

COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)  
CALIFORNIA INSTITUTE OF TECHNOLOGY (USA)  
UNIVERSITY OF PAU, CNRS and INRIA (FRANCE)

# SPECFEM 3D

User Manual  
Version 2.0.0



Min Chen  
Vala Hjörleifsdóttir  
Sue Kientz  
Dimitri Komatitsch  
Qinya Liu  
Alessia Maggi  
Brian Savage  
Leif Strand  
Carl Tape  
Jeroen Tromp



# **SPECFEM3D**

## **User Manual**

© California Institute of Technology (USA) and  
University of Pau / CNRS / INRIA (France)  
Version 2.0.0

November 12, 2010

# Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
1.1	Citation . . . . .	4
1.2	Support . . . . .	4
<b>2</b>	<b>Getting Started</b>	<b>5</b>
<b>3</b>	<b>Mesh Generation</b>	<b>7</b>
3.1	Meshing with CUBIT . . . . .	7
3.1.1	Creating the Mesh with CUBIT . . . . .	8
3.1.2	Exporting the Mesh with <code>cubit2specfem3d.py</code> . . . . .	9
3.1.3	Partitioning the Mesh with <code>xdecompose_mesh_SCOTCH</code> . . . . .	10
3.2	Meshing with <code>xmeshfem3D</code> . . . . .	12
<b>4</b>	<b>Creating the Distributed Databases</b>	<b>15</b>
4.1	Main parameter file <code>Par_file</code> . . . . .	15
4.2	Choosing the time step <code>DT</code> . . . . .	17
<b>5</b>	<b>Running the Solver <code>xspecfem3D</code></b>	<b>18</b>
<b>6</b>	<b>Adjoint Simulations</b>	<b>23</b>
6.1	Adjoint Simulations for Sources . . . . .	23
6.2	Adjoint Simulations for Finite-Frequency Kernels (Kernel Simulation) . . . . .	24
<b>7</b>	<b>Graphics</b>	<b>26</b>
7.1	Meshes . . . . .	26
7.2	Movies . . . . .	26
7.2.1	Movie Surface . . . . .	26
7.3	Finite-Frequency Kernels . . . . .	27
<b>8</b>	<b>Running through a Scheduler</b>	<b>29</b>
8.1	Job submission <code>run_lsf.bash</code> . . . . .	29
8.2	Job script <code>go_mesher_solver_lsf.forward</code> . . . . .	30
<b>9</b>	<b>Post-Processing Scripts</b>	<b>32</b>
9.1	Process Data and Synthetics . . . . .	32
9.1.1	Data processing script <code>process_trinet_data.pl</code> . . . . .	32
9.1.2	Synthetics processing script <code>process_trinet_syn.pl</code> . . . . .	32
9.1.3	Script <code>rotate.pl</code> . . . . .	33
9.2	Collect Synthetic Seismograms . . . . .	33
9.3	Clean Local Database . . . . .	33
9.4	Plot Movie Snapshots and Synthetic Shakemaps . . . . .	34
9.4.1	<code>movie2gif.pl</code> . . . . .	34
9.4.2	<code>plot_shakemap.pl</code> . . . . .	34

<b>CONTENTS</b>	<b>2</b>
9.5 Map Local Database . . . . .	34
<b>A Reference Frame Convention</b>	<b>43</b>
<b>B License</b>	<b>44</b>

# Chapter 1

## Introduction

The software package SPECFEM3D simulates seismic wave propagation at the local or regional scale based upon the spectral-element method (SEM). The SEM is a continuous Galerkin technique, which can easily be made discontinuous [Bernardi et al., 1994, Kopriva et al., 2002, Chaljub et al., 2003, Kopriva, 2006, Wilcox et al., 2010]; it is then a particular case of the discontinuous Galerkin technique [Reed and Hill, 1973, Falk and Richter, 1999, Hu et al., 1999, Cockburn et al., 2000, Giraldo et al., 2002, Rivi  re and Wheeler, 2003, Monk and Richter, 2005, Grote et al., 2006, Bernacki et al., 2006, Dumbser and K  ser, 2006, De Basabe et al., 2008, Wilcox et al., 2010, De Basabe and Sen, 2010, Etienne et al., 2010], with optimized efficiency because of its tensorized basis functions. In particular, it can accurately handle very distorted mesh elements [Oliveira and Seriani, 2011]. Note that in many (most?) geological models in the context of seismic wave propagation studies (except for fault dynamic rupture studies) a discontinuous mesh is not needed because material property contrasts are not drastic and thus a continuous formulation is sufficient. For a detailed introduction to the SEM as applied to regional seismic wave propagation, please consult Komatitsch and Vilotte [1998], Komatitsch and Tromp [1999], Chaljub et al. [2007], Tromp et al. [2008] and in particular Komatitsch et al. [2004].

Effects due to lateral variations in compressional-wave speed, shear-wave speed, density, a 3D crustal model, topography and bathymetry are included. The package can accommodate full 21-parameter anisotropy (see Chen and Tromp [2007]) as well as lateral variations in attenuation. Adjoint capabilities and finite-frequency kernel simulations are included [Liu and Tromp, 2006, Tromp et al., 2008, Fichtner et al., 2009].

The SPECFEM3D package was first developed by Dimitri Komatitsch and Jeroen Tromp at Harvard University, then Caltech and Princeton, USA, starting in 1998, based in part on earlier work by Dimitri Komatitsch and Jean-Pierre Vilotte at IPG in Paris, France from 1994 to 1997. Since then it has been developed and maintained by a development team: in alphabetical order, Emanuele Casarotti, Min Chen, Vala Hj  rleifsd  ttir, Emiljana Jorgji, Sue Kientz, Dimitri Komatitsch, Qinya Liu, Yang Luo, Nicolas Le Goff, Pieyre Le Loher, Alessia Maggi, Roland Martin, Dennis McRitchie, David Mich  a, Daniel Peter, Brian Savage, Leif Strand, Carl Tape, Jeroen Tromp **\*\*\* All: add full list of developers here and update the AUTHORS file accordingly \*\*\*.**

All SPECFEM3D\_GLOBE software is written in Fortran90 with full portability in mind, and conforms strictly to the Fortran95 standard. It uses no obsolete or obsolescent features of Fortran77. The package uses parallel programming based upon the Message Passing Interface (MPI) [Gropp et al., 1994, Pacheco, 1997].

SPECFEM3D won the Gordon Bell award for best performance at the SuperComputing 2003 conference in Phoenix, Arizona (USA) (see Komatitsch et al. [2003] and ([www.sc-conference.org/sc2003/nr\\_finalaward.html](http://www.sc-conference.org/sc2003/nr_finalaward.html))). It was a finalist again in 2008 for a run at 0.16 petaflops (sustained) on 149,784 processors of the ‘Jaguar’ Cray XT5 system at Oak Ridge National Laboratories (USA) [Carrington et al., 2008]. It also won the BULL Joseph Fourier supercomputing award in 2010.

The next release of the code will include support for GPU graphics card acceleration [Komatitsch et al., 2009, 2010a, Mich  a and Komatitsch, 2010, Komatitsch, 2011] as well as Convolutional or Auxiliary Differential Equation Perfectly Matched absorbing Layers (C-PML or ADE-PML) [Komatitsch and Martin, 2007, Martin et al., 2008a,b, Martin and Komatitsch, 2009, Martin et al., 2010]. The next release will use the PT-Scotch parallel library for mesh partitioning.

## 1.1 Citation

If you use SPECFEM3D for your own research, please cite at least one of the following articles: Tromp et al. [2008], Vai et al. [1999], Lee et al. [2008, 2009a,b], Komatitsch et al. [2009, 2010a,b], van Wijk et al. [2004], Komatitsch et al. [2004], Chaljub et al. [2007], Madec et al. [2009], Komatitsch et al. [2010c], Carrington et al. [2008], Tromp et al. [2010], Komatitsch et al. [2002], Komatitsch and Tromp [2002a,b, 1999] or Komatitsch and Vilotte [1998]. If you work on geophysical applications, you may be interested in citing some of these application articles as well, among others: van Wijk et al. [2004], Ji et al. [2005], Krishnan et al. [2006a,b], Lee et al. [2008, 2009a,b], Chevrot et al. [2004], Favier et al. [2004], Ritsema et al. [2002], Godinho et al. [2009], Tromp and Komatitsch [2000], Savage et al. [2010]. The corresponding BibTeX entries may be found in file `USER_MANUAL/bibliography.bib` or in comments at the beginning of file `specfem3D.f90`.

If you use the 3D southern California model, please cite Süss and Shaw [2003] (Los Angeles model), Lovely et al. [2006] (Salton Trough), and Hauksson [2000] (southern California). The Moho map was determined by Zhu and Kanamori [2000]. The 1D SoCal model was developed by Dreger and Helmberger [1990].

## 1.2 Support

This material is based upon work supported by the USA National Science Foundation under Grants No. EAR-0406751 and EAR-0711177, by the French CNRS, French INRIA Sud-Ouest MAGIQUE-3D, French ANR NUMASIS under Grant No. ANR-05-CIGC-002, and European FP6 Marie Curie International Reintegration Grant No. MIRG-CT-2005-017461. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the USA National Science Foundation, CNRS, INRIA, ANR or the European Marie Curie program.

# Chapter 2

## Getting Started

The SPECFEM3D software package comes in a gzipped tar ball. In the directory in which you want to install the package, type

```
tar -zxvf SPECFEM3D_V2.0.0.tar.gz
```

The directory `SPECFEM3D_V2.0.0` will then contain the source code. To configure the software for your system, run the `configure` shell script. This script will attempt to guess the appropriate configuration values for your system. However, at a minimum, it is recommended that you explicitly specify the appropriate command names for your Fortran90 compiler and MPI package:

```
./configure FC=ifort MPIFC=mpif90
```

The SPECFEM3D software package relies on the Scotch library to partition the meshes created with CUBIT. Note that we use CUBIT to create meshes of hexahedra, but other packages can be used as well, for instance GiD from (<http://gid.cimne.upc.es>) or Gmsh from (<http://geuz.org/gmsh>). Even mesh creation packages that generate tetrahedra, for instance TetGen from (<http://tetgen.berlios.de>), can be used because each tetrahedron can then easily be decomposed into four hexahedra as shown in the picture of the TetGen logo at (<http://tetgen.berlios.de/figs/Delaunay-Voronoi-3D.gif>); while this approach does not generate hexahedra of optimal quality, it can ease mesh creation in some situations and it has been shown that the spectral-element method can very accurately handle distorted mesh elements [Oliveira and Seriani, 2011].

The path to the SCOTCH installation needs to be set with the option `--with-scotch-path`. Just as an example:

```
./configure FC=ifort MPIFC=mpif90 --with-scotch-path=/opt/scotch
```

To compile a serial version of the code for small meshes that fit on one compute node and can therefore be run serially, run `configure` with the `--without-mpi` option to suppress all calls to MPI.

A summary of the most important configuration variables follows.

**F90** Path to the Fortran90 compiler.

**MPIF90** Path to MPI Fortran90.

**MPI\_FLAGS** Some systems require this flag to link to MPI libraries.

**FLAGS\_CHECK** Compiler flag for non-critical subroutines.

**FLAGS\_NO\_CHECK** Compiler flag for creating fast, production-run code for critical subroutines.

The configuration scripts automatically creates for each executable a corresponding `Makefile` in the `src/` subdirectory. The `Makefile` contains a number of suggested entries for various compilers, e.g., Portland, Intel, Absoft, NAG, and Lahey. The software has run on a wide variety of compute platforms, e.g., various PC clusters and machines from Sun, SGI, IBM, Compaq, and NEC. Select the compiler you wish to use on your system and choose the related

optimization flags. Note that the default flags in the `Makefile` are undoubtedly not optimal for your system, so we encourage you to experiment with these flags and to solicit advice from your systems administrator. Selecting the right compiler and optimization flags can make a tremendous difference in terms of performance. We welcome feedback on your experience with various compilers and flags.

Now that you have set the compiler information, you need to select a number of flags in the `constants.h` file depending on your system:

**LOCAL\_PATH\_IS\_ALSO\_GLOBAL** Set to `.false.` on most cluster applications. For reasons of speed, the (parallel) distributed database generator typically writes a (parallel) database for the solver on the local disks of the compute nodes. Some systems have no local disks, e.g., BlueGene or the Earth Simulator, and other systems have a fast parallel file system, in which case this flag should be set to `.true..` Note that this flag is not used by the database generator or the solver; it is only used for some of the post-processing.

The package can run either in single or in double precision. The default is single precision mode because this requires exactly half as much memory. Select your preference by selecting the appropriate setting in the `constants.h` file:

**CUSTOM\_REAL** Set to `SIZE_REAL` for single precision and `SIZE_DOUBLE` for double precision.

In the `precision.h` file:

**CUSTOM\_MPI\_TYPE** Set to `MPI_REAL` for single precision and `MPI_DOUBLE_PRECISION` for double precision.

On a new system, it is definitely worth experimenting with single versus double precision simulations to determine which is faster. Note that on many current processors (e.g., Intel, AMD, IBM Power), single precision calculations are often significantly faster; the difference can typically be 10% to 25%. It is therefore often worth using single precision if you can. We recommend running the same calculation once in single precision and in double precision on your system and comparing the seismograms. If they are identical, you should probably select single precision for your future runs.

When running on an SGI add “`setenv TRAP_FPE OFF`” to your `.cshrc` file *before* compiling in order to turn underflow trapping off.

Note that if you run very large meshes on a relatively small number of processors, the memory size needed on each processor might become greater than 2 gigabytes, which is the upper limit for 32-bit addressing; in this case, on some compilers you may need to add “`-mcmodel=medium`” to the compiler options otherwise the compiler will display an error message.

# Chapter 3

## Mesh Generation

The first step in running a spectral-element method computation consists of constructing a high-quality mesh for the region under consideration. We provide two possibilities to do so: (1) relying on an external, hexahedral mesher CUBIT or (2) using the provided, internal mesher `xmeshfem3D`. In the following, we explain these two approaches.

### 3.1 Meshing with CUBIT

CUBIT is a meshing tool suite for the creation of finite-element meshes for arbitrarily shaped models. It has been developed and maintained at Sandia National Laboratories and can be purchased for a small academic institutional fee at (<http://cubit.sandia.gov>). Our experience showed that using CUBIT greatly facilitates and speeds up the generation and preparation of hexahedral, conforming meshes for a variety of geophysical models with increasing complexity.

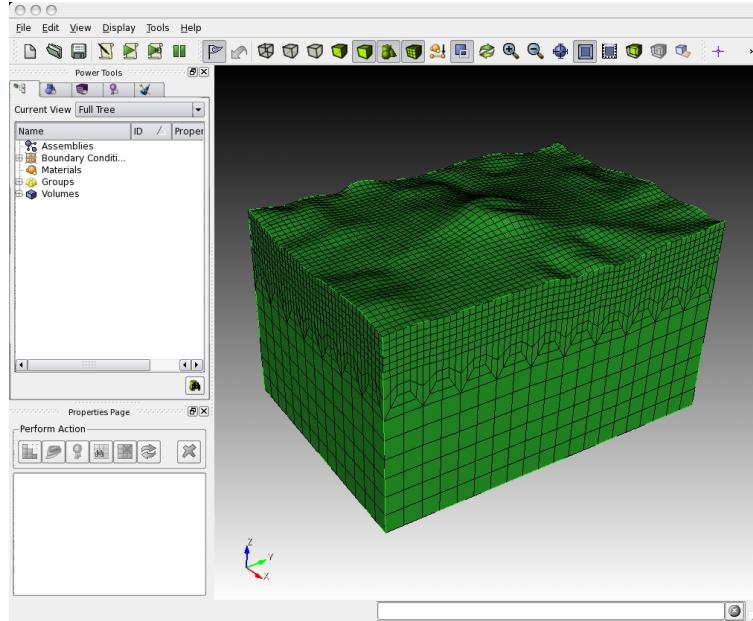


Figure 3.1: Example of the graphical user interface of CUBIT. The hexahedral mesh shown in the main display consists of a hexahedral discretization of a single volume with topography.

