Geant4 physics: particles, processes and physics list

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A lot of material by G.A.P. Cirrone and J. Pipek

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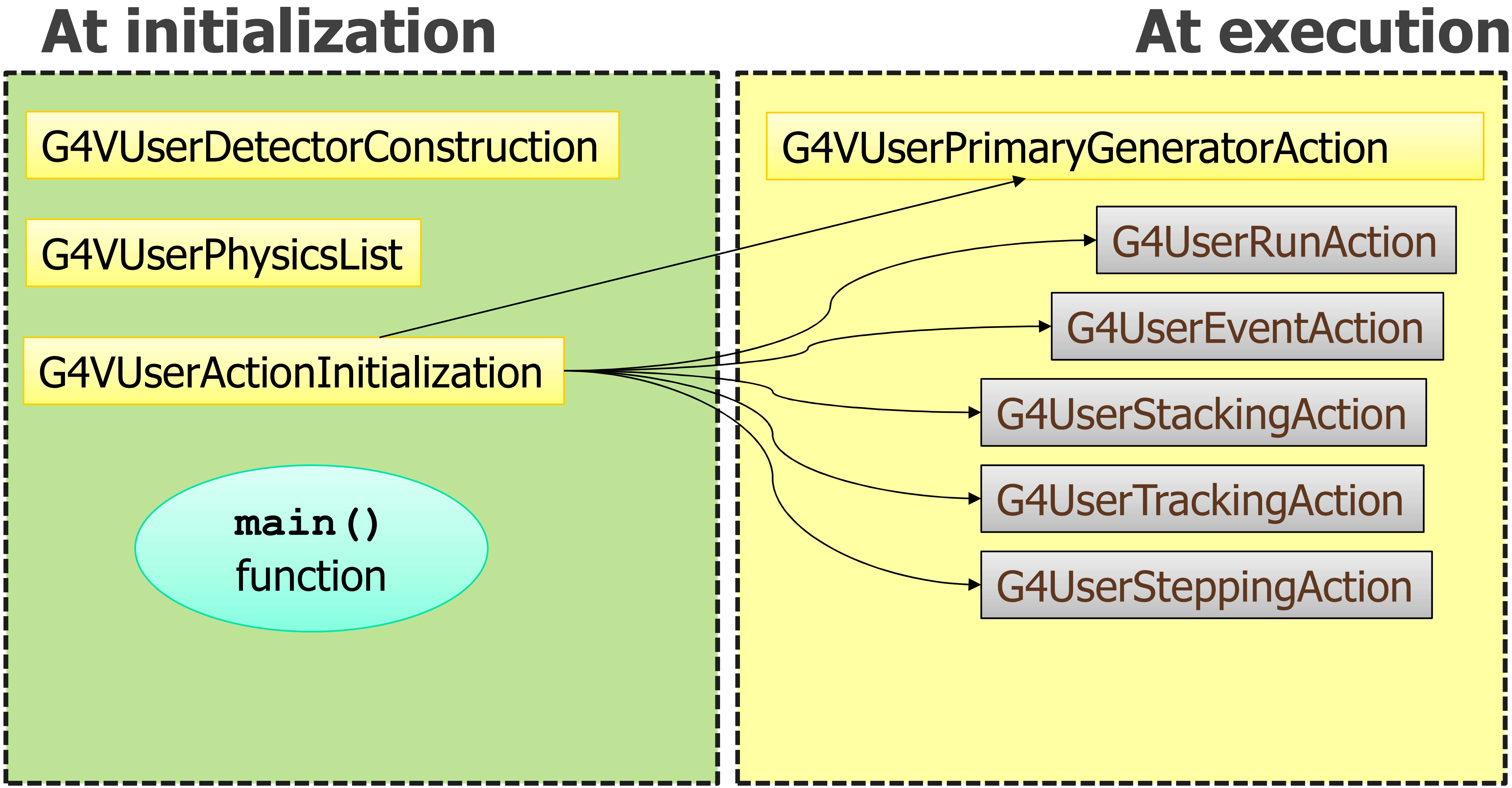
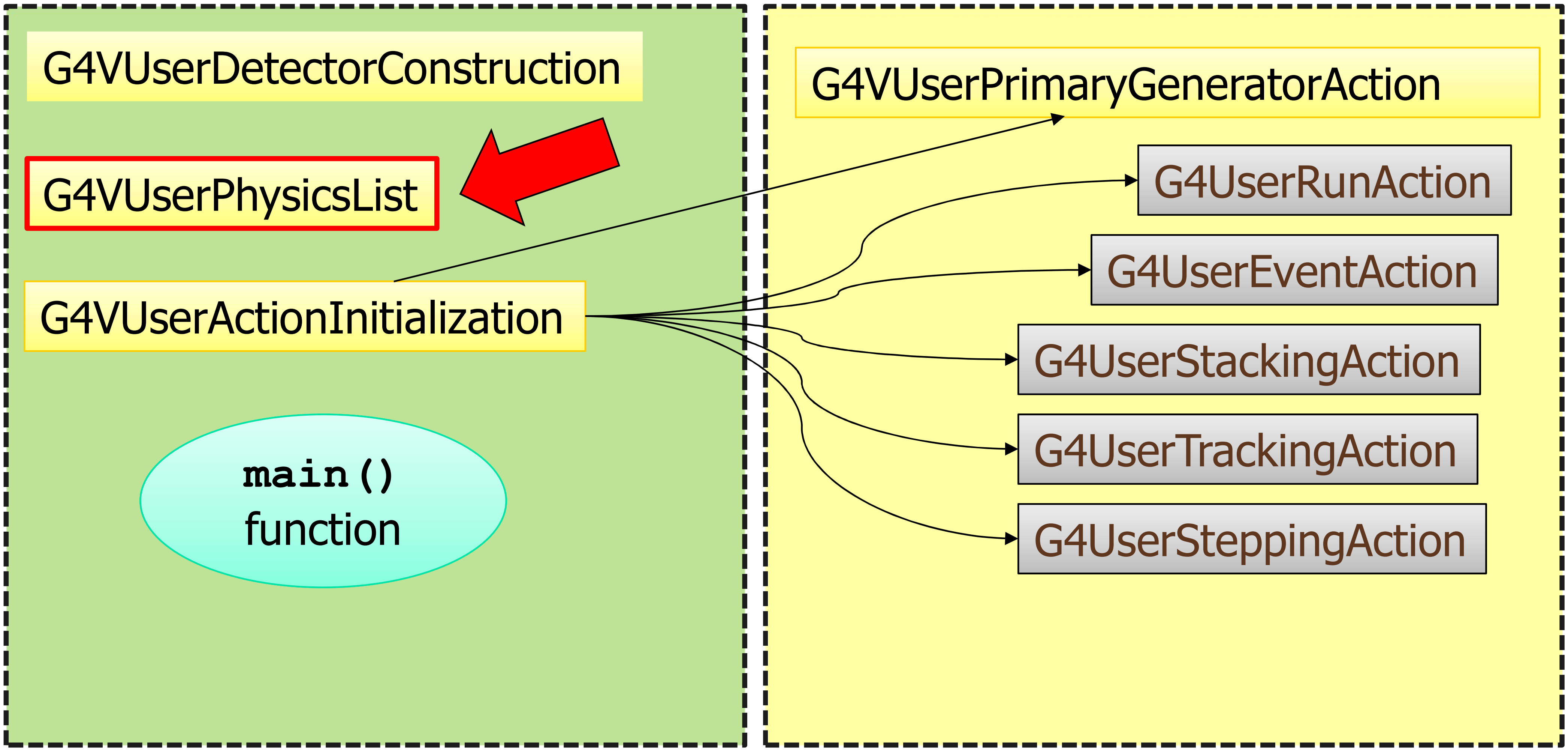
Mandatory (and optional) user classes



Mandatory (and optional) user classes

At initialization **At execution**



Outlook

- Physics in Geant4 – motivation
- Particles
- Processes
- Physics lists

...Part 2:

  - Production cuts
  - Electromagnetic / hadronic physics

“Shouldn’t there be just one universal and complete physics description?”

