Intro to Efficient Programming

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HGS-HIRe power week

Limburg

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Lecture I

Introduction

Who we are

Mikolaj Krzewicki

- in ALICE since 2007
- ALICE High Level Trigger / ALICE O2
- Software validation
- TPC calibration
- Analysis (correlations and flow)

Patrick Huhn

- in ALICE since 2014
- PhD student since 2017
- former participant of this power week
- Analysis (charged particle R_{AA})

Sandro Wenzel

- at CERN since 2012; in ALICE since 2015
- Detector Simulation
- Previous experience in various computing activities (PhD: Quantum Monte Carlo; The Blue Brain Project)

Credits

Material of this course building on previous courses given by Jens Wiechula, David Rohr, Matthias Richter and Jochen Klein.

Outline / Goals of the week

Software development / computing in high energy physics is ubigous and essential knowledge. This week should help you to ...

- Be able to come up with efficient algorithms in C++ implementing software solutions to problems in (particle) physics.
- Be able to use ROOT as a library and to look into data using ROOT
- Be able to decompose problem into small pieces, structure code and work on software projects incrementally
- Understand tools and practices in the software development process
- Know about modern C++11 features and few optimization strategies
- Know about easy parallelism options and SIMD

Introduction

There are many aspects of *efficiency*

- Coding concepts
- Tools
- Fast development (prototyping)
- Fast code execution (optimization)
- Small memory imprint
- Code design
- Code flexibility / configurability
- ...

Programme

What we want to cover:

- Modern C++ features and concepts (C++11, C++14, ...)
- Tools
  - gcc
  - (c)make
  - git
  - doxygen
  - gdb
  - profilers: valgrind, perf, ...
- Methods
  - object orientation, templates
  - libraries
- Algorithms
- Parallelisation
- SIMD vectorisation

Outlook Programme 2

What we can't cover here but intend to do in part 2:

- GP-GPU
- Parallelization in more depth
- distributed computing and messaging
- ...

Course format

There will be some lectures but focus will be on practical side!

- Lot's of do-it yourself exercises/examples
- A real coding project touch typical high energy physics subject
- Possibility to do code reviews / interaction with lecturers

link to dynamic plan
https://tinyurl.com/hgspw1

A small project

- small groups (up to 5 people)
- work shall be carried out over the whole week,
  presentation of results on Friday (20+5),
  code reviews in between
- we want you to
  - use the tools
  - try the methods
  - test the algorithms

  which are discussed during the meeting
- you should learn something
  $\Rightarrow$ try and understand what you are doing

Computing I

- local servers (hostnames: power[1-4].power.week)
  personal user accounts:
  username: first letter of firstname + lastname,
  initial password: pwLimburg
  (reference environment, you can compare to your machine)

- Every groups gets assigned one server (please use it exclusively)

- separate network with WLAN access (or cable)
  SSID: PowerWeek_01
  pw: powerweek

- passwordless login
  often it is convenient to login using ssh keys

```
ssh-keygen
ssh-copy-id <you-user-id>@power[1-4]
```

Computing II

- examples and slides are provided via git

```
git clone https://github.com/hgspowerweek/powerweek1/
cd powerweek1
git pull
```

  do the last step before every session and you will get the latest examples and slides

- Slides are directly in this folder as pdfs
- Examples are in the folder *examples*

`examples/bla`

X

Lecture II

Introduction to code / document management using git – absolute basics

Code repository

Why would you use a code repository?

- keep control over your changes
- keep a history of changes and go back to any previous state
- add logging messages to individual changes
- develop different topics in parallel
- keep a working version as a reference
- create releases for distribution of the code
- synchronize several developers

A code repository can serves as

- back-up solution
- communication medium
- team and product management tool

git - the stupid content tracker

- Developed by Linus Torvalds and others in 2005 for the Linux kernel community
- Nobody knows what git stands for at least one does not get a real answer.
- Instead of beeing stupid - see manpage - it's a extremely powerful scalable, distributed revision control system.

In contrast to other versioning systems (CVS, subversion),

- git allows to use the full functionality of a code repository locally
- can be distributed
- does not require a central server, but can be used with a server

git commands in a nutshell

Basic operations:

- `git init`
- `git clone`
- `git add` – add something to staging area
- `git commit` – commit staging area to local reposity
- `git checkout <commit>` – retrieve certain state

Getting information

- `git log` – show commit history
- `git status`
- `git diff` – show differences (between commits)

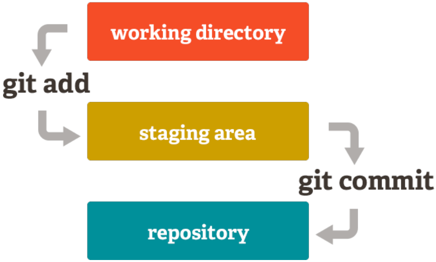
Advanced commands

- `git stash`
- `git push` – publish repo somewhere else (some URL)
- `git pull` – sync/get changes from somwhere else (some URL)
- `git rebase/merge` – integrate someone elses changes; change history

git - the stupid content tracker

How is a git repository structured:

- local copy (tree) - those are your files.
- staging area (intermediate store) - changes (diffs) staged for commit.
- local repository - full repository containing all changes to all branches. Everybody has a full copy, there is no concept of a central repository - you still may declare some repository the central one.



git - One time (identity) setup

- git config Configure git or query configuration
- Some essential setup: Give yourself a git identity:

```
git config --global user.name "Foo Bar"
git config --global user.email foo.bar@cern.ch
```

- `git config -l` will show you the whole configuration including your identity
- configuration is stored in a file `${HOME}/gitconfig` which can also be edited

git - Creating and cloning repositories

Creating an initial repository:

```
mkdir -p ~/src/project
cd ~/src/project
git init
Initialized empty Git repository in ~/src/project/.git
```

Cloning a repository:

```
git clone power1:/data/PowerWeek
Cloning into 'PowerWeek'...
Password:
remote: Counting objects: 6, done.
remote: Compressing objects: 100% (4/4), done.
remote: Total 6 (delta 1), reused 0 (delta 0)
Receiving objects: 100% (6/6), done.
Resolving deltas: 100% (1/1), done.
Checking connectivity... done
```