The basic steps in creating a load-balanced, partitioned mesh with CUBIT are:

1. setting up a hexahedral mesh with CUBIT,

2. exporting the CUBIT mesh into a specfem3d file format and
3. partitioning the specfem3d mesh files for a chosen number of cores.

Examples are provided in the SPECFEM3D package in the subdirectory `examples/`. Please feel free to contribute your own example to this package by contacting the CIG Computational Seismology Mailing List ([cig-seismo@geodynamics.org](mailto:cig-seismo@geodynamics.org)).

### 3.1.1 Creating the Mesh with CUBIT

For the installation and handling of the CUBIT meshing tool suite, please refer to the CUBIT user manual and documentation. In order to give you a basic understanding of how to use CUBIT for our purposes, examples are provided in the SPECFEM3D package in the subdirectory `examples/`. For your convenience, the following examples are provided in the subdirectory `examples/`:

**homogeneous\_halfspace** Basic example creates a single block model and assigns elastic material parameters.

**layered\_halfspace** Combines two different, elastic material volumes and creates a refinement layer between the two. This example can be compared for validation against the solutions provided in subdirectory `VALIDATION_3D_SEM_SIMPLER_LAYER_SOURCE_DEPTH/`.

**waterlayered\_halfspace** Combines an acoustic and elastic material volume as in a schematic marine survey example.

**tomographic\_model** Creates a single block model whose material properties will have to be read in from a tomographic model file during the databases creation by `xgenerate_databases`.

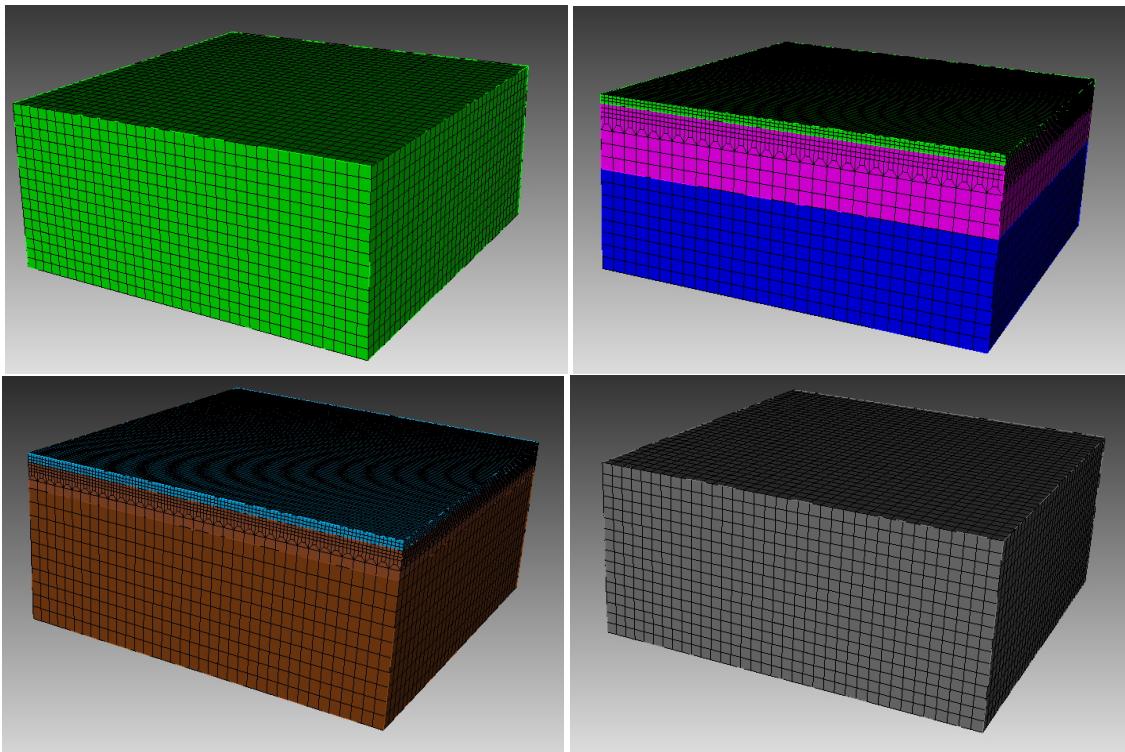


Figure 3.2: Screenshots of the CUBIT examples provided in subdirectory `examples/`: homogeneous halfspace (top-left), layered halfspace (top-right), waterlayered halfspace (bottom-left) and tomographic model (bottom-right).

In each example subdirectory you will find a `README` file, which explains in a step-by-step tutorial the workflow for the example. Please feel free to contribute your own example to this package by contacting the CIG Computational Seismology Mailing List ([cig-seismo@geodynamics.org](mailto:cig-seismo@geodynamics.org)).

### 3.1.2 Exporting the Mesh with `cubit2specfem3d.py`

Once the geometric model volumes in CUBIT are meshed, you prepare the model for the exportation with the definition of the material blocks and of the boundary surfaces. Thus, prior to exporting the mesh, you need to define blocks specifying the materials and absorbing boundaries in CUBIT. This process could be done automatically using the script `boundary_definition.py` if the mesh meets some conditions or manually, following the block convention:

**material\_name** Each material should have a specific block defined by a unique name. The name convention of the material is to start with either 'elastic' or 'acoustic'. It must be then followed by a unique identifier, e.g. 'elastic 1', 'elastic 2', etc. The additional attributes to the block define the material description.

For an elastic material:

**material\_id** An integer value which is unique for this material.

**Vp** P-Velocity of the material (given in m/s).

**Vs** S-Velocity of the material (given in m/s).

**rho** density of the material (given in kg/m<sup>3</sup>).

**Q** quality factor to use in case of a simulation with attenuation turned on. It should be between 1 and 9000.

In case no attenuation information is available, it can be set to zero. Please note that your Vp- and Vs-velocities are given for a reference frequency. To change this reference frequency, you change the value of ATTENUATION\_f0\_REFERENCE in the main constants file `constants.h` found in subdirectory `src/shared/`.

**anisotropic\_flag** Flag describing the anisotropic model to use in case an anisotropic simulation should be conducted. See the file `model_aniso.f90` in subdirectory `src/generate_databases/` for an implementation of the anisotropic models. In case no anisotropy is available, it can be set to zero.

Note that this material block has to be defined using all the volumes which belong to this elastic material. For volumes belonging to another, different material, you will need to define a new material block.

For an acoustic material:

**material\_id** An integer value which is unique for this material.

**Vp** P-Velocity of the material (given in m/s).

**0** S-Velocity of the material is ignored.

**rho** density of the material (given in kg/m<sup>3</sup>).

**face\_topo** Block definition for the surface which defines the free surface (which can have topography). The name of this block must be 'face\_topo', the block has to be defined using all the surfaces which constitute the complete free surface of the model.

**face\_abs\_xmin** Block definition for the faces on the absorbing boundaries, one block for each surface with x=Xmin.

**face\_abs\_xmax** Block definition for the faces on the absorbing boundaries, one block for each surface with x=Xmax.

**face\_abs\_ymin** Block definition for the faces on the absorbing boundaries, one block for each surface with y=Ymin.

**face\_abs\_ymax** Block definition for the faces on the absorbing boundaries, one block for each surface with y=Ymax.

**face\_abs\_bottom** Block definition for the faces on the absorbing boundaries, one block for each surface with z=bottom.

Optionally, instead of specifying for each surface at the boundaries a single block like mentioned above, you can also specify a single block for all boundary surfaces and name it as one of the absorbing blocks above, e.g. 'face\_abs\_xmin'.

After the block definitions are done, you export the mesh using the script `cubit2specfem3d.py` provided in each of the example directories. If the export was successful, you should find the following files in a subdirectory `MESH/`:

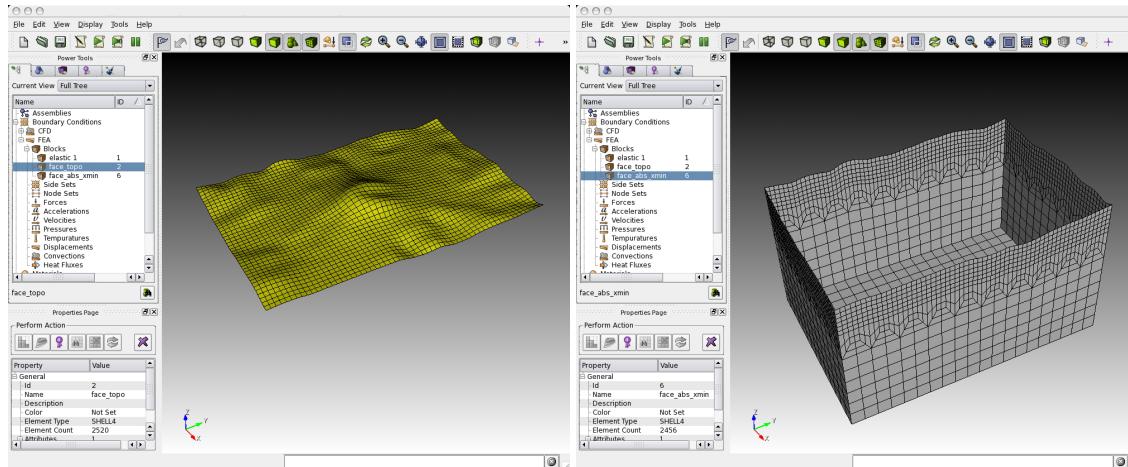


Figure 3.3: Example of the block definitions for the free surface 'face\_topo' (left) and the absorbing boundaries, defined in a single block 'face\_abs\_xmin' in CUBIT.

**nummaterial\_velocity\_file** Defines the material properties. For fully defined materials, the formats is:

```
domain_ID material_ID rho vp vs Q anisotropy_flag
```

where `domain_ID` is 1 for acoustic or 2 for elastic materials, `material_ID` a unique identifier, `rho` the density in  $kg\ m^{-3}$ , `vp` the P-velocity in  $m\ s^{-1}$ , `vs` the S-velocity in  $m\ s^{-1}$ , `Q` the quality factor and `anisotropy_flag` an identifier for anisotropic models. For a tomographic model, the material definition format is:

```
domain_ID material_ID tomography name
```

where `domain_ID` is 1 for acoustic or 2 for elastic materials, `material_ID` a negative, unique identifier, `tomography` keyword for tomographic material definition and `name` the name of the tomography file. The name is not used so far, rather change the filename defined in the file `model_tomography.f90` located in the `src/generate_databases/` directory.

**materials\_file** Contains the material associations for each element.

**nodes\_coords\_file** Contains the point locations in Cartesian coordinates of the mesh element corners.

**mesh\_file** Contains the mesh element connectivity.

**free\_surface\_file** Contains the free surface connectivity.

**absorbing\_surface\_file\_xmax** Contains the surface connectivity of the absorbing boundary surface at the Xmax.

**absorbing\_surface\_file\_xmin** Contains the surface connectivity of the absorbing boundary surface at the Xmin.

**absorbing\_surface\_file\_ymax** Contains the surface connectivity of the absorbing boundary surface at the Ymax.

**absorbing\_surface\_file\_ymin** Contains the surface connectivity of the absorbing boundary surface at the Ymin.

**absorbing\_surface\_file\_bottom** Contains the surface connectivity of the absorbing boundary surface at the bottom.

### 3.1.3 Partitioning the Mesh with `xdecompose_mesh_SCOTCH`

The SPECFEM3D software package performs large scale simulations in a parallel 'Single Process Multiple Data' way. The spectral element mesh created with CUBIT needs to be distributed on the processors. This partitioning is executed once and for all prior to the execution of the solver so it is referred to as a static mapping.

An efficient partitioning is important because it leverages the overall running time of the application. It amounts to balance the number of elements in each slice while minimizing the communication costs resulting from the placement of adjacent elements to different processors. `decompose_mesh_SCOTCH` depends on the Scotch library which provides efficient static mapping, graph and mesh partitioning routines. Scotch is a free software package developed by François Pellegrini et al. from LaBRI and INRIA in Bordeaux, France, downloadable from the web page (<https://gforge.inria.fr/projects/scotch/>). It is more recent than METIS, actively maintained and performs better in many cases.

Prior to compiling `decompose_mesh_SCOTCH`, make sure you have correctly specified the path of the Scotch library with the option `--with-scotch-path` of the `configure` script. For convenience we provide the source code of SCOTCH, which is released open source under the French CeCILL-C version 1 license, in directory `src/decompose_mesh_SCOTCH/scotch_5.1.10b`. Please refer to file `INSTALL.txt` in that directory to see how to compile it. In the future you should be able to find for recent versions at ([http://www.labri.fr/perso/pelegrin/scotch/scotch\\_en.html](http://www.labri.fr/perso/pelegrin/scotch/scotch_en.html)).

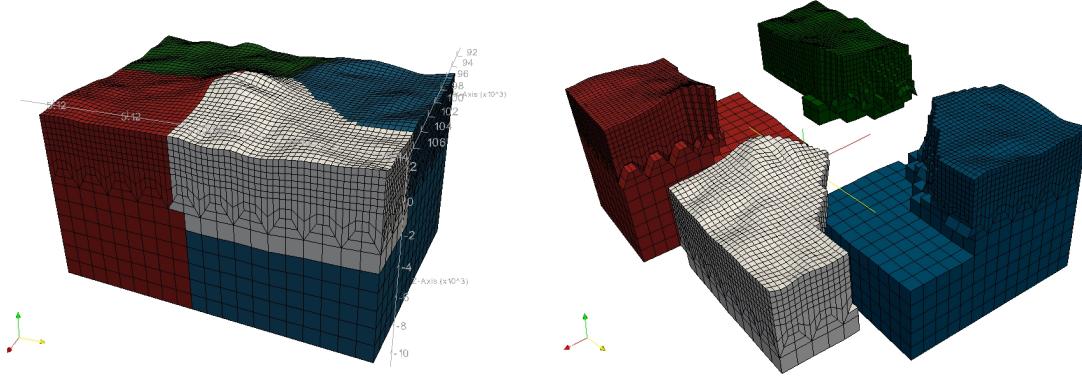


Figure 3.4: Example of a mesh partitioning onto four cores. Each single core partition is colored differently. The executable `xdecompose_mesh_SCOTCH` can equally distribute the mesh on any arbitrary number of cores.

Then you are ready to compile, in the main directory type '`make decompose_mesh_SCOTCH`'. If all paths and flags have been set correctly, the executable `bin/xdecompose_mesh_SCOTCH` should be produced.

The partitioning is done in serial for now (in the next release we will provide a parallel version of that code), the synopsis is:

```
./bin/xdecompose_mesh_SCOTCH nparts input_directory output_directory
```

where

- `nparts` is the number of partitions, i.e. number of cores for the parallel simulations,
- `input_directory` is the directory which holds all the files generated by the Python script `cubit2specfem3d.py` explained in the previous Section 3.1.2, e.g. `MESH/`, and
- `output_directory` is the directory for the output of this partitioner which stores ACII-format files named like `proc*****_Database` for each partition. These files will be needed for creating the distributed databases, and have to reside in the directory `LOCAL_PATH` specified in the main `Par_file`, e.g. in directory `in_out_files/DATABASES_MPI`. Please see Chapter 4 for further details.

Note that all the files generated by the Python script `cubit2specfem3d.py` must be placed in the `input_directory` folder before running the program.