No.

Physics – the challenge

- Huge amount of different processes for various purposes (*only a handful relevant*)
- Competing descriptions of the same physics phenomena *(necessary to choose)*
  - fundamentally different **approaches**
  - balance between **speed** and **precision**
  - different **parameterizations**
- Hypothetical processes & exotic physics

Solution: Atomistic approach with modular **physics lists**

Part I: Particles and Processes

Particles: basic concepts

- There are three levels of class to describe particles in Geant4:
- **`G4ParticleDefinition`**
  - Particle static properties: name, mass, spin, PDG number, etc.
- **`G4DynamicParticle`**
  - Particle dynamic state: energy, momentum, polarization, etc.
- **`G4Track`**
  - Information for tracking in a detector simulation: position, step, current volume, track ID, parent ID, etc.

Particles in Geant4

- Particle Data Group (PDG) particles
- Optical photons (different from gammas!)
- Special particles: geantino and charged geantino
  - Only transported in the geometry (no interactions)
  - Charged geantino also feels the EM fields
- Short-lived particles ($\tau < 10^{-14}$ s) are not transported by Geant4 *(decay applied)*
- Light ions (as deuterons, tritons, alphas)
- Heavier ions represented by a single class: `G4Ions`

Particle name	Class name	Name (in GPS...)	PDG
electron	G4Electron	e-	11
positron	G4Positron	e+	-11
muon +/-	G4MuonPlus G4MuonMinus	mu+ mu-	-13 13
tauon +/-	G4TauPlus G4TauMinus	tau+ tau-	-15 15
electron (anti)neutrino	G4NeutrinoE G4AntiNeutrinoE	nu_e anti_nu_e	12 -12
muon (anti)neutrino	G4NeutrinoMu G4AntiNeutrinoMu	nu_mu anti_nu_mu	14 -14
tau (anti)neutrino	G4NeutrinoTau G4AntiNeutrinoTau	nu_tau anti_nu_tau	16 -16
photon (γ, X)	G4Gamma	gamma	22
photon (optical)	G4OpticalPhoton	opticalphoton	(0)
geantino	G4Geantino	geantino	(0)
charged geantino	G4ChargedGeantino	chargedgeantino	(0)

Processes

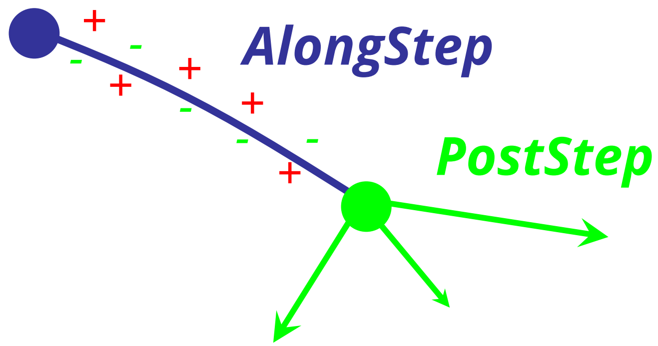
How do particles interact with materials?

- Responsibilities:
  - decide when and where an **interaction** occurs
    - GetPhysicalInteractionLength...() → limit the step
    - this requires a cross section
    - for the transportation process, the distance to the nearest object
  - generate the **final state** of the interaction
    - changes momentum, generates secondaries, etc.
    - method: DoIt...()
    - this requires a model of the physics

The G4VProcess

- Physics processes are derived from the **G4VProcess** base class
- Abstract class defining the common interface of all processes in Geant4, used by all physics processes

- Three kinds of "actions":
  - AtRest actions
    - Decays, e^+ annihilation
  - AlongStep actions
    - To describe continuous (inter)actions, occurring along the path of the particle, i.e. **"soft" interactions**
  - PostStep actions
    - To describe the point-like (inter)actions, like decay in flight, hadronic interactions, i.e. **"hard" interactions**