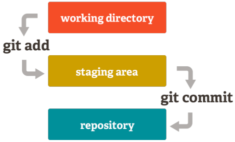
git - status of the local repository

Command: `git status`

```
richterm@power1 ~ git status
# On branch master
# Changes not staged for commit:
#   (use "git add <file>..." to update what will be committed)
#   (use "git checkout -- <file>..." to discard changes in working directory)
#
#       modified:   twoparticle.C
#
# Untracked files:
#   (use "git add <file>..." to include in what will be committed)
#
#       result.root
#       twoparticle_C.d
#       twoparticle_C.so
no changes added to commit (use "git add" and/or "git commit -a")
```

- information about the current branch
- files which are staged for commit
- tracked files whith local changes
- untracked files (can be masked by `.gitignore`)

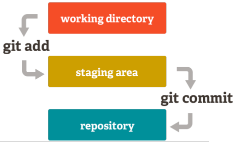
git - committing



Step 1: `git add` mark changes to be committed

```
richterm@power1 ~/src/example_01 $ git add twoparticle.C
richterm@power1 ~/src/example_01 $ git status
# On branch master
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#       modified:   twoparticle.C
#
# Untracked files:
#   (use "git add <file>..." to include in what will be committed)
#
#       result.root
#       twoparticle_C.d
#       twoparticle_C.so
```

git - committing



Step 2: `git commit` changes

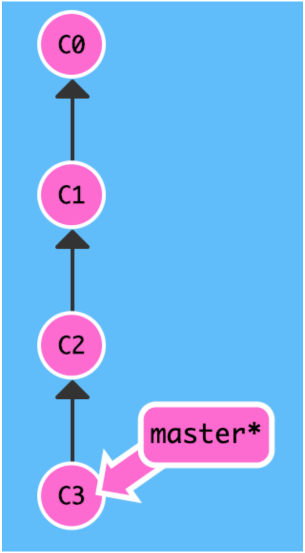
```
richterm@power1 ~/src/example_01  git commit -m "initial version
of particle class"
[master a56e827] initial version of particle class
```

Now it is locally committed, check the log

```
richterm@power1 ~/src/example_01  git log
commit a56e8270fd6f3c99d4cdbcdb0e45f287e1c71711
Author: Matthias Richter <richterm@power1.power.week>
Date:   Tue Nov 26 11:51:09 2013 +0100

    initial version of particle class

commit ea2c328e7ac3e21c5546480dad1a55af4a0f5e35
Author: Jochen Klein <jochen.klein@cern.ch>
Date:   Mon Nov 25 13:51:12 2013 +0100

    - initial commit of example
```

git commits; git checkout

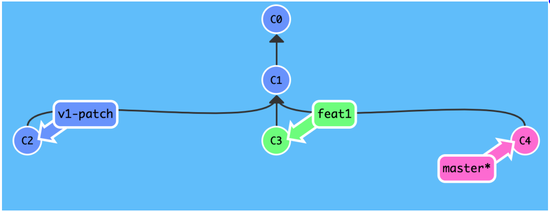
- git organizes commits in a connected **tree** of nodes; A git commit adds a new node
- each node consists of
  - The actual changeset/diff to files
  - Metadata (author, ...)
  - A commit message
  - A SHA-256 hash digest - This hash uniquely identifies the precise node and all its history!
- one can checkout specific nodes by using `git checkout <commit-sha>`
- pointer to last node – of main development line – is typically called `master`



The commit tree and branches

The git commit structure can be a tree. Pointers to leave nodes are called branches.

- The master branch is the main development line
- Other branches typically used for feature development in isolation (`Feat1`) or for releasing a certain stable version and patches (`v1-patch`)
- branches are started with `git checkout -b NewFeature` on the currently checked out commit
- one can switch between branches with `git checkout branchname`

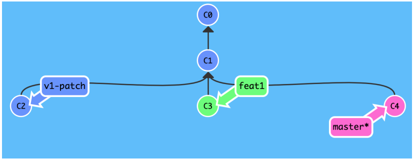



```
$ git checkout -b v1-patch
$ git commit
$ git checkout master
$ git checkout -b feat1
$ git commit
$ git checkout master
$ git commit
```

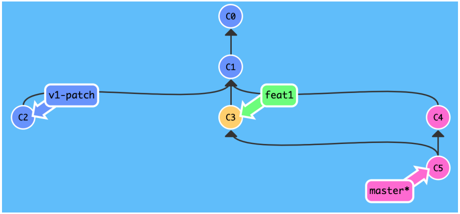
nice online learning platform: `https://learngitbranching.js.org/?NODEMO`

Short intro to merging and rebasing

- merging/rebasing : operations on the tree to bring together 2 branches
- used to integrate commits from one branch into the other
- for example when feature is fully developed

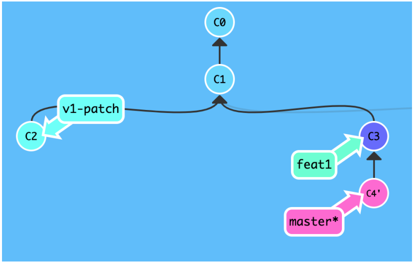


git merge feat1



- tree (old commits) stays intact
- merge creates adds a special commit

git rebase feat2



- branches are linearized
- no new commit; but old commits rewritten

git - looking at the difference

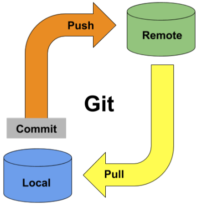
Command: `git diff`

```
richterm@power1 ~/src/example_01 git diff twoparticle.C
diff --git a/twoparticle.C b/twoparticle.C
index fdca6ac..77d77c5 100644
--- a/twoparticle.C
+++ b/twoparticle.C
@@ -1,7 +1,7 @@
 // a simple macro with surprises for the purpose of training usage of valgrind a

 // include header files for the porpose of compilation
-#ifndef __CINT__
+#if !defined(__CINT__) || defined(__MAKECINT__)
 #include "TParticle.h"
 #include "TSystem.h"
 #include "TH1.h"
```