## 3.2 Meshing with `xmeshfem3D`

In case you successfully ran the configuration script, you are also ready to compile the internal mesher. This is an alternative to CUBIT for the mesh generation of relatively simple geological models. The mesher is no longer dedicated to Southern California and more flexibility is provided in this version of the package.

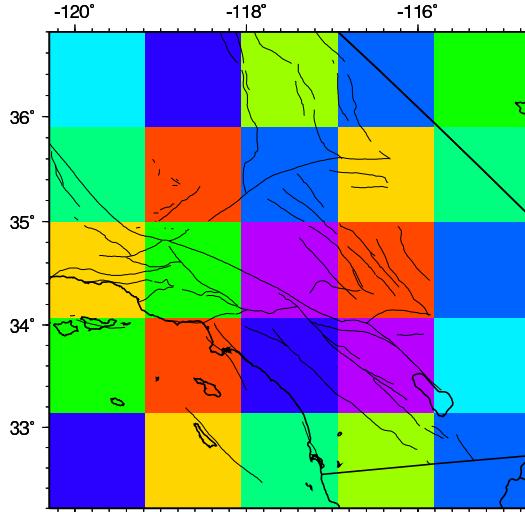


Figure 3.5: For parallel computing purposes, the model block is subdivided in `NPROC_XI`  $\times$  `NPROC_ETA` slices of elements. In this example we use  $5^2 = 25$  processors.

In the main directory type ‘`make meshfem3D`’. If all paths and flags have been set correctly, the mesher should now compile and produce the executable `bin/xmeshfem3D`. Please note that `xmeshfem3D` must be called directly from the `bin/` directory, as most of the binaries of the package.

Input for the mesh generation program is provided through the parameter file `Mesh_Par_file`, which resides in the subdirectory `in_data_files/meshfem3D_files/`. Before running the mesher, a number of parameters need to be set in the `Mesh_Par_file`. This requires a basic understanding of how the SEM is implemented, and we encourage you to read Komatitsch and Vilotte [1998], Komatitsch and Tromp [1999] and Komatitsch et al. [2004].

The mesher and the solver use UTM coordinates internally, therefore you need to define the zone number for the UTM projection (e.g., zone 11 for Los Angeles). Use decimal values for latitude and longitude (no minutes/seconds). These values are approximate; the mesher will round them off to define a square mesh in UTM coordinates. When running benchmarks on rectangular models, turn the UTM projection off by using the flag `SUPPRESS_UTM_PROJECTION`, in which case all ‘longitude’ parameters simply refer to the *x* axis, and all ‘latitude’ parameters simply refer to the *y* axis. To run the mesher for a global simulation, the following parameters need to be set in the `Mesh_Par_file`:

**LATITUDE\_MIN** Minimum latitude in the block (negative for South).

**LATITUDE\_MAX** Maximum latitude in the block.

**LONGITUDE\_MIN** Minimum longitude in the block (negative for West).

**LONGITUDE\_MAX** Maximum longitude in the block.

**DEPTH\_BLOCK\_KM** Depth of bottom of mesh in kilometers.

**UTM\_PROJECTION\_ZONE** UTM projection zone in which your model resides, only valid when `SUPPRESS_UTM_PROJECTION` is `.false..`

**SUPPRESS\_UTM\_PROJECTION** set to be `.false.` when your model range is specified in the geographical coordinates, and needs to be `.true.` when your model is specified in a cartesian coordinates. UTM PROJECTION ZONE IN WHICH YOUR SIMULATION REGION RESIDES.

**INTERFACES\_FILE** File in which contains the description of the topography and of the interfaces between the different layers of the model, if any. The number of spectral elements in the vertical direction within each layer is also defined in this file.

**NEX\_XI** The number of spectral elements along one side of the block. This number *must* be  $8 \times$  a multiple of NPROC\_XI defined below. Based upon benchmarks against semi-analytical discrete wavenumber synthetic seismograms [Komatitsch et al., 2004], determined that a `NEX_XI = 288` run is accurate to a shortest period of roughly 2 s. Therefore, since accuracy is determined by the number of grid points per shortest wavelength, for any particular value of `NEX_XI` the simulation will be accurate to a shortest period determined by

$$\text{shortest period (s)} = (288/\text{NEX\_XI}) \times 2. \quad (3.1)$$

The number of grid points in each orthogonal direction of the reference element, i.e., the number of Gauss-Lobatto-Legendre points, is determined by NGLLX in the `constants.h` file. We generally use `NGLLX = 5`, for a total of  $5^3 = 125$  points per elements. We suggest not to change this value.

**NEX\_ETA** The number of spectral elements along the other side of the block. This number *must* be  $8 \times$  a multiple of NPROC\_ETA defined below.

**NPROC\_XI** The number of processors or slices along one side of the block (see Figure 3.5); we must have `NEX_XI = 8 × c × NPROC_XI`, where  $c \geq 1$  is a positive integer.

**NPROC\_ETA** The number of processors or slices along the other side of the block; we must have `NEX_ETA = 8 × c × NPROC_ETA`, where  $c \geq 1$  is a positive integer.

**USE\_REGULAR\_MESH** set to be `.true.` if you want a perfectly regular mesh or `.false.` if you want to add doubling horizontal layers to coarsen the mesh. In this case, you also need to provide additional information by setting up the next three parameters.

**NDOUBLINGS** The number of horizontal doubling layers. Must be set to 1 or 2 if `USE_REGULAR_MESH` is set to `.true..`

**NZ\_DOUBLING\_1** The position of the first doubling layer (only interpreted if `USE_REGULAR_MESH` is set to `.true..`).

**NZ\_DOUBLING\_2** The position of the second doubling layer (only interpreted if `USE_REGULAR_MESH` is set to `.true.` and if `NDOUBLINGS` is set to 2).

**CREATE\_ABAQUS\_FILES** Set this flag to `.true.` to save Abaqus FEA ([www.simulia.com](http://www.simulia.com)) mesh files for subsequent viewing. Turning the flag on generates files in the `LOCAL_PATH` directory. See Section 7.1 for a discussion of mesh viewing features.

**CREATE\_DX\_FILES** Set this flag to `.true.` to save OpenDX ([www.opendx.org](http://www.opendx.org)) mesh files for subsequent viewing.

**LOCAL\_PATH** Directory in which the partitions generated by the mesher will be written. Generally one uses a directory on the local disk of the compute nodes, although on some machines these partitions are written on a parallel (global) file system (see also the earlier discussion of the `LOCAL_PATH_IS_ALSO_GLOBAL` flag in Chapter 2). The mesher generates the necessary partitions in parallel, one set for each of the `NPROC_XI × NPROC_ETA` slices that constitutes the mesh (see Figure 3.5). After the mesher finishes, you can log in to one of the compute nodes and view the contents of the `LOCAL_PATH` directory to see the files generated by the mesher. These files will be needed for creating the distributed databases, and have to reside in the directory `LOCAL_PATH` specified in the main `Par_file`, e.g. in directory `in_out_files/DATABASES_MPI`. Please see Chapter 4 for further details.

**NMATERIALS** The number of different materials in your model. In the following lines, each material needs to be defined as :

```
material_ID rho vp vs Q anisotropy_flag domain_ID
```

where

- $Q : 0 = \text{no attenuation} / \text{standard } Q \text{ attenuation value}$
- $\text{anisotropy\_flag} : 0 = \text{no anisotropy} / 1, 2, \dots \text{ check with implementation in aniso\_model.f90}$
- $\text{domain\_id} : 1 = \text{acoustic} / 2 = \text{elastic} / 3 = \text{poroelastic}$

**NMATERIALS** The number of regions in the mesh. In the following lines, because the mesh is regular or 'almost regular', each region is defined as :

```
XI_begin XI_end ETA_begin ETA_end material_ID
```

The topography of the model is defined as a set of elevation values on a regular 2D grid. It is also possible to define interfaces between the layers of the model in the same way.

The file defined in `INTERFACES_FILE` contains the settings of the topography grid and of the interfaces grids. The number of interfaces, including the topography, needs to be set at the first line. Then, from the bottom to the top of the model, you need to define the grids with several parameters : number of points along  $x$  and  $y$ , minimal  $x$  and  $y$  coordinates, spacing between points and the file in which the elevation values are stored. At the end of this file, you simply need to set the number of spectral elements in the vertical direction for each layer.

Finally, depending on your system, you might need to provide a file that tells MPI what compute nodes to use for the simulations. The file must have a number of entries (one entry per line) at least equal to the number of processors needed for the run. A sample file is provided in the file `mymachines`. This file is not used by the mesher or solver, but is required by the `go_mesher` and `go_solver` default job submission scripts. See Chapter 8 for information about running the code on a system with a scheduler, e.g., LSF.

Now that you have set the appropriate parameters in the `Par_file` and have compiled the mesher, you are ready to launch it! This is most easily accomplished based upon the `go_mesher` script. When you run on a PC cluster, the script assumes that the nodes are named `n001`, `n002`, etc. If this is not the case, change the `tr -d 'n'` line in the script. You may also need to edit the last command at the end of the script that invokes the `mpirun` command. See Chapter 8 for information about running the code on a system with a scheduler, e.g., LSF.

Mesher output is provided in the `in_out_files/OUTPUT_FILES` directory in `output_mesher.txt`; this file provides lots of details about the mesh that was generated. Alternatively, output can be directed to the screen instead by uncommenting a line in `constants.h`:

```
! uncomment this to write messages to the screen
! integer, parameter :: IMAIN = ISTANDARD_OUTPUT
```

The quality of the mesh may be inspected more precisely based upon the serial code in the file `check_mesh_quality_CUBIT_Abaqus.f90`. In the directory `check_mesh_quality_CUBIT_Abaqus`, type

```
make check_mesh_quality_CUBIT_Abaqus
```

and then use

```
xcheck_mesh_quality_CUBIT_Abaqus
```

to generate an AVS output file (`AVS_meshquality.inp` in AVS UCD format) or OpenDX output file (`DX_meshquality.dx`) that can be used to investigate mesh quality, e.g. skewness of elements and a Gnuplot histogram (`mesh_quality_histogram.txt`) that can be plotted with gnuplot (type '`gnuplot plot_mesh_quality_histogram.gnu`'). The histogram is also printed to the screen. If you want to start designing your own meshes, this tool is useful for viewing your creations. You are striving for meshes with elements with 'cube-like' dimensions, e.g., the mesh should contain no very elongated or skewed elements.

Running this code is optional because no information needed by the solver is generated.

# Chapter 4

## Creating the Distributed Databases

Either you previously used `xmeshfem3D` or `xdecompose_mesh_SCOTCH`, the next step in the workflow is to compile `xgenerate_databases`. This program is going to create all the missing information needed by the SEM solver.

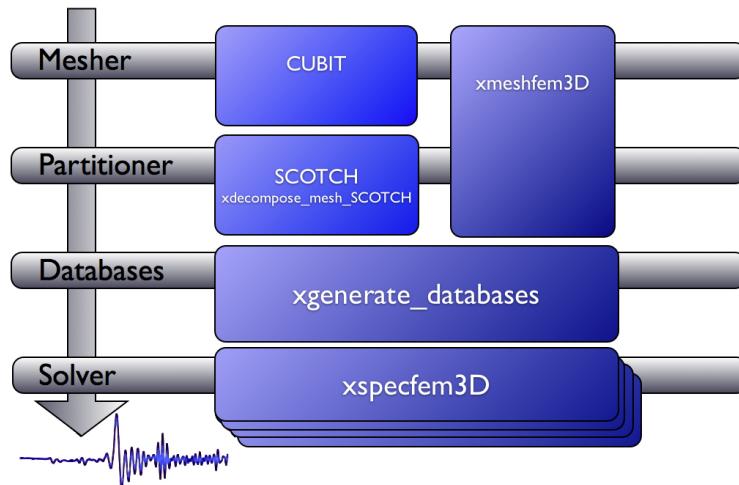


Figure 4.1: Schematic workflow for a SPECFEM3D simulation. The executable `xgenerate_databases` creates the GLL mesh points and assigns the specific model parameters.

In the main directory type 'make generate\_databases'. Input for the program is provided through the main parameter file `Par_file`, which resides in the subdirectory `in_data_files/`. Please note that `xgenerate_databases` must be called directly from the `bin/` directory, as most of the binaries of the package.

### 4.1 Main parameter file `Par_file`

Before running `xgenerate_databases`, a number of parameters need to be set in the main parameter `Par_file` located in the subdirectory `in_data_files/`:

`SIMULATION_TYPE` is set to 1 for forward simulations, 2 for adjoint simulations (see Section 6.2) and 3 for kernel simulations (see Section 7.3).

`SAVE_FORWARD` is only set to `.true.` for a forward simulation with the last frame of the simulation saved, as part of the finite-frequency kernel calculations (see Section 7.3). For a regular forward simulation, leave

**SIMULATION\_TYPE** and **SAVE\_FORWARD** at their default values.

**UTM\_PROJECTION\_ZONE** UTM projection zone in which your model resides, only valid when **SUPPRESS\_UTM\_PROJECTION** is `.false.`.

**SUPPRESS\_UTM\_PROJECTION** set to be `.false.` when your model range is specified in the geographical coordinates, and needs to be `.true.` when your model is specified in a cartesian coordinates. UTM PROJECTION ZONE IN WHICH YOUR SIMULATION REGION RESIDES.

**NPROC** The number of MPI processors, each one is assigned one slice of the whole mesh.

**NSTEP** The number of time steps of the simulation. This controls the length of the numerical simulation, i.e., twice the number of time steps requires twice as much CPU time. This feature is not used at the time of generating the distributed databases but is required for the solver, i.e., you may change this parameter after running `xgenerate_databases`.

**DT** The length of each time step in seconds. This feature is not used at the time of generating the distributed databases but is required for the solver. Please see also Section 4.2 for further details.

**OCEANS** Set to `.true.` if the effect of the oceans on seismic wave propagation should be incorporated based upon the approximate treatment discussed in Komatitsch and Tromp [2002b]. This feature is inexpensive from a numerical perspective, both in terms of memory requirements and CPU time. This approximation is accurate at periods of roughly 20 s and longer. At shorter periods the effect of water phases/reverberations is not taken into account, even when the flag is on.

**ATTENUATION** Set to `.true.` if attenuation should be incorporated. Turning this feature on increases the memory requirements significantly (roughly by a factor of 1.5), and is numerically fairly expensive. See Komatitsch and Tromp [1999, 2002a] for a discussion on the implementation of attenuation based upon standard linear solids. Please note that the Vp- and Vs-velocities of your model are given for a reference frequency. To change this reference frequency, you change the value of **ATTENUATION\_f0\_REFERENCE** in the main constants file `constants.h` found in subdirectory `src/shared/`.

**USE\_OLSEN\_ATTENUATION** Set to `.true.` if you want to use the attenuation model that scaled from the velocity model using Olsen's empirical relation (reference).

**ANISOTROPY** Set to `.true.` if you want to use an anisotropy model. Please see the file `model_aniso.f90` in subdirectory `src/generate_databases/` for the current implementation of anisotropic models.

**ABSORBING\_CONDITIONS** Set to `.true.` to turn on Clayton-Enquist absorbing boundary conditions (see Komatitsch and Tromp [1999]).

**MOVIE\_SURFACE** Set to `.false.`, unless you want to create a movie of seismic wave propagation on the Earth's surface. Turning this option on generates large output files. See Section 7.2 for a discussion on the generation of movies. This feature is only relevant for the solver.

**MOVIE\_VOLUME** Set to `.false.`, unless you want to create a movie of seismic wave propagation in the Earth's interior. Turning this option on generates huge output files. See Section 7.2 for a discussion on the generation of movies. This feature is only relevant for the solver.