A process can implement a combination of them (decay = AtRest + PostStep)

Example processes

- Discrete process: Compton Scattering, hadronic inelastic, ...
  - step determined by cross section, interaction at end of step
    - PostStepGPIL(), PostStepDoIt()
- Continuous process: Čerenkov effect
  - photons created along step, roughly proportional to step length
    - AlongStepGPIL(), AlongStepDoIt()
- At rest process: muon capture at rest
  - interaction at rest
    - AtRestGPIL(), AtRestDoIt()

pure

- Rest + discrete: positron annihilation, decay, ...
  - both in flight and at rest
- Continuous + discrete: ionization
  - energy loss is continuous
  - knock-on electrons (δ-ray) are discrete

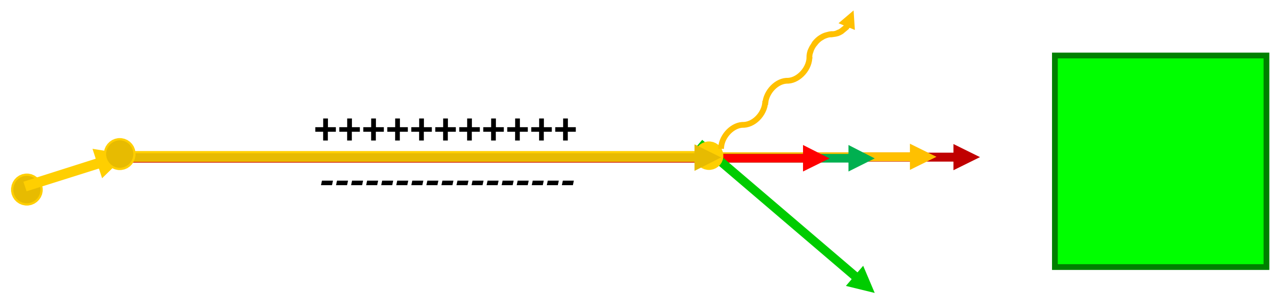
combined

Geant4 transportation in one slide

1. a particle is shot and "transported"
2. all processes associated to the particle propose a geometrical step length (depends on process cross-section)
3. the process proposing the shortest step "wins" and the particle is moved to destination (if shorter than "Safety")
4. **all** processes along the step are executed (e.g. ionization)
5. post step phase of the process that limited the step is executed
   - New tracks are "pushed" to the stack
   - Dynamic properties are updated
6. if E_{kin}=0 all at rest processes are executed; if particle is stable the track is **killed**