- shows local differences in tracked files
- without arguments: for all tracked files
- can be used to show differences between revisions

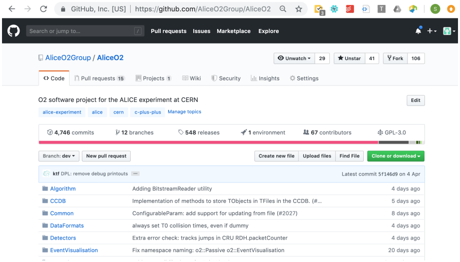
Distributed gits: push and pull

- A git repository can exist at various locations (or in multiple copies) at the same time (it's distributed); one speaks of local and remote repositories.
- the authorative version of a git repository is often hosted on some web server (remote)
  - if you cloned from the remote it is called 'origin'
  - otherwise you can declare a remote repo with `git remote add foo URL`
- Users syncronize local and remote repositories via git pull and git push commands.
  - git pull [–rebase] foo get all remote changes and apply locally
  - git push foo publish your own changes to the remote



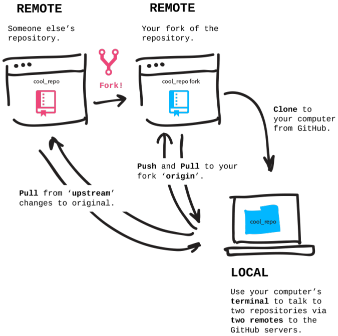
Github/Gitlab/Bitbucket

- many open source projects host git on platforms like Github, Gitlab or Bitbucket
- free git server and infrastructure
- collaborative code reviews
- integrations with other services
  - task tracking
  - continuous integration (CI) - automatic testing of new code and accepting only if good
  - documentation



Github/Gitlab/Bitbucket - workflow

- A typical workflow on those platforms uses 3 repositories
  - the authorative repo (remote)
  - a fork (a user copy remote)
  - the local user repository
- Changes are integrated via push to fork and pull requests to real repo



git - Further reading

We found the following nice looking pages ... but there are tons other really

- https://rogerdudler.github.io/git-guide/index.de.html
- https://try.github.io/ – resources to learn git;
- https://www.atlassian.com/git/tutorials
- https://www.edureka.co/blog/git-tutorial/
- `git help`

git - stash

You are in the middle of developing and get a request to fix something or update your clone

⇒ `stash` allows to save your current status

```
> git pull
# ... pull fails due to merge conflicts ...
> git stash save
> git pull
> git stash pop
```

git - checking logs revisited

tig; gitk; etc

Exercises

- Create a git repo; Do some add-commit cycles
- Play with branching merging:
  - locally
  - as an interactive game `https://learngitbranching.js.org/`
- Get familiar with github by forking or cloning the PowerWeek github repo `https://github.com/hgspowerweek/powerweek1`.
  - Look around
  - Contribute to the documentation of F.A.Q. section
- In order to contribute to an github repo, you need to create a github account
- For the coding project, we suggest to use gitlab.cern.ch in a private repository
  - needs CERN lightweight account account.cern.ch
  - keeps code private (also for future power weeks participants)
  - enables code review features

Lecture III

Code compilation

What is GCC

- Originally ‘only’ GNU C Compiler
- Release in March 1987 as the first **free** ANSI C optimizing compiler
- C++ support was added in December of that year
- Now, many other languages are supported as well, e.g. Objective-C, Objective-C++, Fortran (gfortran), Java (gcj), ...
- In addition, many different CPU architectures supported, e.g. Intel, ARM, Alpha, PowerPC, ...
- Today GCC stands for GNU Compiler Collection

Compilers

A compiler translates the human readable code into machine executable code

The main compilers of the GCC suite we are interested in are the GNU C and C++ compilers: gcc and g++

Brian Gough
`http://www.network-theory.co.uk/docs/gccintro/`

`examples/gcc`

First steps with g++

```
#include <iostream>
int main()
{
  std::cout << "hello world" << std::endl;
  return 0;
}
```

The hello world example above (hello_world.cpp) can be compiled using

```
g++ -Wall hello_world.cpp -o hello_world
```

`-o` specifies the name of the executable (default it is *a.out*)
`-Wall` turns on most commonly used compiler warning → **highly recommended to use**
To run the program simply type

```
./hello_world
```

⇒ Try it!

First steps with g++

```cpp
#include <iostream>
int main()
{
  std::cout << "hello world" << std::endl;
  return 0;
}
```

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Splitting code

Often it is useful to split the code into separate logical files

- Enhances readability and maintenance
- Enables to compile code parts independently
  - Saves compilation time, not all code needs to be recompiled if somethings changes
- Allows to compile code using the functionality of other code without knowing the actual implementation

We split the hello_world example into three files:

- main.cpp
- hello_fn.h
- hello_fn.cpp

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We split the hello_world example into three files:

- main.cpp
- hello_fn.h
- hello_fn.cpp

Splitting code - example

main.cpp

```
#include "hello_fn.h"
int main()
{
  hello("world");
  return 0;
}
```

hello_fn.h

```
void hello(const char* to);
```

hello_fn.cpp

```
#include <iostream>
void hello(const char* to)
{
  // function to print hello to someone on the command line
  std::cout << "Hello " << to << std::endl;
}
```

Splitting code - header files

- Separate the *declaration* of classes / functions from the actual *implementation*
- The declaration is given in the *header file* ending on `.h`
- When using external code in an own class, during compilation only the declaration is needed
- A declaration should not be included several times (compilation time), this is handled by a pre-compiler directive (*header guard*)

```
#ifndef MYCODE_H
#define MYCODE_H
void myfunction(int x, float y);
#endif
```

Compile multiple source files

To compile the code run

```
g++ -Wall main.cpp hello_fn.cpp -o hello_world
```

⇒ Try it!

Not won too much, still all code is compiled all the time

- compile parts of the code into separate *object files*
- *link* the *object files* to the executable

Compile multiple source files

To compile the code run

```
g++ -Wall main.cpp hello_fn.cpp -o hello_world
```

⇒ Try it!