**NTSTEP\_BETWEEN\_FRAMES** Determines the number of timesteps between movie frames. Typically you want to save a snapshot every 100 timesteps. The smaller you make this number the more output will be generated! See Section 7.2 for a discussion on the generation of movies. This feature is only relevant for the solver.

**CREATE\_SHAKEMAP** Set this flag to `.true.` to create a ShakeMap®, i.e., a peak ground velocity map of the maximum absolute value of the two horizontal components of the velocity vector.

**SAVE\_DISPLACEMENT** Set this flag to `.true.` if you want to save the displacement instead of velocity for the movie frames.

**USE\_HIGHRES\_FOR\_MOVIES** Set this flag to `.true.` if you want to save the values at all the NGLL grid points for the movie frames.

**HDUR\_MOVIE** determines the half duration of the source time function for the movie simulations. When this parameter is set to be 0, a default half duration that corresponds to the accuracy of the simulation is provided. Otherwise, it adds this half duration to the half duration specified in the source file `CMTSOLUTION`, thus simulates longer periods to make the movie images look smoother.

**SAVE\_MESH\_FILES** Set this flag to `.true.` to save AVS ([www.avs.com](http://www.avs.com)), OpenDX ([www.opendx.org](http://www.opendx.org)), or ParaView ([www.paraview.org](http://www.paraview.org)) mesh files for subsequent viewing. Turning the flag on generates large (distributed) files in the `LOCAL_PATH` directory. See Section 7.1 for a discussion of mesh viewing features.

**LOCAL\_PATH** Directory in which the distributed databases will be written. Generally one uses a directory on the local disk of the compute nodes, although on some machines these databases are written on a parallel (global) file system (see also the earlier discussion of the `LOCAL_PATH_IS ALSO_GLOBAL` flag in Chapter 2). `xgenerate_databases` generates the necessary databases in parallel, one set for each of the `NPROC` slices that constitutes the mesh (see Figure 3.4 and Figure 3.5). After the executable finishes, you can log in to one of the compute nodes and view the contents of the `LOCAL_PATH` directory to see the (many) files generated by `xgenerate_databases`. Please note that the `LOCAL_PATH` directory should already contain the output files of the partitioner, i.e. from `xdecompose_mesh_SCOTCH` or `xmeshfem3D`.

**NTSTEP\_BETWEEN\_OUTPUT\_INFO** This parameter specifies the interval at which basic information about a run is written to the file system (`timestamp*` files in the `in_out_files/OUTPUT_FILES` directory). If you have access to a fast machine, set `NTSTEP_BETWEEN_OUTPUT_INFO` to a relatively high value (e.g., at least 100, or even 1000 or more) to avoid writing output text files too often. This feature is not used at the time of meshing. One can set this parameter to a larger value than the number of time steps to avoid writing output during the run.

**NTSTEP\_BETWEEN\_OUTPUT\_SEISMOS** This parameter specifies the interval at which synthetic seismograms are written in the `LOCAL_PATH` directory. If a run crashes, you may still find usable (but shorter than requested) seismograms in this directory. On a fast machine set `NTSTEP_BETWEEN_OUTPUT_SEISMOS` to a relatively high value to avoid writing to the seismograms too often. This feature is only relevant for the solver.

**PRINT\_SOURCE\_TIME\_FUNCTION** Turn this flag on to print information about the source time function in the file `in_out_files/OUTPUT_FILES/plot_source_time_function.txt`. This feature is only relevant for the solver.

## 4.2 Choosing the time step DT

The parameter `DT` sets the length of each time step in seconds. The value of this parameter is crucial for the stability of the spectral-element simulation. Your time step `DT` will depend on the minimum ratio between the distance  $h$  of neighboring mesh points and the wave speeds  $v$  defined in your model. The condition for the time step  $\Delta t$  is:

$$\Delta t < C \min_{\Omega} ( h/v )$$

where  $C$  is the so-called Courant number and  $\Omega$  denotes the model volume. The distance  $h$  depends on the mesh element size and the number of GLL points `NGLL` specified in the main constants file `constants.h` located in the `src/shared/` subdirectory. The wave speed  $v$  is determined based on your model's P- (or S-) velocity values.

The database generator `xgenerate_databases`, as well as the internal mesher `xmeshfem3D`, are trying to evaluate the value of  $\Delta t$  for empirically chosen Courant numbers  $C \sim 0.3$ . If you used the mesher `xmeshfem3D` to generate your mesh, you should set the value suggested in `in_out_files/OUTPUT_FILES/output_mesher.txt` file, which is created after the mesher completed. In case you used CUBIT to create the mesh, you might use an arbitrary value when running `xgenerate_databases` and then use the value suggested in the `in_out_files/OUTPUT_FILES/output_mesher.txt` file after the database generation completed. Note that the implemented Newmark time scheme uses this time step globally, thus your simulations become more expensive for very small mesh elements in high wave-speed regions. Please be aware of this restriction when constructing your mesh in Chapter 3.

# Chapter 5

## Running the Solver `xspecfem3D`

Now that you have successfully generated the databases, you are ready to compile the solver. In the main directory type ‘`make specfem3D`’. Please note that `xspecfem3D` must be called directly from the `bin/` directory, as most of the binaries of the package.

The solver needs three input files in the `in_data_files/` directory to run:

**Par\_file** the main parameter file which was discussed in detail in the previous Chapter 4,

**CMTSOLUTION** the earthquake source parameter file, and

**STATIONS** the stations file.

Most parameters in the `Par_file` should be set prior to running the databases generation. Only the following parameters may be changed after running `xgenerate_databases`:

- the simulation type control parameters: `SIMULATION_TYPE` and `SAVE_FORWARD`
- the time step parameters `NSTEP` and `DT`
- the attenuation control parameters `ATTENUATION` and `USE_OLSEN_ATTENUATION`
- the absorbing boundary control parameter `ABSORBING_CONDITIONS`
- the movie control parameters `MOVIE_SURFACE`, `MOVIE_VOLUME`, and `NTSTEPS_BETWEEN_FRAMES`
- the ShakeMap®option `CREATE_SHAKEMAP`
- the output information parameters `NTSTEP_BETWEEN_OUTPUT_INFO` and `NTSTEP_BETWEEN_OUTPUT_SEISMOS`
- the `PRINT_SOURCE_TIME_FUNCTION` flags

Any other change to the `Par_file` implies rerunning both the database generator `xgenerate_databases` and the solver `xspecfem3D`.

For any particular earthquake, the `CMTSOLUTION` file that represents the point source may be obtained directly from the Harvard Centroid-Moment Tensor (CMT) web page ([www.seismology.harvard.edu](http://www.seismology.harvard.edu)). It looks like this:

Preliminary Determination of Epicenter										body-wave magnitude	surface-wave magnitude
year	month	day	hour	min	sec	latitude	longitude	depth	mb	Ms	PDE event name
PDE	2001	9	9	23	59	17.78	34.0745	-118.3792	6.4	4.2	4.2 HOLLYWOOD
event name:											
time shift:											
half duration:											
latitude:											
longitude:											
depth:											
Mrr:											
Mtt:											
Mpp:											
Mrt:											
Mrp:											
Mtp:											

Harvard CMT solution

$$\mathbf{M} = \begin{bmatrix} M_{rr} & M_{r\theta} & M_{r\phi} \\ M_{r\theta} & M_{\theta\theta} & M_{\theta\phi} \\ M_{r\phi} & M_{\theta\phi} & M_{\phi\phi} \end{bmatrix}$$

$$M_0 = \frac{1}{\sqrt{2}} (\mathbf{M} : \mathbf{M})^{1/2} \approx 2.18 \times 10^{22} \text{ dyne cm}$$

$$M_w = \frac{2}{3} (\log_{10} M_0 - 16.1) \approx 4.19$$

Figure 5.1: CMTSOLUTION file based on the format from the Harvard CMT catalog.  $\mathbf{M}$  is the moment tensor,  $M_0$  is the seismic moment, and  $M_w$  is the moment magnitude.

The CMTSOLUTION should be edited in the following way:

- Set the time shift parameter equal to 0.0 (the solver will not run otherwise.) The time shift parameter would simply apply an overall time shift to the synthetics, something that can be done in the post-processing (see Section 9.1).
- For point-source simulations (see finite sources, page 20) we recommend setting the source half-duration parameter half duration equal to zero, which corresponds to simulating a step source-time function, i.e., a moment-rate function that is a delta function. If half duration is not set to zero, the code will use a Gaussian (i.e., a signal with a shape similar to a ‘smoothed triangle’, as explained in Komatitsch and Tromp [2002a] and shown in Fig 5.2) source-time function with half-width half duration. We prefer to run the solver with half duration set to zero and convolve the resulting synthetic seismograms in post-processing after the run, because this way it is easy to use a variety of source-time functions (see Section 9.1). Komatitsch and Tromp [2002a] determined that the noise generated in the simulation by using a step source time function may be safely filtered out afterward based upon a convolution with the desired source time function and/or low-pass filtering. Use the serial code `convolve_source_timefunction.f90` and the script `convolve_source_timefunction.csh` for this purpose, or alternatively use signal-processing software packages such as SAC ([www.llnl.gov/sac](http://www.llnl.gov/sac)). Type

```
make convolve_source_timefunction
```

to compile the code and then set the parameter hdur in `convolve_source_timefunction.csh` to the desired half-duration.

- The zero time of the simulation corresponds to the center of the triangle/Gaussian, or the centroid time of the earthquake. The start time of the simulation is  $t = -1.5 * \text{half duration}$  (the 1.5 is to make sure the moment rate function is very close to zero when starting the simulation). To convert to absolute time  $t_{\text{abs}}$ , set

$$t_{\text{abs}} = t_{\text{pde}} + \text{time shift} + t_{\text{synthetic}}$$

where  $t_{\text{pde}}$  is the time given in the first line of the CMTSOLUTION, time shift is the corresponding value from the original CMTSOLUTION file and  $t_{\text{synthetic}}$  is the time in the first column of the output seismogram.

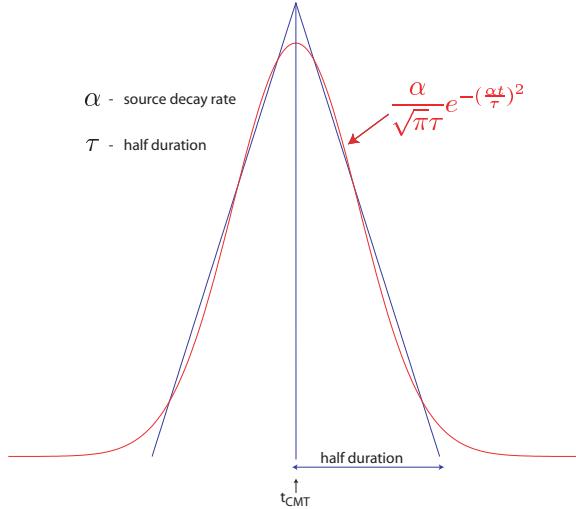


Figure 5.2: Comparison of the shape of a triangle and the Gaussian function actually used.

Centroid latitude and longitude should be provided in geographical coordinates. The code converts these coordinates to geocentric coordinates [Dahlen and Tromp, 1998]. Of course you may provide your own source representations by designing your own CMTSOLUTION file. Just make sure that the resulting file adheres to the Harvard CMT conventions (see Appendix A). Note that the first line in the CMTSOLUTION file is the Preliminary Determination of Earthquakes (PDE) solution performed by the USGS NEIC, which is used as a seed for the Harvard CMT inversion. The PDE solution is based upon P waves and often gives the hypocenter of the earthquake, i.e., the rupture initiation point, whereas the CMT solution gives the ‘centroid location’, which is the location with dominant moment release. The PDE solution is not used by our software package but must be present anyway in the first line of the file.

To simulate a kinematic rupture, i.e., a finite-source event, represented in terms of  $N_{\text{sources}}$  point sources, provide a CMTSOLUTION file that has  $N_{\text{sources}}$  entries, one for each subevent (i.e., concatenate  $N_{\text{sources}}$  CMTSOLUTION files to a single CMTSOLUTION file). At least one entry (not necessarily the first) must have a zero time shift, and all the other entries must have non-negative time shift. Each subevent can have its own half duration, latitude, longitude, depth, and moment tensor (effectively, the local moment-density tensor).

Note that the zero in the synthetics does NOT represent the hypocentral time or centroid time in general, but the timing of the *center* of the source triangle with zero time shift (Fig 5.3).

Although it is convenient to think of each source as a triangle, in the simulation they are actually Gaussians (as they have better frequency characteristics). The relationship between the triangle and the gaussian used is shown in Fig 5.2. For finite fault simulations it is usually not advisable to use a zero half duration and convolve afterwards, since the half duration is generally fixed by the finite fault model.

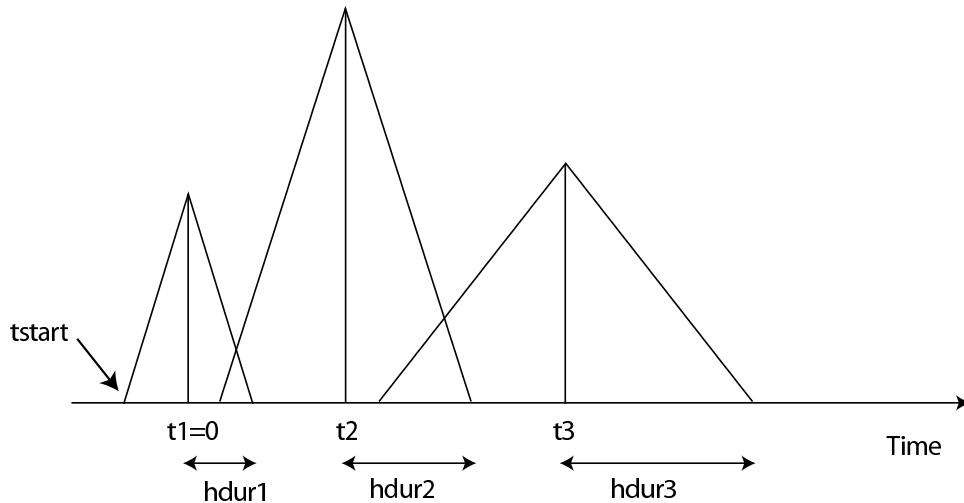


Figure 5.3: Example of timing for three sources. The center of the first source triangle is defined to be time zero. Note that this is NOT in general the hypocentral time, or the start time of the source (marked as `tstart`). The parameter `time shift` in the `CMTSOLUTION` file would be  $t1(=0)$ ,  $t2$ ,  $t3$  in this case, and the parameter `half duration` would be `hdur1`, `hdur2`, `hdur3` for the sources 1, 2, 3 respectively.

The solver can calculate seismograms at any number of stations for basically the same numerical cost, so the user is encouraged to include as many stations as conceivably useful in the `STATIONS` file, which looks like this:

Station	Network		Longitude (deg)		Burial (m)	
			Latitude (deg)	Elevation (m)		
ASBS	AZ	33.6208	-116.4664	0.0	0.0	
BZN	AZ	33.4915	-116.6670	0.0	0.0	
CRY	AZ	33.5654	-116.7373	0.0	0.0	
ELKS	AZ	33.5813	-116.4496	0.0	0.0	
AGA	CI	33.6384	-116.4011	0.0	0.0	
AGO	CI	34.1465	-118.7670	0.0	0.0	
ALP	CI	34.6870	-118.2995	0.0	0.0	
BAK	CI	35.3444	-119.1044	0.0	0.0	
BAR	CI	32.6801	-116.6722	0.0	0.0	
BBA	CI	34.1955	-118.3534	0.0	0.0	
BBB	CI	33.3526	-115.7332	0.0	0.0	
BBR	CI	34.2623	-116.9207	0.0	0.0	
BBS	CI	33.9214	-116.9805	0.0	0.0	
:	:	:	:	:	:	:

Figure 5.4: Sample `STATIONS` file. Station latitude and longitude should be provided in geographical coordinates. The width of the station label should be no more than 32 characters (see `MAX_LENGTH_STATION_NAME` in the `constants.h` file), and the network label should be no more than 8 characters (see `MAX_LENGTH_NETWORK_NAME` in the `constants.h` file).