Else

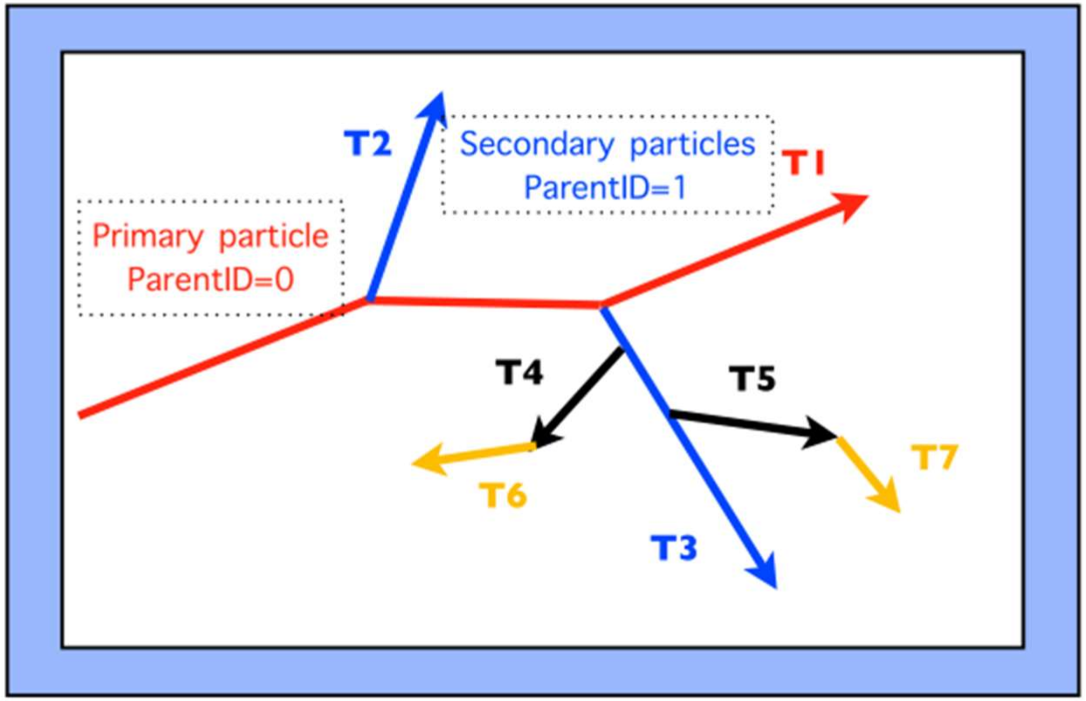
7. new step starts and sequence repeats...



Geant4 transportation in one slide – P.S.

- Processes return a "true path length". The multiple scattering "virtually *folds up*" this true path length into a shorter "geometrical" path length
- Transportation process can limit the step to geometrical boundaries

Geant4 way of tracking



- **Force step** at geometry boundaries
- All AlongStep processes **co-work**, the PostStep **compete** (= only one selected)
- Call AtRest actions for particles at rest

- Secondaries saved at the top of the stack: tracking order follows **'last in first out'** rule: T1 → T3 → T5 → T7 → T4 → T6 → T2

Tracking verbosity

UI command: **`/tracking/verbose 1`**

```
*****************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 1,   Parent ID = 0
*****************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     47.4      -53     -150         6        0        0         0    Envelope initStep
    1     47.4      -53      -58     0.844        0       92        92    Envelope compt
    2      -46     15.9     5.55      0.47        0      132       224    Envelope compt
    3     -100     6.37    -3.62      0.47        0     55.6       280       World
Transportation
    4     -120     2.84    -7.02      0.47        0     20.6       301  OutOfWorld
Transportation
*****************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 3,   Parent ID = 1
*****************************************************************************
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0      -46     15.9     5.55     0.375        0        0         0    Envelope initStep
    1    -46.1     16.4     5.98    0.0482    0.327     1.16      1.16    Envelope eIoni
    2    -46.1     16.3     5.98         0   0.0482   0.0408       1.2    Envelope eIoni
```

Primary γ

Compton e⁻

Part II: Physics lists & Co.

A physics list: what it is, what it does

- One instance per application
  - registered to run manager in `main()`
  - inheriting from `G4VUserPhysicsList`
- Responsibilities
  - all **particle types** (electron, proton, gamma, ...)
  - all **processes** (photoeffect, bremsstrahlung, ...)
  - all **process parameters** (...)
  - **production cuts** (e.g. 1 mm for electrons, ...)

G4VUserPhysicsList

- All physics lists **must** derive from this class
  - And then be registered to the G4(MT)RunManager
  - Mandatory class in Geant4

```
class MyPhysicsList: public G4VUserPhysicsList {
public:
MyPhysicsList();
~MyPhysicsList();
void ConstructParticle();
void ConstructProcess();
void SetCuts();
}
```

- User must implement the following (purely virtual) methods:
  - `ConstructParticle(), ConstructProcess()`
- Optional Virtual method:
  - `SetCuts()` (used to be purely virtual up to 10.2)

Three ways to get a physics list

- **Manual**: Write your own class, to specify all particles & processes that may occur in the simulation (very flexible, but difficult)
- **Physics constructors**: Combine your physics from pre-defined sets of particles and processes. Still you define your own class – modular physics list (easier)
- **Reference physics lists**: Take one of the pre-defined physics lists. You don't create any class (easy)