Not won too much, still all code is compiled all the time

- compile parts of the code into separate *object files*
- *link* the *object files* to the executable

Creating object files

We create one *object file* per input file:

```
g++ -Wall -c main.cpp hello_fn.cpp
```

- `-c` tells the compiler to create an object
- object files are machine code, but not yet executable

Produces the object files *main.o* and *hello_fn.o*

This can also be run separately for each file

```
g++ -Wall -c main.cpp
g++ -Wall -c hello_fn.cpp
```

⇒ Try it!

Creating object files

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```
g++ -Wall -c main.cpp hello_fn.cpp
```

- `-c` tells the compiler to create an object
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Produces the object files *main.o* and *hello_fn.o*

This can also be run separately for each file

```
g++ -Wall -c main.cpp
g++ -Wall -c hello_fn.cpp
```

⇒ Try it!

Linking objects to an executable

Now the objects can be *linked* together to the executable:

```
g++ main.o hello_fn.o -o hello_world
```

NOTE:

The code is already compiled → You don't need warning options

⇒ Try it!

- Modify something in one of the files (e.g. world → moon in main.cpp)
- Recompile only main.cpp
- Link all files to one executable

⇒ Try it!

Linking objects to an executable

Now the objects can be *linked* together to the executable:

```
g++ main.o hello_fn.o -o hello_world
```

NOTE:
The code is already compiled → You don't need warning options

⇒ Try it!

- Modify something in one of the files (e.g. world → moon in main.cpp)
- Recompile only main.cpp
- Link all files to one executable

⇒ Try it!

Makefiles

- The steps mentioned above can be automatized using the *make system*
- Define dependencies (e.g. the executable can only be built if all objects files are available)
- Only compiles code which changed

Documentation:
`https://www.gnu.org/software/make/manual/make.html`

Makefiles – An example

```
CXX        = /usr/bin/g++
CXXFLAGS   = -Wall -Wextra -Wconversion -Wshadow -g
LDFLAGS    =

OBJ      = hello_fn.o main.o

split: $(OBJ)
        $(CXX) -o $@ $(OBJ) $(LDFLAGS)

main.o: main.cpp hello_fn.h
        $(CXX) -o $@ -c $< $(CXXFLAGS)

%.o: %.cpp %.h
         $(CXX) $(CXXFLAGS) -c $< -o $@


clean:
        @rm -f ${OBJ} split
```

Makefiles – Primer

Makefiles consist of rules that tell the make system what to do. A rule has the form:

```
target ... : prerequisites ...
<tab> recipe
<tab> ...
<tab> ...
```

`target` is usually an output file name, `prerequisites` can be other targets or e.g. file names

NOTE: A `recipe` MUST be started with a < *tab* >

When the `make` command is called, it looks for a file called *Makefile* or *makefile* in the present directory and processes the first target (*default target*).

Makefiles – Primer

A few important automatic variables are defined in the `make` system:

- `$@` The target name
- `$<` The first prerequisite
- `$^` The names of all the prerequisites, with spaces between them

For more see `https://www.gnu.org/software/make/manual/make.html#Automatic-Variables`

⇒ Try it!

CMake - introduction

- treatment of dependencies and automatic re-compilation
  covered by Makefiles and make
- manual maintenance of Makefiles can become tedious and error-prone
- configuration for specific setup of SDK and external dependencies
  covered by autotools suite or CMake

CMake - introduction

CMake is an open-source, cross-platform family of tools designed to build, test and package software.

- universal (toolchain agnostic) description of build flow in CMakeLists.txt
- automated creation of Makefiles depending on configuration options environment found
- automatic re-evaluation when needed
- possibly add testing and packaging steps

here: CMake with Makefiles

typical build layout

- separate build into different directories:
    - source: no generated files
    - build: generated files, object files, libraries, executables
      possibly more than one with different build options
    - install: final files only
- test stage
- delivering/deploying stage

a minimal CMake project

```
cmake_minimum_required(VERSION 3.9)
project(MyPowerProject CXX)

add_executable(testExe test.cc)
```

- always specify minimum version of CMake (depending on the features you use)
- declare project and language used
- add targets (here just one executable)

---

example project:

```
examples/cmake_simple
```

a CMake run

```
cd <build directory>
cmake <source directory>
make -j$(nproc)
```

build happens in phases:

- configuration:
  evaluation of CMakeLists.txt files, additional options, toolchain probing
- generation:
  generation of build files (depending on selected generator)
- compilation:
  actual build using Makefiles

libraries

```
...

add_library(power power.cc)
add_executable(main main.cc)
target_link_libraries(main power)
```

- add target for library and source files needed to build it
- link executable against library
- include directories are propagated to the targets using the library

using lists

```
...

set(SOURCES s1.cc s2.cc s3.cc)
add_library(s ${SOURCES})

set(EXECUTABLES e1 e2 e3)
foreach(EXE ${EXECUTABLES})
  add_executable(${EXE} ${EXE}.cc)
  target_link_libraries(${EXE} power)
endforeach()
```

- define lists that can be reused
- avoid overly repetitive code

ROOT integration

```
...

find_package(ROOT)
include(${ROOT_USE_FILE})
if(ROOT_FOUND)
  message(STATUS "Using ROOT: ${ROOT_VERSION} <${ROOT_CONFIG}>")
  target_compile_definitions(power PUBLIC "-DUSE_ROOT")
  target_include_directories(power PRIVATE ${ROOT_INCLUDE_DIRS})
  target_include_directories(power PRIVATE .)
  ROOT_GENERATE_DICTIONARY(G__Power ${CMAKE_CURRENT_SOURCE_DIR}/power.h LINKDEF Li
  target_sources(power PRIVATE power_rooted.cc G__Power)
  target_link_libraries(power ROOT::Core ROOT::Gui ROOT::Tree)
endif(ROOT_FOUND)
```

- ROOT comes with additional tools to build dictionaries

warnings and errors