Each line represents one station in the following format:

```
Station Network Latitude (degrees) Longitude (degrees) Elevation (m) burial (m)
```

The solver xspecfem3D filters the list of stations in file `in_data_files/STATIONS` to exclude stations that are not located within the region given in the `Par_file` (between `LATITUDE_MIN` and `LATITUDE_MAX` and between `LONGITUDE_MIN` and `LONGITUDE_MAX`). The filtered file is called `in_data_files/STATIONS_FILTERED`.

Solver output is provided in the `in_out_files/OUTPUT_FILES` directory in the `output_solver.txt` file. Output can be directed to the screen instead by uncommenting a line in `constants.h`:

```
! uncomment this to write messages to the screen
! integer, parameter :: IMAIN = ISTANDARD_OUTPUT
```

On PC clusters the seismogram files are generally written to the local disks (the path `LOCAL_PATH` in the `Par_file`) and need to be gathered at the end of the simulation.

While the solver is running, its progress may be tracked by monitoring the ‘`timestamp*`’ files in the `in_out_files/OUTPUT_FILES` directory. These tiny files look something like this:

```
Time step #      10000
Time:    108.4890      seconds
Elapsed time in seconds =   1153.28696703911
Elapsed time in hh:mm:ss =   0 h 19 m 13 s
Mean elapsed time per time step in seconds =   0.115328696703911
Max norm displacement vector U in all slices (m) =   1.0789589E-02
```

The `timestamp*` files provide the Mean elapsed time per time step in seconds, which may be used to assess performance on various machines (assuming you are the only user on a node), as well as the Max norm displacement vector `U` in all slices (m). If something is wrong with the model, the mesh, or the source, you will see the code become unstable through exponentially growing values of the displacement and fluid potential with time, and ultimately the run will be terminated by the program. You can control the rate at which the `timestamp` files are written based upon the parameter `NTSTEP_BETWEEN_OUTPUT_INFO` in the `Par_file`.

Having set the `Par_file` parameters, and having provided the `CMTSOLUTION` and `STATIONS` files, you are now ready to launch the solver! This is most easily accomplished based upon the `go_solver` script (See Chapter 8 for information about running through a scheduler, e.g., LSF). You may need to edit the last command at the end of the script that invokes the `mpirun` command. The `runall` script compiles and runs both `xgenerate_databases` and `xspecfem3D` in sequence. This is a safe approach that ensures using the correct combination of distributed database output and solver input.

It is important to realize that the CPU and memory requirements of the solver are closely tied to choices about attenuation (`ATTENUATION`) and the nature of the model (i.e., isotropic models are cheaper than anisotropic models). We encourage you to run a variety of simulations with various flags turned on or off to develop a sense for what is involved.

For the same model, one can rerun the solver for different events by simply changing the `CMTSOLUTION` file, or for different stations by changing the `STATIONS` file. There is no need to rerun the `xgenerate_databases` executable. Of course it is best to include as many stations as possible, since this does not add to the cost of the simulation.

# Chapter 6

## Adjoint Simulations

Adjoint simulations are generally performed for two distinct applications. First, they can be used for earthquake source inversions, especially earthquakes with large ruptures such as the Lander's earthquake [Wald and Heaton, 1994]. Second, they can be used to generate finite-frequency sensitivity kernels that are a critical part of tomographic inversions based upon 3D reference models [Tromp et al., 2005, Liu and Tromp, 2006, Tromp et al., 2008, Liu and Tromp, 2008]. In either case, source parameter or velocity structure updates are sought to minimize a specific misfit function (e.g., waveform or traveltime differences), and the adjoint simulation provides a means of computing the gradient of the misfit function and further reducing it in successive iterations. Applications and procedures pertaining to source studies and finite-frequency kernels are discussed in Sections 6.1 and 6.2, respectively. The two related parameters in the `Par_file` are `SIMULATION_TYPE` (1 or 2) and the `SAVE_FORWARD` (boolean).

### 6.1 Adjoint Simulations for Sources

In the case where a specific misfit function is minimized to invert for the earthquake source parameters, the gradient of the misfit function with respect to these source parameters can be computed by placing time-reversed seismograms at the receivers and using them as sources in an adjoint simulation, and then the value of the gradient is obtained from the adjoint seismograms recorded at the original earthquake location.

#### 1. Prepare the adjoint sources

- (a) First, run a regular forward simulation (`SIMULATION_TYPE = 1` and `SAVE_FORWARD = .false.`). You can automatically set these two variables using the `UTILS/change_simulation_type.pl` script:

```
UTILS/change_simulation_type.pl -f
```

and then collect the recorded seismograms at all the stations given in `in_data_files/STATIONS`.

- (b) Then select the stations for which you want to compute the time-reversed adjoint sources and run the adjoint simulation, and compile them into the `in_data_files/STATIONS_ADJOINT` file, which has the same format as the regular `in_data_files/STATIONS` file.

- Depending on what type of misfit function is used for the source inversion, adjoint sources need to be computed from the original recorded seismograms for the selected stations and saved in the `SEM/` directory with the format `STA.NT.BH?.adj`, where STA, NT are the station name and network code given in the `in_data_files/STATIONS_ADJOINT` file, and BH? represents the component name of a particular adjoint seismogram.
- The adjoint seismograms are in the same format as the original seismogram (`STA.NT.BH?.sem?`), with the same start time, time interval and record length.

- (c) Notice that even if you choose to time reverse only one component from one specific station, you still need to supply all three components because the code is expecting them (you can set the other two components to be zero).

- (d) Also note that since time-reversal is done in the code itself, no explicit time-reversing is needed for the preparation of the adjoint sources, i.e., the adjoint sources are in the same forward time sense as the original recorded seismograms.

## 2. Set the related parameters and run the adjoint simulation

In the `in_data_files/Par_file`, set the two related parameters to be `SIMULATION_TYPE = 2` and `SAVE_FORWARD = .false.`. More conveniently, use the scripts `UTILS/change_simulation_type.pl` to modify the `Par_file` automatically (`change_simulation_type.pl -a`). Then run the solver to launch the adjoint simulation.

## 3. Collect the seismograms at the original source location

After the adjoint simulation has completed successfully, collect the seismograms from `LOCAL_PATH`.

- These adjoint seismograms are recorded at the locations of the original earthquake sources given by the `in_data_files/CMTSOLUTION` file, and have names of the form `S?????.NT.S???.sem` for the six-component strain tensor (`SNN, SEE, SZZ, SNE, SNZ, SEZ`) at these locations, and `S?????.NT.BH?.sem` for the three-component displacements (`BHN, BHE, BHZ`) recorded at these locations.
- `S?????` denotes the source number; for example, if the original `CMTSOLUTION` provides only a point source, then the seismograms collected will start with `S00001`.
- These adjoint seismograms provide critical information for the computation of the gradient of the misfit function.

## 6.2 Adjoint Simulations for Finite-Frequency Kernels (Kernel Simulation)

Finite-frequency sensitivity kernels are computed in two successive simulations (please refer to Liu and Tromp [2006] and Tromp et al. [2008] for details).

### 1. Run a forward simulation with the state variables saved at the end of the simulation

Prepare the `CMTSOLUTION` and `STATIONS` files, set the parameters `SIMULATION_TYPE = 1` and `SAVE_FORWARD = .true.` in the `Par_file` (`change_simulation_type -F`), and run the solver.

- Notice that attenuation is not implemented yet for the computation of finite-frequency kernels; therefore set `ATTENUATION = .false.` in the `Par_file`.
- We also suggest you modify the half duration of the `CMTSOLUTION` to be similar to the accuracy of the simulation (see Equation 3.1) to avoid too much high-frequency noise in the forward wavefield, although theoretically the high-frequency noise should be eliminated when convolved with an adjoint wavefield with the proper frequency content.
- This forward simulation differs from the regular simulations (`SIMULATION_TYPE = 1` and `SAVE_FORWARD = .false.`) described in the previous chapters in that the state variables for the last time step of the simulation, including wavefields of the displacement, velocity, acceleration, etc., are saved to the `LOCAL_PATH` to be used for the subsequent simulation.
- For regional simulations, the files recording the absorbing boundary contribution are also written to the `LOCAL_PATH` when `SAVE_FORWARD = .true..`

### 2. Prepare the adjoint sources

The adjoint sources need to be prepared the same way as described in the Section 1.

- In the case of travel-time finite-frequency kernel for one source-receiver pair, i.e., point source from the `CMTSOLUTION`, and one station in the `STATIONS_ADJOINT` list, we supply a sample program in `UTILS/xcut_velocity` to cut a certain portion of the original displacement seismograms and convert it into the proper adjoint source to compute the finite-frequency kernel.

```
xcut_velocity t1 t2 ifile[0-5] E/N/Z-ascii-files [baz]
```

where  $t_1$  and  $t_2$  are the start and end time of the portion you are interested in, `ifile` denotes the component of the seismograms to be used (0 for all three components, 1 for East, 2 for North, and 3 for vertical, 4 for transverse, and 5 for radial component), `E/N/Z-ascii-files` indicate the three-component displacement seismograms in the right order, and `baz` is the back-azimuth of the station. Note that `baz` is only supplied when `ifile = 4 or 5`.

### 3. Run the kernel simulation

With the successful forward simulation and the adjoint source ready in `SEM/`, set `SIMULATION_TYPE = 3` and `SAVE_FORWARD = .false.` in the `Par_file(change_simulation_type.pl -b)`, and rerun the solver.

- The adjoint simulation is launched together with the back reconstruction of the original forward wavefield from the state variables saved from the previous forward simulation, and the finite-frequency kernels are computed by the interaction of the reconstructed forward wavefield and the adjoint wavefield.
- The back-reconstructed seismograms at the original station locations are saved to the `LOCAL_PATH` at the end of the kernel simulations, and can be collected to the local disk.
- These back-constructed seismograms can be compared with the time-reversed original seismograms to assess the accuracy of the backward reconstruction, and they should match very well.
- The arrays for density, P-wave speed and S-wave speed kernels are also saved in the `LOCAL_PATH` with the names `proc??????_rho(alpha,beta)_kernel.bin`, where `proc???????` represents the processor number, `rho(alpha,beta)` are the different types of kernels.

In general, the three steps need to be run sequentially to assure proper access to the necessary files. If the simulations are run through some cluster scheduling system (e.g., LSF), and the forward simulation and the subsequent kernel simulations cannot be assigned to the same set of computer nodes, the kernel simulation will not be able to access the database files saved by the forward simulation. Solutions for this dilemma are provided in Chapter 8. Visualization of the finite-frequency kernels is discussed in Section 7.3.

# Chapter 7

# Graphics

## 7.1 Meshes

Use the serial code `combine_AVSDX.f90` (type ‘`make combine_AVSDX`’ and then ‘`xcombine_AVSDX`’) to generate AVS ([www.avs.com](http://www.avs.com)) output files (in AVS UCD format) or OpenDX ([www.opendx.org](http://www.opendx.org)) output files showing the mesh, the MPI partition (slices), the NCHUNKS chunks, the source and receiver location, etc. Use the AVS UCD files `AVS_continent_boundaries.inp` and `AVS_plate_boundaries.inp` or the OpenDX files `DX_continent_boundaries.dx` and `DX_plate_boundaries.dx` for reference.

## 7.2 Movies

To make a surface or volume movie of the simulation, set parameters `MOVIE_SURFACE`, `MOVIE_VOLUME`, and `NTSTEP_BETWEEN_FRAMES` in the `Par_file`. Turning on the movie flags, in particular `MOVIE_VOLUME`, produces large output files. `MOVIE_VOLUME` files are saved in the `LOCAL_PATH` directory, whereas `MOVIE_SURFACE` output files are saved in the `in_out_files/OUTPUT_FILES` directory. We save the velocity field. The look of a movie is determined by the half-duration of the source. The half-duration should be large enough so that the movie does not contain frequencies that are not resolved by the mesh, i.e., it should not contain numerical noise. This can be accomplished by selecting a CMT `HALF_DURATION > 1.1 × smallest period` (see figure 5.1). When `MOVIE_SURFACE = .true.`, the half duration of each source in the `CMTSOLUTION` file is replaced by

$$\sqrt{(\text{HALF_DURATION}^2 + \text{HDUR_MOVIE}^2)}$$

**NOTE:** If `HDUR_MOVIE` is set to 0.0, the code will select the appropriate value of  $1.1 \times \text{smallest period}$ . As usual, for a point source one can set `HALF_DURATION` in the `Par_file` to be 0.0 and `HDUR_MOVIE = 0.0` to get the highest frequencies resolved by the simulation, but for a finite source one would keep all the `HALF_DURATIONS` as prescribed by the finite source model and set `HDUR_MOVIE = 0.0`.

### 7.2.1 Movie Surface

When running `xspecfem3D` with the `MOVIE_SURFACE` flag turned on, the code outputs `moviedata?????` files in the `in_out_files/OUTPUT_FILES` directory. The files are in a fairly complicated binary format, but there are two programs provided to convert the output into more user friendly formats. The first one, `create_movie_AVSDX.f90`, outputs data in ASCII, OpenDX, AVS, or ParaView format. Run the code from the source directory (type ‘`make create_movie_AVSDX`’ first) to create an input file in your format of choice. The code will prompt the user for input parameters. The second program `create_movie_GMT.f90` outputs ascii xyz files, convenient for use with GMT. This code uses significantly less memory than `create_movie_AVSDX.f90` and is therefore useful for high resolution runs.

The SPECFEM3D code is running in near real-time to produce animations of southern California earthquakes via the web; see Southern California ShakeMovie®([www.shakemovie.caltech.edu](http://www.shakemovie.caltech.edu)).

## 7.3 Finite-Frequency Kernels

The finite-frequency kernels computed as explained in Section 6.2 are saved in the `LOCAL_PATH` at the end of the simulation. Therefore, we first need to collect these files on the front end, combine them into one mesh file, and visualize them with some auxilliary programs.

### 1. Create slice files

We will only discuss the case of one source-receiver pair, i.e., the so-called banana-doughnut kernels. Although it is possible to collect the kernel files from all slices on the front end, it usually takes up too much storage space (at least tens of gigabytes). Since the sensitivity kernels are the strongest along the source-receiver great circle path, it is sufficient to collect only the slices that are along or close to the great circle path.

A Perl script `UTILS/slice_number.pl` that calls MATLAB can help to figure out the slice numbers that lie along the great circle path (both the minor and major arcs), as well as the slice numbers required to produce a full picture of the inner core if your kernel also illuminates the inner core.

- (a) On machines where you have MATLAB access, copy the `CMTSOLUTION` file, `STATIONS_ADJOINT`, and `Par_file`, and run:

```
UTILS/slice_number.pl Par_file output_solver.txt slice_file
```

which will generate a `slices_file`.

- (b) For cases with multiple sources and multiple receivers, you need to provide a slice file before proceeding to the next step.

### 2. Collect the kernel files

After obtaining the slice files, you can collect the corresponding kernel files from the given slices.

- (a) You can use or modify the script `UTILS/copy_databases.pl` to accomplish this:

```
UTILS/copy_database.pl slice_file lsf_machine_file filename [jobid]
```

where `lsf_machine_file` is the machine file generated by the LSF scheduler, `filename` is the kernel name (e.g., `rho_kernel`, `alpha_kernel` and `beta_kernel`), and the optional `jobid` is the name of the subdirectory under `LOCAL_PATH` where all the kernel files are stored.

