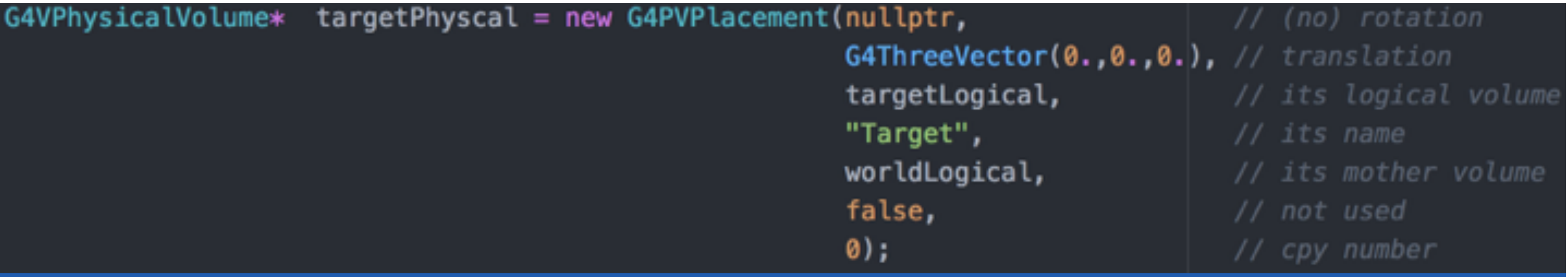
- the abstract base class for representation of physically **positioned volumes**
- a volume is **positioned in** a **mother volume** relative to its coordinate system
- the positioning can be:
  - **placement** volume: **one positioned volume,** i.e. **one `G4VPhysicalVolume`** object represents **one "real" volume**
  - **repeated** volume: **one** volume **positioned many times,** i.e. **one `G4VPhysicalVolume`** object represents **multiple copies of "real" volumes** (reduces memory by exploiting symmetry)
    - **Replica** volumes: the multiple **copies** of the volume **are** all **identical**
    - **Parameterised** volumes: the multiple **copies of** a volume can be different in **size**, **solid** type, or **material** that can all be **parameterised** as a **function of the copy number**
- we will have a look only to the **placement** but see all at the **Geometry: Physical Volume** documentation

Physical volume

G4VPhysicalVolume - G4PVPlacement:

- represent **one positioned `G4LogicalVolume`**
- created by **associating a `G4LogicalVolume` with a Transformation** that defines the **position** of the volume **in the mother volume**
- the **Transformation** can be given either as a single **`G4Transform3d`** object or as combination of rotation **`G4RotationMatrix`** and translation **`G4ThreeVector`**
- a **mother volume must be specified** for all volumes **except** the "**`world`**"
- (one of the two) constructor with the rotation matrix and translation vector:

```
G4PVPlacement(       G4RotationMatrix*  pRot,             // rot.-matrix
               const G4ThreeVector&     tlate,            // translation
                     G4LogicalVolume*   pCurrentLogical,  // logical volume
               const G4String&          pName,            // name
                     G4LogicalVolume*   pMotherLogical,   // mother logical volume
                     G4bool             pMany,            //
                     G4int              pCopyNo,          // unique identifier
                     G4bool             pSurfChk=false )  // check overlap ?
```



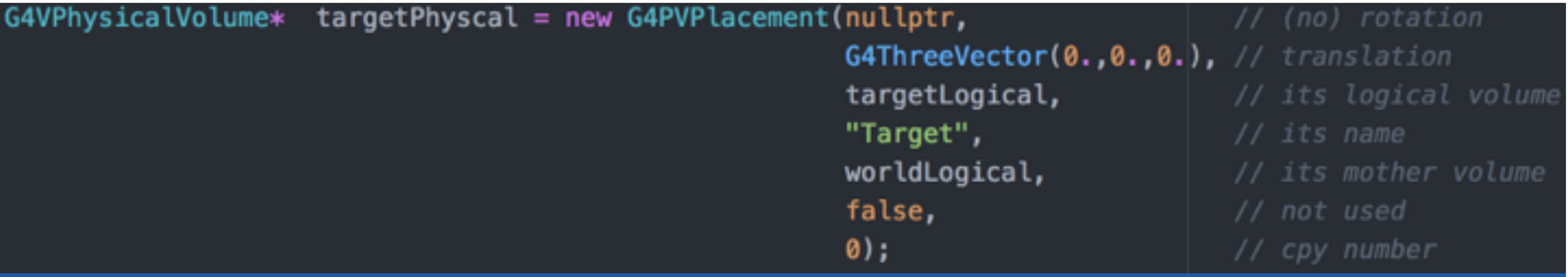
```
G4VPhysicalVolume*  targetPhyscal = new G4PVPlacement(nullptr,                  // (no) rotation
                                                      G4ThreeVector(0.,0.,0.), // translation
                                                      targetLogical,           // its logical volume
                                                      "Target",                // its name
                                                      worldLogical,            // its mother volume
                                                      false,                   // not used
                                                      0);                      // cpy number
```

Physical volume

`G4VPhysicalVolume - G4PVPlacement:`

- represent **one positioned `G4LogicalVolume`**
- created by **associating a `G4LogicalVolume` with a Transformation** that defines the **position** of the volume **in the mother volume**
- the **Transformation** can be given either as a single **`G4Transform3d`** object or as combination of rotation **`G4RotationMatrix`** and translation **`G4ThreeVector`**
- a **mother volume must be specified** for all volumes **except** the "**`world`**"
- (one of the two) constructor with the rotation matrix and translation vector:

```
G4PVPlacement(       G4RotationMatrix*  pRot,             // rot.-matrix
               const G4ThreeVector&     tlate,            // translation
                     G4LogicalVolume*   pCurrentLogical,  // logical volume
               const G4String&          pName,            // name
                     G4LogicalVolume*   pMotherLogical,   // mother logical volume
                     G4bool             pMany,            //
                     G4int              pCopyNo,          // unique identifier
                     G4bool             pSurfChk=false )  // check overlap ?
```



```
G4VPhysicalVolume*  targetPhyscal = new G4PVPlacement(nullptr,              // (no) rotation
                                               G4ThreeVector(0.,0.,0.), // translation
                                               targetLogical,           // its logical volume
                                               "Target",                // its name
                                               worldLogical,            // its mother volume
                                               false,                   // not used
                                               0);                      // cpy number
```

Everything has shown that is necessary to write
`YourDetectorConstruction`

START TO DEVELOP OUR APPLICATION