Way 1

Derived class from **G4VUserPhysicsList**

- Implement 3 methods:

```
class MyPhysicsList : public G4VUserPhysicsList {
public:
    // ...
    void ConstructParticle();   // pure virtual
    void ConstructProcess();    // pure virtual
    void SetCuts();
    // ...
}
```

Advantage: most flexible

Disadvantages:

- most verbose
- most difficult to get right

`G4VUserPhysicsList`: implementation

- **`ConstructParticle()`**
  - choose the particles you need in your simulation, define **all of them** here
- **`ConstructProcess()`**
  - for each particle, assign all the physics processes relevant to your simulation
- **`SetCuts()`** **MORE ON THIS LATER**
  - set the range cuts for secondary production for processes with infrared divergence

1) ConstructParticle()

Due to the large number of particles can be necessary to instantiate, this method sometimes can be not so comfortable

```
void MyPhysicsList::ConstructParticle()
{
    G4Electron::ElectronDefinition();
    G4Proton::ProtonDefinition();
    G4Neutron::NeutronDefinition();
    G4Gamma::GammaDefinition();
    ....
}
```

It is possible to define **all** the particles belonging to a **Geant4 category:**

- G4LeptonConstructor
- G4MesonContructor
- G4BaryonConstructor
- G4BosonConstructor
- G4ShortlivedConstructor
- G4IonConstructor

```
void MyPhysicsList::ConstructParticle()
{
    // Construct all baryons
    G4BaryonConstructor bConstructor;
    bConstructor.ConstructParticle();
    // Construct all leptons
    G4LeptonConstructor lConstructor;
    lConstructor.ConstructParticle();
}
```

2) ConstructProcess()

1. For each particle, get its **process manager**.

```
G4ProcessManager *elManager = G4Electron::ElectronDefinition()
->GetProcessManager();
```

2. Construct all **processes** and **register** them.

```
elManager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
elManager->AddProcess(new G4eIonisation, -1, 2, 2);
elManager->AddProcess(new G4eBremsstrahlung, -1, -1, 3);
elManager->AddDiscreteProcess(new G4StepLimiter);
```

3. Don't forget **transportation**.

```
AddTransportation();
```

3) SetCuts()

- Define all **production** cuts ... amma, electrons and positrons
  - Recently also for pro...
- Notice: this is a **pr... tion cut**, not a tracking cut

MORE ON THIS LATER

```cpp
void StandardPhysics::ConstructParticle()
{
	// We are interested in gamma, electrons and possibly positrons
	G4Electron::ElectronDefinition();
	G4Positron::PositronDefinition();
	G4Gamma::GammaDefinition();
}

void StandardPhysics::ConstructProcess()
{
	// Transportation is necessary
	AddTransportation();

	// Electrons
	G4ProcessManager *elManager = G4Electron::ElectronDefinition()->GetProcessManager();
	elManager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
	elManager->AddProcess(new G4eIonisation, -1, 2, 2);
	elManager->AddProcess(new G4eBremsstrahlung, -1, -1, 3);
	elManager->AddDiscreteProcess(new G4StepLimiter);

	// Positrons
	G4ProcessManager *posManager = G4Positron::PositronDefinition()->GetProcessManager();
	posManager->AddProcess(new G4eMultipleScattering, -1, 1, 1);
	posManager->AddProcess(new G4eIonisation, -1, 2, 2);
	posManager->AddProcess(new G4eBremsstrahlung, -1, -1, 3);
	posManager->AddProcess(new G4eplusAnnihilation, 0, -1, 4);
	posManager->AddDiscreteProcess(new G4StepLimiter);

	// Gamma
	G4ProcessManager *phManager = G4Gamma::GammaDefinition()->GetProcessManager();
	phManager->AddDiscreteProcess(new G4ComptonScattering);
	phManager->AddDiscreteProcess(new G4PhotoElectricEffect);
	phManager->AddDiscreteProcess(new G4GammaConversion);

	// TODO: Introduce Rayleigh scattering. It has large cross-section than Pair production
}

void StandardPhysics::SetCuts()
{
	// TODO: Create a messenger for this
	defaultCutValue = 0.03 * mm;
	SetCutsWithDefault();
}
```