- (b) After executing this script, all the necessary mesh topology files as well as the kernel array files are collected to the local directory of the front end.

### 3. Combine kernel files into one mesh file

We use an auxilliary program `combine_paraview_data.f90` to combine the kernel files from all slices into one mesh file.

- (a) Compile it in the global code directory:

```
make combine_paraview_data
xcombine_paraview_data slice_list filename input_dir output_dir high/low-resolution
```

where `input_dir` is the directory where all the individual kernel files are stored, and `output_dir` is where the mesh file will be written.

- (b) Use 1 for a high-resolution mesh, outputting all the GLL points to the mesh file, or use 0 for low resolution, outputting only the corner points of the elements to the mesh file.
- (c) The output mesh file will have the name `filename_rho(alpha,beta).mesh`

### 4. Convert mesh files into .vtu files

- (a) We next convert the `.mesh` file into the VTU (Unstructured grid file) format which can be viewed in ParaView, for example:

```
UTILS/mesh2vtu.pl -i file.mesh -o file.vtu
```

- (b) Notice that this Perl script uses a program `mesh2vtu` in the `UTILS/mesh2vtu` directory, which further uses the VTK (<http://www.vtk.org/>) run-time library for its execution. Therefore, make sure you have them properly set in the script according to your system.

### 5. Copy over the source and receiver .vtk file

In the case of a single source and a single receiver, the simulation also generates the file `sr.vtk` located in the `in_out_files/OUTPUT_FILES/` directory to describe the source and receiver locations, which can also be viewed in Paraview in the next step.

### 6. View the mesh in ParaView

Finally, we can view the mesh in ParaView ([www.paraview.org](http://www.paraview.org)).

- (a) Open ParaView.
- (b) From the top menu, File → Open data, select `file.vtu`, and click the Accept button.
  - If the mesh file is of moderate size, it shows up on the screen; otherwise, only the bounding box is shown.
- (c) Click Display Tab → Display Style → Representation and select wireframe or surface to display it.
- (d) To create a cross-section of the volumetric mesh, choose Filter → cut, and under Parameters Tab, choose Cut Function → plane.
- (e) Fill in center and normal information given by the `global_slice_number.pl` script (either from the standard output or from `normal_plane.txt` file).
- (f) To change the color scale, go to Display Tab → Color → Edit Color Map and reselect lower and upper limits, or change the color scheme.
- (g) Now load in the source and receiver location file by File → Open data, select `sr.vtk`, and click the Accept button. Choose Filter → Glyph, and represent the points by ‘spheres’.
- (h) For more information about ParaView, see the ParaView Users Guide ([www.paraview.org/files/v1.6/ParaViewUsersGuide.PDF](http://www.paraview.org/files/v1.6/ParaViewUsersGuide.PDF)).

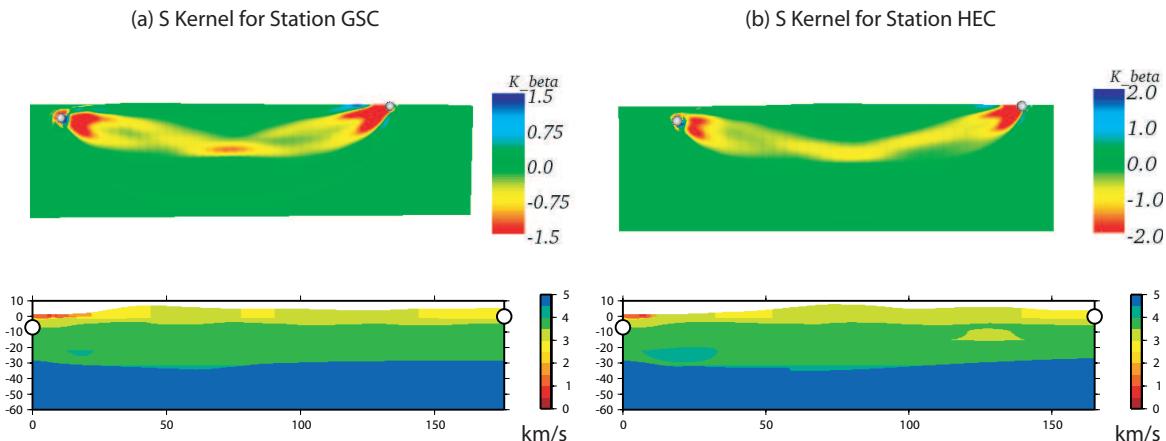


Figure 7.1: (a) Top Panel: Vertical source-receiver cross-section of the S-wave finite-frequency sensitivity kernel  $K_\beta$  for station GSC at an epicentral distance of 176 km from the September 3, 2002, Yorba Linda earthquake. Lower Panel: Vertical source-receiver cross-section of the 3D S-wave velocity model used for the spectral-element simulations [Komatitsch et al., 2004]. (b) The same as (a) but for station HEC at an epicentral distance of 165 km [Liu and Tromp, 2006].

# Chapter 8

## Running through a Scheduler

The code is usually run on large parallel machines, often PC clusters, most of which use schedulers, i.e., queuing or batch management systems to manage the running of jobs from a large number of users. The following considerations need to be taken into account when running on a system that uses a scheduler:

- The processors/nodes to be used for each run are assigned dynamically by the scheduler, based on availability. Therefore, in order for the `xgenerate_databases` and the `xspecfem3D` executables (or between successive runs of the solver) to have access to the same database files (if they are stored on hard drives local to the nodes on which the code is run), they must be launched in sequence as a single job.
- On some systems, the nodes to which running jobs are assigned are not configured for compilation. It may therefore be necessary to pre-compile both the `xgenerate_databases` and the `xspecfem3D` executables.
- One feature of schedulers/queuing systems is that they allow submission of multiple jobs in a “launch and forget” mode. In order to take advantage of this property, care needs to be taken that output and intermediate files from separate jobs do not overwrite each other, or otherwise interfere with other running jobs.

Examples of job scripts can be found in `UTILS/Cluster/` directory and can straightforwardly be modified and adapted to meet more specific running needs.

We describe here in some detail a job submission procedure for the Caltech 1024-node cluster, CITerra, under the LSF scheduling system. We consider the submission of a regular forward simulation using the internal mesher to create mesh partitions. The two main scripts are `run_lsf.bash`, which compiles the Fortran code and submits the job to the scheduler, and `go_mesher_solver_lsf_basin.forward`, which contains the instructions that make up the job itself. These scripts can be found in `UTILS/Cluster/lsf/` directory

### 8.1 Job submission `run_lsf.bash`

This script first sets the job queue to be ‘normal’. It then compiles the mesher, database generator and solver together, figures out the number of processors required for this simulation from the `in_data_files/Par_file`, and submits the LSF job.

```
#!/bin/bash
# use the normal queue unless otherwise directed queue="-q normal"
if [ $# -eq 1 ]; then
    echo "Setting the queue to $1"
    queue="-q $1"
fi

# compile the mesher and the solver
d='date' echo "Starting compilation $d"
make clean
```

```

make meshfem3D
make generate_databases
make specfem3D
d='date'
echo "Finished compilation $d"

# get total number of nodes needed for solver
NPROC=`grep NPROC in_data_files/Par_file | cut -c 34- `

# compute total number of nodes needed for mesher
NPROC_XI=`grep NPROC_XI in_data_files/meshfem3D_files/Mesh_Par_file | cut -c 34- `
NPROC_ETA=`grep NPROC_ETA in_data_files/meshfem3D_files/Mesh_Par_file | cut -c 34- `
# total number of nodes is the product of the values read
numnodes=$(( $NPROC_XI * $NPROC_ETA ))

# checks total number of nodes
if [ $numnodes -neq $NPROC ]; then
    echo "error number of procs mismatch"
    exit
fi

echo "Submitting job"
bsub $queue -n $numnodes -W 60 -K <go_mesher_solver_lsf.forward

```

## 8.2 Job script go\_mesher\_solver\_lsf.forward

This script describes the job itself, including setup steps that can only be done once the scheduler has assigned a job-ID and a set of compute nodes to the job, the `run_lsf.bash` commands used to run the mesher, database generator and the solver, and calls to scripts that collect the output seismograms from the compute nodes and perform clean-up operations.

1. First the script directs the scheduler to save its own output and output from `stdout` into `in_out_files/OUTPUT_FILES/%J.o`, where `%J` is short-hand for the job-ID; it also tells the scheduler what version of `mpich` to use (`mpich_gm`) and how to name this job (`go_mesher_solver_lsf`).
2. The script then creates a list of the nodes allocated to this job by echoing the value of a dynamically set environment variable `LSB_MCPU_HOSTS` and parsing the output into a one-column list using the Perl script `UTILS/remap_lsf_machines.pl`. It then creates a set of scratch directories on these nodes (`/scratch/$USER/DATABASES_MPI`) to be used as the `LOCAL_PATH` for temporary storage of the database files. The scratch directories are created using `shmux`, a shell multiplexor that can execute the same commands on many hosts in parallel. `shmux` is available from Shmux (`web.taranis.org/shmux/`). Make sure that the `LOCAL_PATH` parameter in `in_data_files/Par_file` is also set properly.
3. The next portion of the script launches the mesher, database generator and then the solver using `run_lsf.bash`.
4. The final portion of the script collects the seismograms and performs clean up on the nodes, using the Perl scripts `collect_seismo_lsf_multi.pl` and `cleanmulti.pl`.

```

#!/bin/bash -v
#BSUB -o in_out_files/OUTPUT_FILES/%J.o
#BSUB -a mpich_gm
#BSUB -J go_mesher_solver_lsf

# set up local scratch directories
BASEMPIDIR=/scratch/$USER/DATABASES_MPI

```

```
mkdir -p in_out_files/OUTPUT_FILES
echo "$LSB MCPU_HOSTS" > in_out_files/OUTPUT_FILES/lsf_machines
echo "$LSB_JOBID" > in_out_files/OUTPUT_FILES/jobid
remap_lsf_machines.pl in_out_files/OUTPUT_FILES/lsf_machines >
in_out_files/OUTPUT_FILES/machines
shmux -M50 -Sall -c "rm -r -f /scratch/$USER; \
mkdir -p /scratch/$USER; mkdir -p $BASEMPIDIR" \
- < in_out_files/OUTPUT_FILES/machines >/dev/null

# run the specfem program
current_pwd=$PWD
cd bin/
run_lsf.bash --gm-no-shmem --gm-copy-env $current_pwd/xmeshfem3D
run_lsf.bash --gm-no-shmem --gm-copy-env $current_pwd/xgenerate_databases
run_lsf.bash --gm-no-shmem --gm-copy-env $current_pwd/xspecfem3D

# collect seismograms and clean up
cd current_pwd/
mkdir -p in_out_files/SEM
cd in_out_files/SEM/
collect_seismo.pl ../OUTPUT_FILES/lsf_machines
cleanbase.pl ../OUTPUT_FILES/machines
```

# Chapter 9

## Post-Processing Scripts

Several post-processing scripts/programs are provided in the `UTILS/` directory, and most of them need to be adjusted when used on different systems, for example, the path of the executable programs. Here we only list a few of the available scripts and provide a brief description, and you can either refer to the related sections for detailed usage or, in a lot of cases, type the script/program name without arguments for its usage.

### 9.1 Process Data and Synthetics

In many cases, the SEM synthetics are calculated and compared to data seismograms recorded at seismic stations. Since the SEM synthetics are accurate for a certain frequency range, both the original data and the synthetics need to be processed before a comparison can be made. We generally use the following scripts provided in the `UTILS/seis_process/` directory:

#### 9.1.1 Data processing script `process_trinet_data.pl`

This script cuts a given portion of the original data, filters it, transfers the data into a displacement record, and picks the first P and S arrivals. For more functionality, type ‘`process_trinet_data.pl`’ without any argument. An example of the usage of the script:

```
process_trinet_data.pl -m CMTSOLUTION -l 0/180 -t 2/40 -i dir -p -x bp 9703873*.BH?.SAC
```

which has cut all the sac files between 0 and 180 seconds, filtered them between 2 and 40 seconds, transferred them into displacement records using the polezero files in `dir` directory, picked the first P and S arrivals, and added suffix ‘`bp`’ to the file names.

Note that all of the scripts in this section actually use the SAC and/or IASP91 to do the core operations; therefore make sure that the SAC and IASP91 packages are installed properly on your system, and that all the environment variables are set properly before running these scripts.

#### 9.1.2 Synthetics processing script `process_trinet_syn.pl`

This script converts the synthetic output from the SEM code from ASCII to SAC format, and performs similar operations as ‘`process_trinet_data.pl`’. An example of the usage of the script:

```
process_trinet_syn.pl -m CMTSOLUTION -a STATIONS -l 0/180 -t 2/40 -p -x bp syn/*.BH?.semd
```

which will convert the synthetics into SAC format, add event and station information into the SAC headers, cut the SAC files between 0 and 180 seconds, filter them between 2 and 40 seconds, pick the first P and S arrivals, and add the suffix ‘`bp`’ to the file names.

More options are available for this script, such as adding time shift to the origin time of the synthetics, convolving the synthetics with a triangular source time function with a given half duration, etc. Type `process_trinet_syn.pl` without any argument for a detailed usage.

### 9.1.3 Script `rotate.pl`

The original data and synthetics have three components: vertical (BHZ), north (BHN) and east (BHE). However, for most seismology applications, transverse and radial components are also desirable. Therefore, we need to rotate the horizontal components of both the data and the synthetics to the transverse and radial direction, and `rotate.pl` can be used to accomplish this:

```
rotate.pl -l 0 -L 180 -d DATA/*.BHE.SAC.bp
rotate.pl -l 0 -L 180 SEM/*.BHE.semd.sac.bp
```

where the first command performs rotation on the SAC data obtained through Seismogram Transfer Program (STP) (<http://www.data.scec.org/STP/stp.html>), while the second command rotates the processed SEM synthetics.

## 9.2 Collect Synthetic Seismograms

The forward and adjoint simulations generate synthetic seismograms in the `in_out_files/OUTPUT_FILES/` directory by default. For the forward simulation, the files are named `STA.NT.BH?.semd` for two-column time series, or `STA.NT.BH?.semd.sac` for ASCII SAC format, where STA and NT are the station name and network code, and BH? stands for the component name. The adjoint simulations generate synthetic seismograms with the name `S?????.NT.S???.sem` (refer to Section 6.1 for details). The kernel simulations output the back-reconstructed synthetic seismogram in the name `STA.NT.BH?.semd`, mainly for the purpose of checking the accuracy of the reconstruction. Refer to Section 6.2 for further details.

You do have two options to change this default output behavior, given in the main constants file `constants.h` located in `src/shared/` directory:

**WRITE\_SEISMOGRAMS\_BY\_MASTER** Set to `.true.` to have only the master process writing out seismograms.  
This can be useful on a cluster, where only the master process node has access to the output directory.

**USE\_OUTPUT\_FILES\_PATH** Set to `.false.` to have the seismograms output to `LOCAL_PATH` directory specified in the main parameter file `in_data_files/Par_file`. In this case, you could collect the synthetics onto the frontend using the `collect_seismo_lsf_multi.pl` script located in the `UTILS/Cluster/lsf/` directory. The usage of the script would be e.g.:

```
collect_seismo.pl machines in_data_files/Par_file
```

where `machines` is a file containing the node names and `in_data_files/Par_file` the parameter file used to extract the `LOCAL_PATH` directory used for the simulation.

## 9.3 Clean Local Database

After all the simulations are done, the seismograms are collected, and the useful database files are copied to the frontend, you may need to clean the local scratch disk for the next simulation. This is especially important in the case of kernel simulation, where very large files are generated for the absorbing boundaries to help with the reconstruction of the regular forward wavefield. A sample script is provided in `UTILS/`:

```
cleanbase.pl machines
```

where `machines` is a file containing the node names.