```
message("something important")
message(STATUS "just a status message")
message(WARNING "something's fishy here")
message(ERROR "this is plain wrong")
message(FATAL_ERROR "this is too wrong, I rather die ...")
```

- use messages to check on your build,
  don't be blind on what is happening

language options

```
...

set(CMAKE_CXX_STANDARD 14)
set(CMAKE_CXX_STANDARD_REQUIRED ON)
message(STATUS "Using C++${CMAKE_CXX_STANDARD}")

enable_language(CUDA)
```

- compiler-agnostic settings of language standard
  N.B.: you can also request specific language features
- enabling of additional programming languages

build types and compiler options

```
set(CMAKE_CXX_FLAGS_DEBUG "-O0 -ggdb -DDEBUG -D__DEBUG")
set(CMAKE_CXX_FLAGS_RELWITHDEBINFO "${CMAKE_CXX_FLAGS_RELEASE} -ggdb")
set(CMAKE_CXX_FLAGS_RELEASE "-O3 -march=native -ftree-vectorize -ffast-math -DNODEB
message(STATUS "Using CXX flags for ${CMAKE_BUILD_TYPE}: ${CMAKE_CXX_FLAGS_${CMAKE_
```

- compiler options/flags are controlled by build types
- can be changed separately for different build types
- don't put target-specific stuff here

```
cmake -DCMAKE_BUILD_TYPE=DEBUG <source dir>
```

default build type

```
# by default build optimized code with debug symbols
if(NOT CMAKE_BUILD_TYPE AND NOT CMAKE_CONFIGURATION_TYPES)
  set(CMAKE_BUILD_TYPE RELWITHDEBINFO)
endif()

set(CMAKE_ALLOWED_BUILD_TYPES DEBUG RELEASE RELWITHDEBINFO)
if(NOT CMAKE_BUILD_TYPE IN_LIST CMAKE_ALLOWED_BUILD_TYPES)
  message(FATAL_ERROR "Invalid build type ${CMAKE_BUILD_TYPE}. Use one of: ${CMAKE_
endif()
```

- explicit control over default build type

install

```
install(TARGETS main power
  LIBRARY DESTINATION lib
  RUNTIME DESTINATION bin
)
```

- this should install only the final build products
- try and adhere to conventions about installation paths

some more involved stuff

- nested projects
- tests

nested projects

```
add_subdirectory(sub1)
add_subdirectory(sub2)
```

- include sub-projects in sub-directories, hierarchical layout
- sub-directories can contain project, this allows to build the sub-project independently
- different directories:
  - CMAKE_SOURCE_DIRECTORY: directory from which cmake was run
  - CMAKE_PROJECT_SOURCE_DIRECTORY: (sub-)project directory
  - CMAKE_CURRENT_SOURCE_DIRECTORY: current directory in source tree

CTest

- you can add tests which can be run programatically

```
enable_testing()

add_test(NAME MyPowerTest COMMAND echo done)
```

```
ctest
```

You can also run this using the *make* process by

```
make test
```

summary

- surely not an extensive coverage of CMake,
  but it should get you started

- extensive documentation on project pages
  but not always good explanation of the underlying concepts

Lecture IV

Project

The problem

- consider an experiment to measure the X particle

- a renowned theorist told us some expectations:
  - decay to three charged pions
  - mass $50 - 100\ \mathrm{GeV}$, known lifetime $c\tau = 0.5\ \mathrm{mm}$
  - production flat in η and $\propto p_{\mathrm{T}}^{-5}$
  - in every n-th event (poisson around that mean), n most probably 5

- available detector covers $|\eta| < 2$ and full azimuth,
  provides one point at $R = 5\ \mathrm{cm}$ with $\sigma = 0.1\ \mathrm{mm}$ in z and $r\varphi$ direction,
  θ with a resolution of 1 degree and p_{T} with a resolution of
  $\Delta p_{\mathrm{T}}/p_{\mathrm{T}} = 0.5\ \%/(\mathrm{GeV}/c) \cdot p_{\mathrm{T}}$,

- on average 10 (poisson with mean 10) other primary particles (pions)
  produced, flat in η and $\propto p_{\mathrm{T}}^{-8}$
  exploit the known lifetime

- find a way to prove (or falsify) the existance of the X, which properties
  can be measured

Your task

Write the code to

- simulate the production of the X particle
  and its decay according to the specified properties
- simulate background particles produced in association with X
- smear the measured track properties ($\vec{x}$, p_{T}, η)
  (fast detector simulation)
- reconstruct the X particle
- analyze the performance of the reconstruction
- develop clever cuts on the analysis level

Simulation, smearing, reconstruction, and analysis should be kept separated!

Some thoughts

- IO is usually quite slow, but might be important, optionally, for debugging purposes ⇒ use root trees
- simulation writes information to memory structure(s)
  what information needed? how structured?
- smearing runs on these data / tree input
  modify? copy? extend? file structure?
- reconstruction runs on these in memory structure(s) / tree input
  what information is needed? what is produced?
- analysis runs on these in memory structure(s) / tree input
  what information is needed?
- for specific problems (e.g. three-body decay) you might want to use external libraries (ROOT – e.g. TGenPhaseSpace)

You are free to do what you want.

Details

- Primary particles are created at the origin (exact position, no smearing).
- All spectra are flat in η and follow a power law in p_T, cut of at 100 MeV.
- The resolution of the tracking layers is $\sigma = 1\ \mathrm{mm}$ in z and in $r\varphi$ direction (Gaussian). There is no error in r.
- The detector has full acceptance, every particle crossing a layer produces exactly one hit.
- For generating the hits, assume perfectly cylindrical detector layers.
- Mass of particles: X: $50 - 100\ \mathrm{GeV}$
- Lifetime of particles: X: $c\tau = 0.5\ \mathrm{mm}$
- The mean number of background particles is $dN/d\eta = 2.5$, the mean number of X particles is $dN/d\eta = 0.25$ (Poissonian Distribution).
- The p_T spectrum of the X is proportional to p_T^{-5}, the p_T spectrum of the background is proportional to p_T^{-8}.

Lecture V

Object-oriented programming

Why object-oriented programming?

- paradigms:
  - machine operations (assembler)
  - functional formulation (Lisp, Lua, ...)
  - procedural languages (Fortran, C)
  - object-oriented (C++, Java, ...)
- problems before object-oriented programming:
  - inter-dependencies
  - name clashes
  - change of internal representations difficult
- solution:
  - encapsulate data and methods to access it
  - make it reusable without knowing the interna
  - C with objects $\rightsquigarrow$ C++

Objects

- user-defined type,
  on equal footing with language types
- aggregate of
  - member variables (data)
  - methods
  - access policies
- use a object to describe a concept, e.g.
  - particle with properties
  - functor (map)
- C++ supports you to use objects,
  it does not force you to write everything as a object!
- Object can be a *class* or a *struct*

Classes

Example