Way 2

G4VModularPhysicsList

- Similar structure as **G4VUserPhysicsList** (same methods to override – though not necessary):

```
class MyPhysicsList : public G4VModularPhysicsList {
public:
    MyPhysicsList();                // define physics constructors
    void ConstructParticle();       // optional
    void ConstructProcess();        // optional
    void SetCuts();                 // optional
}
```

Differences to "manual" way:

- Particles and processes typically handled by **physics constructors** (still customizable)
- **Transportation** automatically included

Physics constructors (1)

- "**Building blocks**" of a modular physics list
- Inherit from **`G4VPhysicsConstructor`**
- Defines **`ConstructParticle()`** and **`ConstructProcess()`**
  - to be fully imported in modular list (behaving in the same way)
- **`GetPhysicsType()`**
  - enables switching physics of the same type, if possible (see next slide)

Physics constructors (2)

- Huge set of pre-defined ones
  - **EM**: Standard, Livermore, Penelope
  - **Hadronic inelastic:** QGSP_BIC, FTFP_Bert, ...
  - **Hadronic elastic:** G4HadronElasticPhysics, ...
  - ... (decay, optical physics, EM extras, ...)
- You can implement your own *(of course)* by inheriting from the **`G4VPhysicsConstructor`** class

Code: **`$G4INSTALL/source/physics_lists/constructors`**

How to use physics constructors

Add **physics constructor** in the class **constructor**:

```
MyModularList::MyModularList() {
     // Hadronic physics
     RegisterPhysics(new G4HadronElasticPhysics());
     RegisterPhysics(new G4HadronPhysicsFTFP_BERT_TRV());
     // EM physics
     RegisterPhysics(new G4EmStandardPhysics());
}
```

This already works and no further method overriding is necessary ☺

To be continued (if you want to customize)...

Customizing a G4ModularPhysicsList

- You can override the `CreateParticle()`, `CreateProcess()`, and `SetCuts()` methods:

```
void MyModularList::ConstructProcess() {
     // Call the default implementation, otherwise you break the behaviour
     G4VModularPhysicsList::ConstructProcess();

     // Add your customization
     G4ProcessManager *elManager = G4Electron::Definition()->GetProcessManager();
     elManager->AddDiscreteProcess(new MyElectronProcess);
}
```

Don't forget!

Replace physics constructors

You can **add** or **remove** the physics constructors after the list instance is created:

- e.g. in response to **UI command**
- only before initialization
- physics of the same type can be replaced

```
void MyModularList::SelectAlternativePhysics() {
    AddPhysics(new G4OpticalPhysics);
    RemovePhysics(fDecayPhysics);
    ReplacePhysics(new G4EmLivermorePhysics);
}
```

Way 3

Reference physics lists

- Pre-defined ("plug-and-play") physics lists
  - already containing a **complete set** of particles & processes (that work together)
  - targeted at specific area of interest (HEP, medical physics, ...)
  - constructed as modular physics lists, built on top of **physics constructors**
  - customizable (by calling appropriate methods before initialization)

Using a reference physics list

- Super-easy: in the **main()** function, just register an instance of the physics list to the **G4(MT)RunManager**:

```
#include "QGSP_BERT.hh"
int main() {
    // Run manager
    G4RunManager * runManager = new G4RunManager();
    // ...
    G4VUserPhysicsList* physics = new QGSP_BERT();
    // Here, you can customize the "physics" object
    runManager->SetUserInitialization(physics);
    // ...
}
```