## 9.4 Plot Movie Snapshots and Synthetic Shakemaps

### 9.4.1 movie2gif.pl

With the movie data saved in `in_out_files/OUTPUT_FILES/` at the end of a movie simulation (`MOVIE_SURFACE=.true.`), you can run the ‘`create_movie_GMT`’ code to convert these binary movie data into GMT xyz files for further processing. A sample script `movie2gif.pl` is provided to do this conversion, and then plot the movie snapshots in GMT, for example:

```
movie2gif.pl -m CMTSOLUTION -g -f 1/40 -n -2 -p
```

which for the first through the 40th movie frame, converts the `moviedata` files into GMT xyz files, interpolates them using the ‘`nearneighbor`’ command in GMT, and plots them on a 2D topography map. Note that ‘`-2`’ and ‘`-p`’ are both optional.

### 9.4.2 plot\_shakemap.pl

With the shakemap data saved in `in_out_files/OUTPUT_FILES/` at the end of a shakemap simulation (`CREATE_SHAKEMAP=.true.`), you can also run ‘`create_movie_GMT`’ code to convert the binary shakemap data into GMT xyz files. A sample script `plot_shakemap.pl` is provided to do this conversion, and then plot the shakemaps in GMT, for example:

```
plot_shakemap.pl data_dir type(1,2,3) CMTSOLUTION
```

where `type=1` for a displacement shakemap, 2 for velocity, and 3 for acceleration.

## 9.5 Map Local Database

A sample program `remap_database` is provided to map the local database from a set of machines to another set of machines. This is especially useful when you want to run mesher and solver, or different types of solvers separately through a scheduler (refer to Chapter 8).

```
run_lsf.bash --gm-no-shmem --gm-copy-env remap_database old_machines 150
```

where `old_machines` is the LSF machine file used in the previous simulation, and 150 is the number of processors in total.

# **Bug Reports and Suggestions for Improvements**

To report bugs or suggest improvements to the code, please send an e-mail to the CIG Computational Seismology Mailing List ([cig-seismo@geodynamics.org](mailto:cig-seismo@geodynamics.org)) or Jeroen Tromp ([jtromp-AT-princeton.edu](mailto:jtromp-AT-princeton.edu)), and/or use our online bug tracking system Roundup ([www.geodynamics.org/roundup](http://www.geodynamics.org/roundup)).

# Notes & Acknowledgments

In order to keep the software package thread-safe in case a multithreaded implementation of MPI is used, developers should not add modules or common blocks to the source code but rather use regular subroutine arguments (which can be grouped in “derived types” if needed for clarity).

The Gauss-Lobatto-Legendre subroutines in `gll_library.f90` are based in part on software libraries from the Massachusetts Institute of Technology, Department of Mechanical Engineering (Cambridge, Massachusetts, USA). The non-structured global numbering software was provided by Paul F. Fischer (Brown University, Providence, Rhode Island, USA, now at Argonne National Laboratory, USA).

OpenDX (<http://www.opendx.org>) is open-source based on IBM Data Explorer, AVS (<http://www.avs.com>) is a trademark of Advanced Visualization Systems, and ParaView (<http://www.paraview.com>) is an open-source visualization platform.

The main developers of the SPECFEM3D source code are Dimitri Komatitsch, Jeroen Tromp, and Qinya Liu. The following individuals (listed in alphabetical order) have also contributed to the development or improvement of the source code: Min Chen, Vala Hjörleifsdóttir, Jesús Labarta, and Leif Strand. The following individuals (listed in alphabetical order) contributed to this manual: Min Chen, Vala Hjörleifsdóttir, Sue Kientz, Dimitri Komatitsch, Qinya Liu, Alessia Maggi, Carl Tape, and Jeroen Tromp. The manual’s cover graphic was created by Santiago Lombeyda from Caltech’s Center for Advanced Computing Research (CACR) (<http://www.cacr.caltech.edu>). Older versions of the code were initially developed by Dimitri Komatitsch at Institut de Physique du Globe (France) and then by Dimitri Komatitsch and Jeroen Tromp at Harvard University (USA).

Please e-mail your feedback, questions, comments, and suggestions to Jeroen Tromp (`jtromp-AT-princeton.edu`) or to the CIG Computational Seismology Mailing List (`cig-seismo@geodynamics.org`).

# Copyright

Main authors: Dimitri Komatitsch and Jeroen Tromp

Seismological Laboratory, California Institute of Technology, USA, and University of Pau / CNRS / INRIA, France

© California Institute of Technology and University of Pau / CNRS / INRIA, February 2010

This program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation (see Appendix B).

# Bibliography

- K. Aki and P. G. Richards. *Quantitative seismology, theory and methods*. W. H. Freeman, San Francisco, USA, 1980.
- M. Bernacki, S. Lanteri, and S. Piperno. Time-domain parallel simulation of heterogeneous wave propagation on unstructured grids using explicit, nondiffusive, discontinuous Galerkin methods. *J. Comput. Acoust.*, 14(1):57–81, 2006.
- C. Bernardi, Y. Maday, and A. T. Patera. A new nonconforming approach to domain decomposition: the Mortar element method. In H. Brezis and J. L. Lions, editors, *Nonlinear partial differential equations and their applications*, Séminaires du Collège de France, pages 13–51, Paris, 1994. Pitman.
- L. Carrington, D. Komatitsch, M. Laurenzano, M. Tikir, D. Michéa, N. Le Goff, A. Snavely, and J. Tromp. High-frequency simulations of global seismic wave propagation using SPECFEM3D\_GLOBE on 62 thousand processor cores. *Proceedings of the ACM/IEEE Supercomputing SC’2008 conference*, pages 1–11, 2008. doi: 10.1145/1413370.1413432. Article #60, Gordon Bell Prize finalist article.
- E. Chaljub, Y. Capdeville, and J. P. Vilotte. Solving elastodynamics in a fluid-solid heterogeneous sphere: a parallel spectral-element approximation on non-conforming grids. *J. Comput. Phys.*, 187(2):457–491, 2003.
- E. Chaljub, D. Komatitsch, J. P. Vilotte, Y. Capdeville, B. Valette, and G. Festa. Spectral element analysis in seismology. In R.-S. Wu and V. Maupin, editors, *Advances in wave propagation in heterogeneous media*, volume 48 of *Advances in Geophysics*, pages 365–419. Elsevier - Academic Press, London, UK, 2007.
- M. Chen and J. Tromp. Theoretical and numerical investigations of global and regional seismic wave propagation in weakly anisotropic earth models. *Geophys. J. Int.*, 168(3):1130–1152, 2007. doi: 10.1111/j.1365-246X.2006.03218.x.
- S. Chevrot, N. Favier, and D. Komatitsch. Shear wave splitting in three-dimensional anisotropic media. *Geophys. J. Int.*, 159(2):711–720, 2004. doi: 10.1111/j.1365-246X.2004.02432.x.
- B. Cockburn, G. E. Karniadakis, and C.-W. Shu. *Discontinuous Galerkin Methods: Theory, Computation and Applications*. Springer, Heidelberg, Germany, 2000.
- F. A. Dahlen and J. Tromp. *Theoretical Global Seismology*. Princeton University Press, Princeton, New-Jersey, USA, 1998.
- J. D. De Basabe and M. K. Sen. Stability of the high-order finite elements for acoustic or elastic wave propagation with high-order time stepping. *Geophys. J. Int.*, 181(1):577–590, 2010. doi: 10.1111/j.1365-246X.2010.04536.x.
- J. D. De Basabe, M. K. Sen, and M. F. Wheeler. The interior penalty discontinuous Galerkin method for elastic wave propagation: grid dispersion. *Geophys. J. Int.*, 175(1):83–93, 2008. doi: 10.1111/j.1365-246X.2008.03915.x.
- D. S. Dreger and D. V. Helmberger. Broadband modeling of local earthquakes. *Bull. Seismol. Soc. Am.*, 80:1162–1179, 1990.
- M. Dumbser and M. Käser. An arbitrary high-order discontinuous Galerkin method for elastic waves on unstructured meshes-II. The three-dimensional isotropic case. *Geophys. J. Int.*, 167(1):319–336, 2006. doi: 10.1111/j.1365-246X.2006.03120.x.

- V. Etienne, E. Chaljub, J. Virieux, and N. Glinsky. An hp-adaptive discontinuous Galerkin finite-element method for 3-D elastic wave modelling. *Geophys. J. Int.*, 183(2):941–962, 2010. doi: 10.1111/j.1365-246X.2010.04764.x.
- R. S. Falk and G. R. Richter. Explicit finite element methods for symmetric hyperbolic equations. *SIAM J. Numer. Anal.*, 36(3):935–952, 1999. doi: 10.1137/S0036142997329463.
- N. Favier, S. Chevrot, and D. Komatitsch. Near-field influences on shear wave splitting and traveltime sensitivity kernels. *Geophys. J. Int.*, 156(3):467–482, 2004. doi: 10.1111/j.1365-246X.2004.02178.x.
- A. Fichtner, H. Igel, H.-P. Bunge, and B. L. N. Kennett. Simulation and inversion of seismic wave propagation on continental scales based on a spectral-element method. *Journal of Numerical Analysis, Industrial and Applied Mathematics*, 4(1-2):11–22, 2009.
- F. X. Giraldo, J. S. Hesthaven, and T. Warburton. Nodal high-order discontinuous Galerkin methods for the spherical shallow water equations. *J. Comput. Phys.*, 181(2):499–525, 2002. doi: 10.1006/jcph.2002.7139.
- L. Godinho, P. A. Mendes, A. Tadeu, A. Cadena-Isaza, C. Smerzini, F. J. Sánchez-Sesma, R. Madec, and D. Komatitsch. Numerical simulation of ground rotations along 2D topographical profiles under the incidence of elastic plane waves. *Bull. Seismol. Soc. Am.*, 99(2B):1147–1161, 2009. doi: 10.1785/0120080096.
- W. Gropp, E. Lusk, and A. Skjellum. *Using MPI, portable parallel programming with the Message-Passing Interface*. MIT Press, Cambridge, USA, 1994.
- M. J. Grote, A. Schneebeli, and D. Schützau. Discontinuous Galerkin finite element method for the wave equation. *SIAM Journal on Numerical Analysis*, 44(6):2408–2431, 2006. doi: 10.1137/05063194X.
- E. Hauksson. Crustal structure and seismicity distribution adjacent to the Pacific and North America plate boundary in Southern California. *J. Geophys. Res.*, 105:13875–13903, 2000.
- F. Q. Hu, M. Y. Hussaini, and P. Rasetarinera. An analysis of the discontinuous Galerkin method for wave propagation problems. *J. Comput. Phys.*, 151(2):921–946, 1999. doi: 10.1006/jcph.1999.6227.
- C. Ji, S. Tsuboi, D. Komatitsch, and J. Tromp. Rayleigh-wave multipathing along the west coast of north america. *Bull. Seismol. Soc. Am.*, 95(6):2115–2124, 2005. doi: 10.1785/0120040180.
- D. Komatitsch. Fluid-solid coupling on a cluster of GPU graphics cards for seismic wave propagation. *Comptes Rendus de l'Académie des Sciences - Mécanique*, 2011. in press.
- D. Komatitsch and R. Martin. An unsplit convolutional Perfectly Matched Layer improved at grazing incidence for the seismic wave equation. *Geophysics*, 72(5):SM155–SM167, 2007. doi: 10.1190/1.2757586.
- D. Komatitsch and J. Tromp. Spectral-element simulations of global seismic wave propagation-I. Validation. *Geophys. J. Int.*, 149(2):390–412, 2002a. doi: 10.1046/j.1365-246X.2002.01653.x.
- D. Komatitsch and J. Tromp. Spectral-element simulations of global seismic wave propagation-II. 3-D models, oceans, rotation, and self-gravitation. *Geophys. J. Int.*, 150(1):303–318, 2002b. doi: 10.1046/j.1365-246X.2002.01716.x.
- D. Komatitsch and J. Tromp. Introduction to the spectral-element method for 3-D seismic wave propagation. *Geophys. J. Int.*, 139(3):806–822, 1999. doi: 10.1046/j.1365-246x.1999.00967.x.
- D. Komatitsch and J. P. Vilotte. The spectral-element method: an efficient tool to simulate the seismic response of 2D and 3D geological structures. *Bull. Seismol. Soc. Am.*, 88(2):368–392, 1998.
- D. Komatitsch, J. Ritsema, and J. Tromp. The spectral-element method, Beowulf computing, and global seismology. *Science*, 298(5599):1737–1742, 2002. doi: 10.1126/science.1076024.
- D. Komatitsch, S. Tsuboi, C. Ji, and J. Tromp. A 14.6 billion degrees of freedom, 5 teraflops, 2.5 terabyte earthquake simulation on the Earth Simulator. *Proceedings of the ACM/IEEE Supercomputing SC'2003 conference*, pages 4–11, 2003. doi: 10.1109/SC.2003.10023. Gordon Bell Prize winner article.

- D. Komatitsch, Q. Liu, J. Tromp, P. Süss, C. Stidham, and J. H. Shaw. Simulations of ground motion in the Los Angeles basin based upon the spectral-element method. *Bull. Seismol. Soc. Am.*, 94(1):187–206, 2004. doi: 10.1785/0120030077.
- D. Komatitsch, D. Michéa, and G. Erlebacher. Porting a high-order finite-element earthquake modeling application to NVIDIA graphics cards using CUDA. *Journal of Parallel and Distributed Computing*, 69(5):451–460, 2009. doi: 10.1016/j.jpdc.2009.01.006.
- D. Komatitsch, G. Erlebacher, D. Göddeke, and D. Michéa. High-order finite-element seismic wave propagation modeling with MPI on a large GPU cluster. *J. Comput. Phys.*, 229(20):7692–7714, 2010a. doi: 10.1016/j.jcp.2010.06.024.
- D. Komatitsch, D. Göddeke, G. Erlebacher, and D. Michéa. Modeling the propagation of elastic waves using spectral elements on a cluster of 192 GPUs. *Computer Science Research and Development*, 25(1-2):75–82, 2010b. doi: 10.1007/s00450-010-0109-1.
- D. Komatitsch, L. P. Vinnik, and S. Chevrot. SHdiff/SVdiff splitting in an isotropic Earth. *J. Geophys. Res.*, 115(B7):B07312, 2010c. doi: 10.1029/2009JB006795.
- D. A. Kopriva. Metric identities and the discontinuous spectral element method on curvilinear meshes. *Journal of Scientific Computing*, 26(3):301–327, 2006. doi: 10.1007/s10915-005-9070-8.
- D. A. Kopriva, S. L. Woodruff, and M. Y. Hussaini. Computation of electromagnetic scattering with a non-conforming discontinuous spectral element method. *Int. J. Numer. Meth. Eng.*, 53(1):105–122, 2002. doi: 10.1002/nme.394.
- S. Krishnan, C. Ji, D. Komatitsch, and J. Tromp. Case studies of damage to tall steel moment-frame buildings in Southern California during large San Andreas earthquakes. *Bull. Seismol. Soc. Am.*, 96(4A):1523–1537, 2006a. doi: 10.1785/0120050145.
- S. Krishnan, C. Ji, D. Komatitsch, and J. Tromp. Performance of two 18-story steel moment-frame buildings in Southern California during two large simulated San Andreas earthquakes. *Earthquake Spectra*, 22(4):1035–1061, 2006b. doi: 10.1193/1.2360698.
- S. J. Lee, H. W. Chen, Q. Liu, D. Komatitsch, B. S. Huang, and J. Tromp. Three-dimensional simulations of seismic wave propagation in the Taipei basin with realistic topography based upon the spectral-element method. *Bull. Seismol. Soc. Am.*, 98(1):253–264, 2008. doi: 10.1785/0120070033.
- S. J. Lee, Y. C. Chan, D. Komatitsch, B. S. Huang, and J. Tromp. Effects of realistic surface topography on seismic ground motion in the Yangminshan region of Taiwan based upon the spectral-element method and LiDAR DTM. *Bull. Seismol. Soc. Am.*, 99(2A):681–693, 2009a. doi: 10.1785/0120080264.
- S. J. Lee, D. Komatitsch, B. S. Huang, and J. Tromp. Effects of topography on seismic wave propagation: An example from northern Taiwan. *Bull. Seismol. Soc. Am.*, 99(1):314–325, 2009b. doi: 10.1785/0120080020.
- Q. Liu and J. Tromp. Finite-frequency kernels based on adjoint methods. *Bull. Seismol. Soc. Am.*, 96(6):2383–2397, 2006. doi: 10.1785/0120060041.
- Q. Liu and J. Tromp. Finite-frequency sensitivity kernels for global seismic wave propagation based upon adjoint methods. *Geophys. J. Int.*, 174(1):265–286, 2008. doi: 10.1111/j.1365-246X.2008.03798.x.
- P. Lovely, J. Shaw, Q. Liu, and J. Tromp. A structural model of the Salton Trough and its implications for seismic hazard. *Bull. Seismol. Soc. Am.*, 96:1882–1896, 2006.
- R. Madec, D. Komatitsch, and J. Diaz. Energy-conserving local time stepping based on high-order finite elements for seismic wave propagation across a fluid-solid interface. *Comput. Model. Eng. Sci.*, 49(2):163–189, 2009.
- R. Martin and D. Komatitsch. An unsplit convolutional perfectly matched layer technique improved at grazing incidence for the viscoelastic wave equation. *Geophys. J. Int.*, 179(1):333–344, 2009. doi: 10.1111/j.1365-246X.2009.04278.x.