```
class particle {
 public:
  particle() = default;
  ~particle() = default;
  particle(const particle &rhs) = default;
  particle& operator=(const particle &rhs) = default;

  float pt() const
    { return sqrt(p[0]*p[0] + p[1]*p[1]); }

 protected:
 std::array<float, 4> p{};
};
```

- only a concept so far, no object yet

Instances

- you can create objects from a class (instances)

```
// on the stack
particle p1{};
// on the heap
auto p2 = make_unique<particle>();
```

- only then:
  - allocation of memory
  - execution of constructor
- allocation on the stack and heap behave differently, try it out!

Inheritance

- extend the concept described by a base class
- objects of the derived class can be used
  where an object of the base class is asked for
- avoid re-writing code

```
class particle_spin : public particle {
 public:
  particle_spin() : particle(), spin(0) {}

 protected:
  float spin;
};
```

Virtual functions

```
class particle {
  ...
  virtual void decay();
  ...
};

class particle_spin : public particle {
  ...
  virtual void decay();
  ...
};
```

Polymorphism

- code written for a particle should also work for a particle with spin

  ```
  particle_spin p_spin();
  particle &p = p_spin;
  // ...
  p.decay();
  ```

- while you use a reference to a particle,
  you (probably) want the method of the derived class to be called

- decision which method to call must happen at run-time!
  $\rightsquigarrow$ objects have vtable for virtual functions

- only overload virtual functions
  (although C++ does not enforce this)

TFile class hierarchy

- TObject
- TNamed
- TDirectory
- TDirectoryFile
- TFile
- TNetFile, TMemFile, TXMLFile, TAlienFile, ...

have a look at:
`http://root.cern.ch/root/html/TFile.html`

Example

Try it out!

`examples/class`

Inheritance vs Member

- sometimes you can consider a class as a
  - parent class
  - member object
- with inheritance:
  you can use the derived class in place of the parent class
- with member object:
  you hide the details of the object
- think about what you want to achieve

Abstract base class

- you can write a class for which no actual realisation exists
  but which shall serve as the description of an interface
- achievable by requiring the implementation of a virtual function

```
class abstract {
 public:
  abstract();
  virtual int get() const = 0;
};
```

- only when all required virtual functions are implemented in a derived classes, instantiation is possible

override

What will happen?

```
class Foo {
  public:
  virtual void print(const char* something) {
    std::cout << "Foo prints " << something << '\n';
  }
};

class Bar : public Foo {
  public:
  virtual void print(const char* something) const {
    std::cout << "Bar prints " << something << '\n';
  }
};

int main ()
{
  Bar bar;
  Foo &foo = bar;
  foo.print("hi");
}
```

examples/cpp11/override_bad.cpp

override

Help the compiler to find errors in inheritance with function overriding.

```
class Foo {
  public:
  virtual void print(const char* something) {
    std::cout << "Foo prints " << something << '\n';
  }
};

class Bar : public Foo {
  public:
  void print(const char* something) const override {
    std::cout << "Bar prints " << something << '\n';
  }
};

int main ()
{
  Bar bar;
  Foo &foo = bar;
  foo.print("hi");
}
```

examples/cpp11/override_fail.cpp

Templates

- family of classes:
  generic programming of a class unspecified data type

```
template <typename T>
class dummy {
 public:
  dummy();
  const T& get_a();
 protected:
  T a;
};
```

- compiler generates specializations for this class
  when you use them

```
dummy<int> a;
dummy<float> b;
```

- more details and Standard Template Library (STL) later

Lecture VI

Selected c++11 features

Selected c++11 features

Discussed features

- `auto`
- Range based for loops
- `nullptr`
- Strongly typed enums
- `override` and `final`
- move semantics
- default and delete functions

What will not be covered

- Threading Support
- Static Assertions
- Variadic Templates
- decltype
- Alignment control (i.e., alignof, alignas, etc.)
- `static_assert` and type traits
- ...

examples: `git pull`

auto

`auto` leaves the type definition to the compiler. Very convenient in many situation. Can save lots of typing or typedef declarations.

```
auto i = 0; // not that useful
auto f = 0.f;

auto histogram = new TH1F("h", "h", 100,0,100); // more useful

std::vector<int> v{1,4,5};
for (std::vector<int>::iterator it = v.begin(); it != v.end(); ++it) ...
for (auto it = v.begin(); it != v.end(); ++it) ... //save typing!
```

Range based for loops

Simple way to loop over iterable types (stl container, root containers , c-arrays, ...).

```
std::vector<int> v{1,4,5};
for (const auto& val : v) std::cout << val << '\n';

float arr[]={4.,5.,6.};
for (const auto& val : arr) std::cout << val << '\n';

for (auto& val : arr) val*=val;
for (const auto& val : arr) std::cout << val << '\n';

for (auto val : arr) val*=val;
for (const auto& val : arr) std::cout << val << '\n';
```

examples/cpp11/range_based.cpp

Range based for loops

Can also be used with ROOT containers.
BUT: you have to know that a pointer to `TObject` is returned.