Alternative: Reference by name

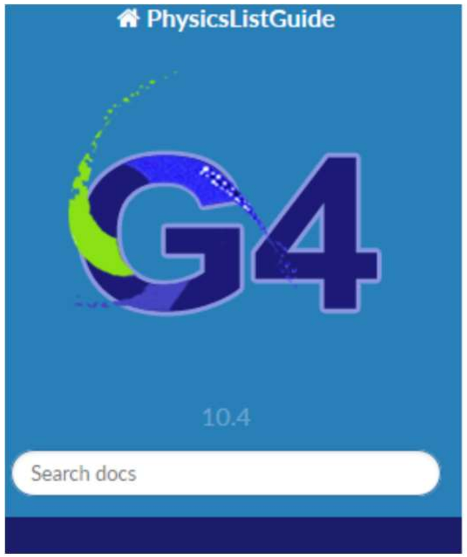
- If you want to get reference physics lists by **name** (e.g. from environment variable), you can use the **G4PhysListFactory** class:

```
#include "G4PhysListFactory.hh"
int main() {
    // Run manager
    G4RunManager* runManager = new G4RunManager();
    // E.g. get the list name from environment varible
    G4String listName{ getenv("PHYSICS_LIST") };
    auto factory = new G4PhysListFactory();
    auto physics = factory->GetReferencePhysList(listName);
    runManager->SetUserInitialization(physics);
    // ...
}
```

The complete lists of Reference Physics List

$G4INSTALL/source/physics_lists/lists

```
FTF_BIC.hh
FTFP_BERT.hh
FTFP_BERT_HP.hh
FTFP_BERT_TRV.hh
FTFP_INCLXX.hh
FTFP_INCLXX_HP.hh
G4GenericPhysicsList.hh
G4PhysListFactoryAlt.hh
G4PhysListFactory.hh
G4PhysListRegistry.hh
G4PhysListStamper.hh
INCLXXPhysicsListHelper.hh
LBE.hh
NuBeam.hh
QBBC.hh
QGS_BIC.hh
QGSP_BERT.hh
QGSP_BERT_HP.hh
QGSP_BIC_AllHP.hh
QGSP_BIC.hh
QGSP_BIC_HP.hh
QGSP_FTFP_BERT.hh
QGSP_INCLXX.hh
QGSP_INCLXX_HP.hh
Shielding.hh
```



Docs » Reference Physics Lists

Reference Physics Lists

A detailed description of key reference physics lists which are included within the source tree of the GEANT4 toolkit. A an incomplete selection of diverse lists is described here in terms of the components within the list and possible use cases and application domains.

Contents:

- FTFP_BERT Physics List
  - Hadronic Component

Where to find information?

https://geant4.web.cern.ch/support

GEANT4
A SIMULATION TOOLKIT

User Support

Submitted by Anonymous (not verified) on Wed, 06/28/2017 - 11:23

1. Getting started
2. Training courses and materials
3. Source code
   a. Download page
   b. LXR code browser
   c. doxygen documentation
   d. GitHub
   e. GitLab @ CERN
4. Frequently Asked Questions (FAQ)
5. Bug reports and fixes
6. User requirements tracker
7. User Forum
8. Documentation
   a. Introduction to Geant4 [pdf]
   b. Installation Guide: [pdf]
   c. Application Developers [pdf]
   d. Toolkit Developers Guide [pdf]
   e. Physics Reference Manual [pdf]
   f. Physics List Guide [pdf]
9. Examples

Summary – three kinds of physics lists for Geant4

- Old-style flat physics list
  - You code what you want, particle by particle and process by process
  - Very much flexible, but **not really encouraged**
- User-custom modular physics list
  - Blocks (constructors) provided by Geant4
  - Can register user-custom constructors
  - Usually the *optimal compromise* between flexibility and user-friendliness
- Ready-for-the-use Geant4 physics list
  - Plug and play (directly registered in the main!)
  - Can still register extra constructors

Hands-on session

- Task3
  - Task3a: Particles and processes
  - Task3b: Physics lists

- **http://geant4.lns.infn.it/pavia2024/task3**