- R. Martin, D. Komatitsch, and A. Ezziani. An unsplit convolutional perfectly matched layer improved at grazing incidence for seismic wave equation in poroelastic media. *Geophysics*, 73(4):T51–T61, 2008a. doi: 10.1190/1.2939484.
- R. Martin, D. Komatitsch, and S. D. Gedney. A variational formulation of a stabilized unsplit convolutional perfectly matched layer for the isotropic or anisotropic seismic wave equation. *Comput. Model. Eng. Sci.*, 37(3):274–304, 2008b.
- R. Martin, D. Komatitsch, S. D. Gedney, and E. Bruthiaux. A high-order time and space formulation of the unsplit perfectly matched layer for the seismic wave equation using Auxiliary Differential Equations (ADE-PML). *Comput. Model. Eng. Sci.*, 56(1):17–42, 2010.
- D. Michéa and D. Komatitsch. Accelerating a 3D finite-difference wave propagation code using GPU graphics cards. *Geophys. J. Int.*, 182(1):389–402, 2010. doi: 10.1111/j.1365-246X.2010.04616.x.
- P. Monk and G. R. Richter. A discontinuous Galerkin method for linear symmetric hyperbolic systems in inhomogeneous media. *Journal of Scientific Computing*, 22-23(1-3):443–477, 2005. doi: 10.1007/s10915-004-4132-5.
- S. P. Oliveira and G. Seriani. Effect of element distortion on the numerical dispersion of spectral element methods. *Communications in Computational Physics*, 9(4):937–958, 2011.
- P. S. Pacheco. *Parallel programming with MPI*. Morgan Kaufmann Press, San Francisco, 1997.
- W. H. Reed and T. R. Hill. Triangular mesh methods for the neutron transport equation. Technical Report LA-UR-73-479, Los Alamos Scientific Laboratory, Los Alamos, USA, 1973.
- J. Ritsema, L. A. Rivera, D. Komatitsch, J. Tromp, and H. J. van Heijst. The effects of crust and mantle heterogeneity on PP/P and SS/S amplitude ratios. *Geophys. Res. Lett.*, 29(10):1430, 2002. doi: 10.1029/2001GL013831.
- B. Rivière and M. F. Wheeler. Discontinuous finite element methods for acoustic and elastic wave problems. *Contemporary Mathematics*, 329:271–282, 2003.
- B. Savage, D. Komatitsch, and J. Tromp. Effects of 3D attenuation on seismic wave amplitude and phase measurements. *Bull. Seismol. Soc. Am.*, 100(3):1241–1251, 2010. doi: 10.1785/0120090263.
- M. P. Süss and J. H. Shaw. P wave seismic velocity structure derived from sonic logs and industry reflection data in the Los Angeles basin, California. *J. Geophys. Res.*, 108(B3):2170, 2003. doi: 10.1029/2001JB001628.
- J. Tromp and D. Komatitsch. Spectral-element simulations of wave propagation in a laterally homogeneous Earth model. In E. Boschi, G. Ekström, and A. Morelli, editors, *Problems in Geophysics for the New Millennium*, pages 351–372. INGV, Roma, Italy, 2000.
- J. Tromp, C. Tape, and Q. Liu. Seismic tomography, adjoint methods, time reversal and banana-doughnut kernels. *Geophys. J. Int.*, 160(1):195–216, 2005. doi: 10.1111/j.1365-246X.2004.02453.x.
- J. Tromp, D. Komatitsch, and Q. Liu. Spectral-element and adjoint methods in seismology. *Communications in Computational Physics*, 3(1):1–32, 2008.
- J. Tromp, D. Komatitsch, V. Hjorleifsdottir, Q. Liu, H. Zhu, D. Peter, E. Bozdag, D. McRitchie, P. Friberg, C. Trabant, and A. Hutko. Near real-time simulations of global CMT earthquakes. *Geophys. J. Int.*, 183(1):381–389, 2010. doi: 10.1111/j.1365-246X.2010.04734.x.
- R. Vai, J. M. Castillo-Covarrubias, F. J. Sánchez-Sesma, D. Komatitsch, and J. P. Villette. Elastic wave propagation in an irregularly layered medium. *Soil Dynamics and Earthquake Engineering*, 18(1):11–18, 1999. doi: 10.1016/S0267-7261(98)00027-X.
- K. van Wijk, D. Komatitsch, J. A. Scales, and J. Tromp. Analysis of strong scattering at the micro-scale. *J. Acoust. Soc. Am.*, 115(3):1006–1011, 2004. doi: 10.1121/1.1647480.
- D. J. Wald and T. H. Heaton. Spatial and temporal distribution of slip for the 1992 Landers, California earthquake. *Bull. Seismol. Soc. Am.*, 84:668–691, 1994.

- L. C. Wilcox, G. Stadler, C. Burstedde, and O. Ghattas. A high-order discontinuous Galerkin method for wave propagation through coupled elastic-acoustic media. *J. Comput. Phys.*, 229(24):9373–9396, 2010. doi: 10.1016/j.jcp.2010.09.008.
- L. Zhu and H. Kanamori. Moho depth variation in southern California from teleseismic receiver functions. *J. Geophys. Res.*, 105:2969–2980, 2000.

## Appendix A

# Reference Frame Convention

The code uses the following convention for the Cartesian reference frame:

- the  $x$  axis points East
- the  $y$  axis points North
- the  $z$  axis points up

Note that this convention is different from both the Aki and Richards [1980] convention and the Harvard Centroid-Moment Tensor (CMT) convention. The Aki & Richards convention is

- the  $x$  axis points North
- the  $y$  axis points East
- the  $z$  axis points down

and the Harvard CMT convention is

- the  $x$  axis points South
- the  $y$  axis points East
- the  $z$  axis points up

# Appendix B

## License

**GNU GENERAL PUBLIC LICENSE Version 2, June 1991. Copyright (C) 1989, 1991 Free Software Foundation, Inc. 59 Temple Place, Suite 330, Boston, MA 02111-1307 USA**

Everyone is permitted to copy and distribute verbatim copies of this license document, but changing it is not allowed.

### Preamble

The licenses for most software are designed to take away your freedom to share and change it. By contrast, the GNU General Public License is intended to guarantee your freedom to share and change free software – to make sure the software is free for all its users. This General Public License applies to most of the Free Software Foundation's software and to any other program whose authors commit to using it. (Some other Free Software Foundation software is covered by the GNU Library General Public License instead.) You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.

To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the software, or if you modify it.

For example, if you distribute copies of such a program, whether gratis or for a fee, you must give the recipients all the rights that you have. You must make sure that they, too, receive or can get the source code. And you must show them these terms so they know their rights.

We protect your rights with two steps:

1. Copyright the software, and
2. Offer you this license which gives you legal permission to copy, distribute and/or modify the software.

Also, for each author's protection and ours, we want to make certain that everyone understands that there is no warranty for this free software. If the software is modified by someone else and passed on, we want its recipients to know that what they have is not the original, so that any problems introduced by others will not reflect on the original authors' reputations.

Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that redistributors of a free program will individually obtain patent licenses, in effect making the program proprietary. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

The precise terms and conditions for copying, distribution and modification follow.

## GNU GENERAL PUBLIC LICENSE TERMS AND CONDITIONS FOR COPYING, DISTRIBUTION AND MODIFICATION

0. This License applies to any program or other work which contains a notice placed by the copyright holder saying it may be distributed under the terms of this General Public License. The "Program" below refers to any such program or work, and a "work based on the Program" means either the Program or any derivative work under copyright law: that is to say, a work containing the Program or a portion of it, either verbatim or with modifications and/or translated into another language. (Hereinafter, translation is included without limitation in the term "modification.") Each licensee is addressed as "you."

Activities other than copying, distribution and modification are not covered by this License; they are outside its scope. The act of running the Program is not restricted, and the output from the Program is covered only if its contents constitute a work based on the Program (independent of having been made by running the Program). Whether that is true depends on what the Program does.

1. You may copy and distribute verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice and disclaimer of warranty; keep intact all the notices that refer to this License and to the absence of any warranty; and give any other recipients of the Program a copy of this License along with the Program.

You may charge a fee for the physical act of transferring a copy, and you may at your option offer warranty protection in exchange for a fee.

2. You may modify your copy or copies of the Program or any portion of it, thus forming a work based on the Program, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:

- (a) You must cause the modified files to carry prominent notices stating that you changed the files and the date of any change.
- (b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License.
- (c) If the modified program normally reads commands interactively when run, you must cause it, when started running for such interactive use in the most ordinary way, to print or display an announcement including an appropriate copyright notice and a notice that there is no warranty (or else, saying that you provide a warranty) and that users may redistribute the program under these conditions, and telling the user how to view a copy of this License. (Exception: if the Program itself is interactive but does not normally print such an announcement, your work based on the Program is not required to print an announcement.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Program, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Program, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Program.

In addition, mere aggregation of another work not based on the Program with the Program (or with a work based on the Program) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may copy and distribute the Program (or a work based on it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you also do one of the following:

- (a) Accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
- (b) Accompany it with a written offer, valid for at least three years, to give any third party, for a charge no more than your cost of physically performing source distribution, a complete machine-readable copy of the corresponding source code, to be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
- (c) Accompany it with the information you received as to the offer to distribute corresponding source code. (This alternative is allowed only for noncommercial distribution and only if you received the program in object code or executable form with such an offer, in accord with Subsection b above.)

The source code for a work means the preferred form of the work for making modifications to it. For an executable work, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the executable. However, as a special exception, the source code distributed need not include anything that is normally distributed (in either source or binary form) with the major components (compiler, kernel, and so on) of the operating system on which the executable runs, unless that component itself accompanies the executable.

If distribution of executable or object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place counts as distribution of the source code, even though third parties are not compelled to copy the source along with the object code.

4. You may not copy, modify, sublicense, or distribute the Program except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense or distribute the Program is void, and will automatically terminate your rights under this License. However, parties who have received copies, or rights, from you under this License will not have their licenses terminated so long as such parties remain in full compliance.
5. You are not required to accept this License, since you have not signed it. However, nothing else grants you permission to modify or distribute the Program or its derivative works. These actions are prohibited by law if you do not accept this License. Therefore, by modifying or distributing the Program (or any work based on the Program), you indicate your acceptance of this License to do so, and all its terms and conditions for copying, distributing or modifying the Program or works based on it.
6. Each time you redistribute the Program (or any work based on the Program), the recipient automatically receives a license from the original licensor to copy, distribute or modify the Program subject to these terms and conditions. You may not impose any further restrictions on the recipients' exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.
7. If, as a consequence of a court judgment or allegation of patent infringement or for any other reason (not limited to patent issues), conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot distribute so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not distribute the Program at all. For example, if a patent license would not permit royalty-free redistribution of the Program by all those who receive copies directly or indirectly through you, then the only way you could satisfy both it and this License would be to refrain entirely from distribution of the Program.

If any portion of this section is held invalid or unenforceable under any particular circumstance, the balance of the section is intended to apply and the section as a whole is intended to apply in other circumstances.

It is not the purpose of this section to induce you to infringe any patents or other property right claims or to contest validity of any such claims; this section has the sole purpose of protecting the integrity of the free software distribution system, which is implemented by public license practices. Many people have made generous contributions to the wide range of software distributed through that system in reliance on consistent application of that system; it is up to the author/donor to decide if he or she is willing to distribute software through any other system and a licensee cannot impose that choice.

This section is intended to make thoroughly clear what is believed to be a consequence of the rest of this License.

8. If the distribution and/or use of the Program is restricted in certain countries either by patents or by copyrighted interfaces, the original copyright holder who places the Program under this License may add an explicit geographical distribution limitation excluding those countries, so that distribution is permitted only in or among countries not thus excluded. In such case, this License incorporates the limitation as if written in the body of this License.
9. The Free Software Foundation may publish revised and/or new versions of the General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies a version number of this License which applies to it and “any later version,” you have the option of following the terms and conditions either of that version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of this License, you may choose any version ever published by the Free Software Foundation.

10. If you wish to incorporate parts of the Program into other free programs whose distribution conditions are different, write to the author to ask for permission. For software which is copyrighted by the Free Software Foundation, write to the Free Software Foundation; we sometimes make exceptions for this. Our decision will be guided by the two goals of preserving the free status of all derivatives of our free software and of promoting the sharing and reuse of software generally.

## NO WARRANTY

11. BECAUSE THE PROGRAM IS LICENSED FREE OF CHARGE, THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM “AS IS” WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.
12. IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MAY MODIFY AND/OR REDISTRIBUTE THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

## END OF TERMS AND CONDITIONS

### How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the “copyright” line and a pointer to where the full notice is found. For example:

One line to give the program’s name and a brief idea of what it does. Copyright © (year) (name of author)

This program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 2 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details.

You should have received a copy of the GNU General Public License along with this program; if not, write to the Free Software Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307 USA

Also add information on how to contact you by electronic and paper mail.

If the program is interactive, make it output a short notice like this when it starts in an interactive mode:

Gnomovision version 69, Copyright © year name of author Gnomovision comes with ABSOLUTELY NO WARRANTY; for details type ‘show w’. This is free software, and you are welcome to redistribute it under certain conditions; type ‘show c’ for details.

The hypothetical commands ‘show w’ and ‘show c’ should show the appropriate parts of the General Public License. Of course, the commands you use may be called something other than ‘show w’ and ‘show c’; they could even be mouse-clicks or menu items – whatever suits your program.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a “copyright disclaimer” for the program, if necessary. Here is a sample; alter the names:

Yoyodyne, Inc., hereby disclaims all copyright interest in the program ‘Gnomovision’ (which makes passes at compilers) written by James Hacker.

(signature of Ty Coon)

1 April 1989

Ty Coon, President of Vice

This General Public License does not permit incorporating your program into proprietary programs. If your program is a subroutine library, you may consider it more useful to permit linking proprietary applications with the library. If this is what you want to do, use the GNU Library General Public License instead of this License.