```
TClonesArray arr("TParticle");
for (int i=0; i<10; ++i) {
  TParticle& part = *static_cast<TParticle*>(arr.ConstructedAt(i));
  part.SetPdgCode(i);
}

for (auto o : arr) {
  TParticle& part = *static_cast<TParticle*>(o);
  std::cout << "Pdg code: " <<  part.GetPdgCode() << '\n';
}
```

examples/cpp11/range_based.cpp

nullptr

A specific *type* for null pointer. Before c++11 mainly 0, 0x0, NULL were used which is not type save. Consider:

```
void print(int *i) { std::cout << "integer pointer: " << i << '\n'; }
void print(int i) { std::cout << "integer: " << i << '\n'; }

int main()
{
  print(0);
  print(NULL);
}
```

which will not compile

examples/cpp11/nullptr_fail.cpp

nullptr

`nullptr` solves this issue:

```
void print(int *i) { std::cout << "integer pointer: " << i << '\n'; }
void print(int i) { std::cout << "integer: " << i << '\n'; }

int main()
{
  print(0);
  print(nullptr);
}
```

will compile.

`examples/cpp11/nullptr.cpp`

Strongly typed enums

While names in normal enums cannot be the same

```
enum Animals {Bear, Cat, Chicken};
enum Birds {Eagle, Duck, Chicken}; // error! Chicken has already been declared!
```

examples/cpp11/enum_fail.cpp

this is perfectly fine using strongly typed enums

```
enum class Fruits { Apple, Pear, Orange };
enum class Colours { Blue, White, Orange }; // no problem!
```

examples/cpp11/enum_strong.cpp

Strongly typed enums

Also unintuitive that you could e.g. make bit operations between enums which are not strongly typed:

```
enum Animals {Bear, Cat};
enum Birds {Eagle, Duck};

bool b = Bear == Duck; // what?
```

Modern compilers should at least give a warning about this.

examples/cpp11/enum_stupid.cpp

Compilation fails with strongly typed enums

```
enum class Fruits { Apple, Pear, Orange };
enum class Colours { Blue, White, Orange };

bool b = Fruits::Orange == Colours::Orange; // what?
```

examples/cpp11/enum_stupid_fail.cpp

Strongly typed enums

You can specify the underlying integral type of C++11 enums:

```
enum class Foo : char { A, B, C };
```

In C++11 this works even for the 'normal' enums:

```
enum Bar : char { A, B, C};
```

override and final

Help the compiler to find errors in inheritance with function overriding.

```
class Foo {
  public:
  virtual void print(const char* something) const final {
    std::cout << "Foo prints " << something << '\n';
  }
};

class Bar : public Foo {
  public:
  void print(const char* something) const override {
    std::cout << "Bar prints " << something << '\n';
  }
};

int main ()
{
  Bar bar;
  Foo &foo = bar;
  foo.print("hi");
}
```

Use `final` if you don't intend a function to be overridden.

examples/cpp11/final_fail.cpp

move semantics

C++11 has introduced the concept of rvalue references (specified with &&) to differentiate a reference to an lvalue or an rvalue. An lvalue is an object that has a name, while an rvalue is an object that does not have a name (a temporary object). The move semantics allow modifying rvalues (previously considered immutable and indistinguishable from const T& types).

```
class Foo {
  public:
    Foo(int i) : val(i) {}
    std::vector<int> val;
};

Foo getBigFoo(i) { Foo foo(100000); return foo; }

int main() {
  Foo foo = getBigFoo();
}
```

The compiler implements a move operator

```
Foo(Foo&& other) ...
const Foo& operator= (Foo&& other) ...
```

examples/cpp11/move_tests.cpp

move semantics

c++11 implements `std::move` which explicitly

```
std::string foo = "foo-string";
std::string bar = "bar-string";
std::vector<std::string> myvector;

myvector.push_back (foo);                    // copies
myvector.push_back (std::move(bar));         // moves

std::cout << "foo is: " << foo << '\n';
std::cout << "bar is: " << bar << '\n';

std::cout << "myvector contains:";
for (const auto& x:myvector) std::cout << ' ' << x;
std::cout << '\n';
```

examples/cpp11/move_string.cpp

default and delete

The compiler will always try to implement e.g. a copy and assignment constructor as well as it's move counter parts. This can be forced as well as forbidden:

```
class Foo {
  Foo::Foo() = default;
  Foo::Foo(const Foo&) = delete;
  Foo::Foo(Foo&&) = delete;
  Foo& operator=(const Foo&) = default;
  Foo& operator=(Foo&&) = delete;
```

if you define 1 the other 5 will be automatically deleted! then you need to implement all 5.

Lambdas

A lambda is a nameless function with special properties:

- first class citizen - can be assigned to variables, passed to functions etc.
- can capture (i.e. copy or reference) variables from the outside scope irrespective of it's signature.

```
int x{4};
int y{5};

auto mylambda = [x,&y] (auto in, const auto& alsoin) {
  return in +  alsoin - x - y;
};

auto result = mylambda(3,7);
```

Lecture VII

Smart Pointers

pointers

- Pointers are a basic feature of C / C++
- Both one of the most powerfull and most dangerous features
- The majority of errors / bugs / security is related to memory management
- Use after free, buffer overflows are the most prominent cases
- (Semi-) Automatic memory management is desired, without loosing flexibility.

pointers

- Ownership problem

```
Particle* p = new Particle;
Collection* c = new Collection;
c->Add(p);
```

- Traditionally, containers need a flag whether they own or not?
- This is asking for trouble

pointers

- The solution in C++11: smart pointers

```
#include<memory>
std::unique_ptr<int>
std::shared_ptr<int>
```

- lifetime of managed resource managed by scoping (unlike raw pointers).
- The unique ptr is THE unique ptr pointing to the object, there cannot be a second one.
- Multiple shared pointers can point to an object, ownership is handled automatically, the last shared pointer that is destroyed also destroys the object.

pointers

- There are some limitations by design:
- Unique pointers cannot be copied or assigned (unique ownership!)

```
std::unique_ptr<int> p1(new int);
std::unique_ptr<int> p2 = p1; //DOES NOT COMPILE!
```

- Operations like this require an explicit move (std::move) - The programmer should know what he does.

examples/smart_pointers

pointers in interfaces

- using raw pointers is still OK - just don't use "owning raw pointers"
- raw pointer only points at something which is guaranteed to exist (or use a reference).
- managed pointer signals ownership (transfer).

```
void function( int* look, std::unique_ptr<Particle> consume) {}
```

Lecture VIII

Standard Template Library

Template programming

Template programming is a different programming technique which allows to provide common functionality to many different data structures.

In this lecture we provide as much knowledge as it is needed to be able to work with the Standard Template Library (STL) functionality.

A template defines and implements a family of functions/classes with open data types.

```
template T class dummy {
 public:
  dummy();
  const T& get_a();
 protected:
  T a;
};
```

A template class or function can be used with any data type fulfilling the requirements. The compiles creates the specialized version for a specific data type.

Motivation - an example

Suppose there is an array of integers

```
const int size=10;
int array[10]={7,5,6,2,3,1,4,0,9,8};
```

An algorithm to *find* the position of an element can be

```
int *first=&array[0], *last=&array[10];
int value=7;
while (first != last && *first != value)
  ++first;
return first;
```

In a function it looks like

```
int* find(int* first, int* last, const int& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Suppose, it's also needed for data type float

```
float* find(float* first, float* last, const float& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Motivation - an example

Suppose there is an array of integers

```
const int size=10;
int array[10]={7,5,6,2,3,1,4,0,9,8};
```

An algorithm to *find* the position of an element can be

```
int *first=&array[0], *last=&array[10];
int value=7;
while (first != last && *first != value)
  ++first;
return first;
```

In a function it looks like

```
int* find(int* first, int* last, const int& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Suppose, it's also needed for data type float

```
float* find(float* first, float* last, const float& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Motivation - an example

Suppose there is an array of integers

```
const int size=10;
int array[10]={7,5,6,2,3,1,4,0,9,8};
```

An algorithm to *find* the position of an element can be

```
int *first=&array[0], *last=&array[10];
int value=7;
while (first != last && *first != value)
  ++first;
return first;
```

In a function it looks like

```
int* find(int* first, int* last, const int& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Suppose, it's also needed for data type `float`

```
float* find(float* first, float* last, const float& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Generalization

The two algorithms are identical, the functions only differ in the type
⇒ here the concept of templates helps to generalize the function

```
template<class T>
T* find(T* first, T* last, const T& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

Even more general, the type of the pointers does not need to be the same as the type of the value to search for

```
template<class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

The requirements to make this work are

- `Iterator` must support the prefix increment operator
- `Iterator` must support the `!=`-comparison operator
- dereferencing `Iterator` must give the type of the search value

Simplifying even further...

With C++14 we can even do:

```
auto find(auto first, auto last, const auto& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

With the same requirements as before

Important to know

- the template class or function has to be implemented in the header file

A layout consisting of header file containing the function/class definition

```
template<class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value);
```

and a source file with the implementation

```
template<class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value) {
  while (first != last && *first != value) ++first;
  return first;
}
```

DOES NOT WORK!

The Standard Template Library

A set of C++ template classes to provide common programming data structures and functions:

- Container classes
  http://en.cppreference.com/w/cpp/container
- iterator:
  - represent position in a container
  - declared to be associated with a single container class type
- algorithm:
  - routines to find, count, sort, search, ... elements in container classes

STL Containers

- Sequences:
  - vector: Dynamic array. Insert data at the end.
  - deque: Dynamic array. insertion/removal at beginning or end
  - list: linked list. Insert/remove anywhere.
- Associative Containers:
  - set: Collection of ordered data (no duplication). Fast search.
  - multiset: Collection of ordered data (duplication allowed). Fast search.
  - map: Collection of associative key-value pair with unique keys
  - multimap: Collection of associative key-value pair, duplicate keys allowed
- Container adapters:
  - stack LIFO
  - queue FIFO
  - priority_queue returns element with highest priority.
- String:
  - string: Character strings and manipulation
  - rope: String storage and manipulation
- bitset: intuitive method of storing and manipulating bits.

Example - the vector container

similar to an array, handles automatically its own storage requirements in case it grows

```
#include <vector>
using std::vector;

vector<int> v;
```

Basic operations:

push_back	Add element to end of collection.
pop_back	Remove element at end of collection
back	Get a reference to element at end of collection
front	Get a reference to element at end of collection
operator[]	Access specified element

Note: the vector keeps the internally allocated memory also if the number of elements is reduced or all elements are erased.

Using a `vector` container

`empty`	determines if the collection is empty
`size`	number of elements in the collection
`capacity`	number of elements which can be added without growing the internal storage
`begin`	forward iterator pointing to the start of the collection
`end`	forward iterator pointing to one past the end of the collection
`rbegin`	backward iterator pointing to the end of the collection
`rend`	backward iterator pointing to one before the start of the collection
`clear`	erases all elements in a collection. Note: pointers must be deleted manually
`erase`	erase element or range of elements from a collection

STL containers vs. ROOT containers

ROOT also provides container classes, e.g. `TObjArray`, `TClonesArray`, `TList`.

Polymorphism is used to implement the ROOT collection classes

- every class needs to inherit from `TObject`
- collection classes only know about `TObject`
  - ⇒ every element return by access functions can only be of type `TObjArray`
  - ⇒ type casts are necessary

STL containers are type-safe because of the template approach

STL algorithms

- https://en.cppreference.com/w/cpp/algorithm
- expressive: say WHAT you mean to do, not HOW
- part of standard: in many compilers are allowed special optimizations.

e.g. instead of a (range-based) for loop:

```
std::vector<int> nums{3, 4, 2, 8, 15, 267};

int size{0};
std::for_each( nums.begin(), nums.end(), [&size] (auto& n) {
  ++n; ++size;
});
```

STL algorithms

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or (a pretty generic) sort:

```
std::vector<int> nums{3, 4, 2, 8, 15, 267};

int ops{0};
std::sort( nums.begin(), nums.end(), [&ops] (const auto& a, const auto& b) {
  ++ops; return a < b;
});
```

Further reading

http://en.cppreference.com/w/cpp/container
http://en.cppreference.com/w/cpp/algorithm

`examples/template`