London Hack Days on the CMB, CLASS and Monte Python

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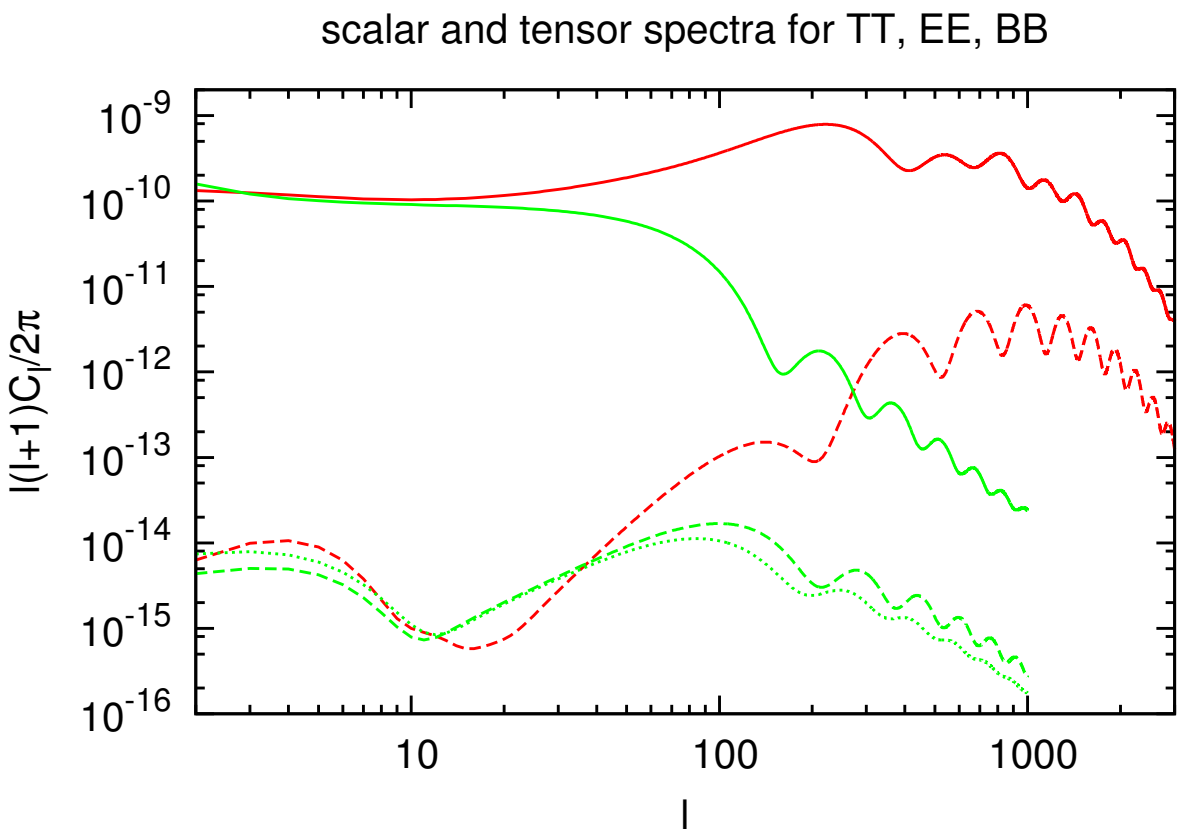
London, 12-16.05.2014

Almost any type of research activity in cosmology will use a Boltzmann code at some point

Computing CMB anisotropy spectra:



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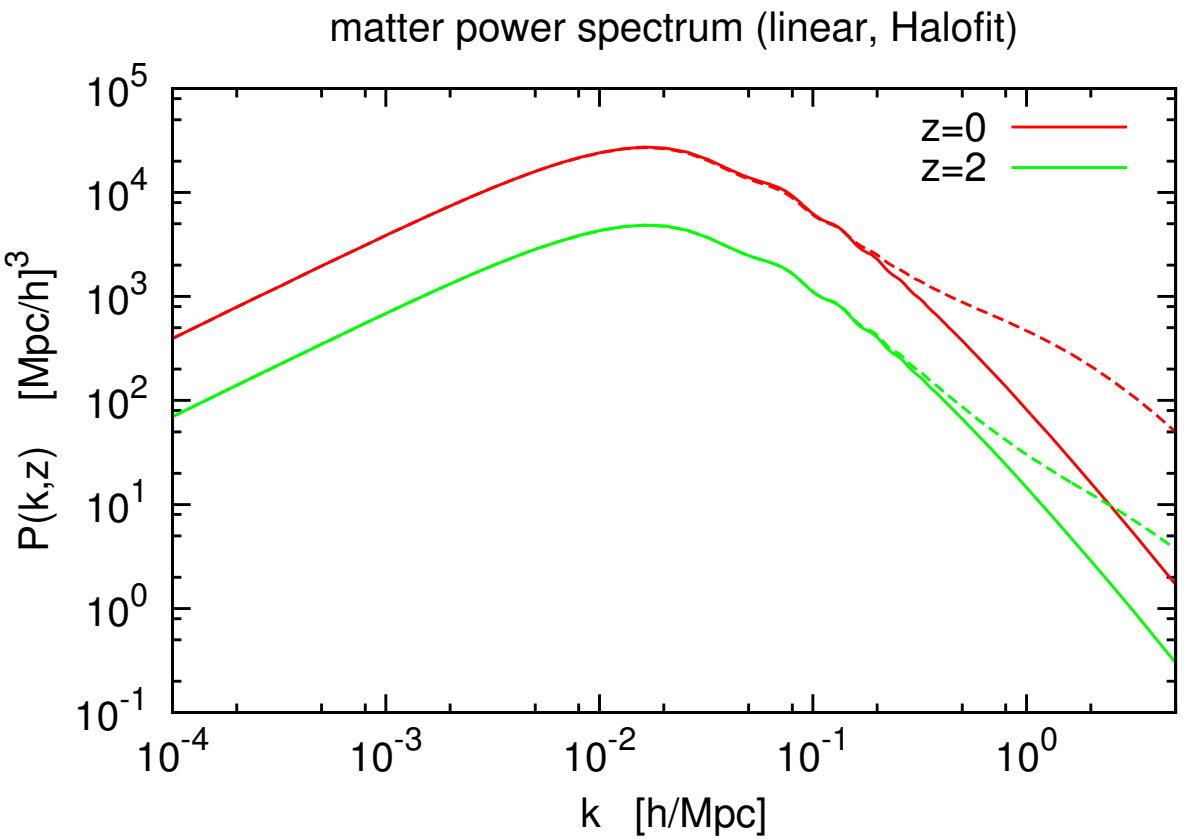
Computing matter power spectrum:



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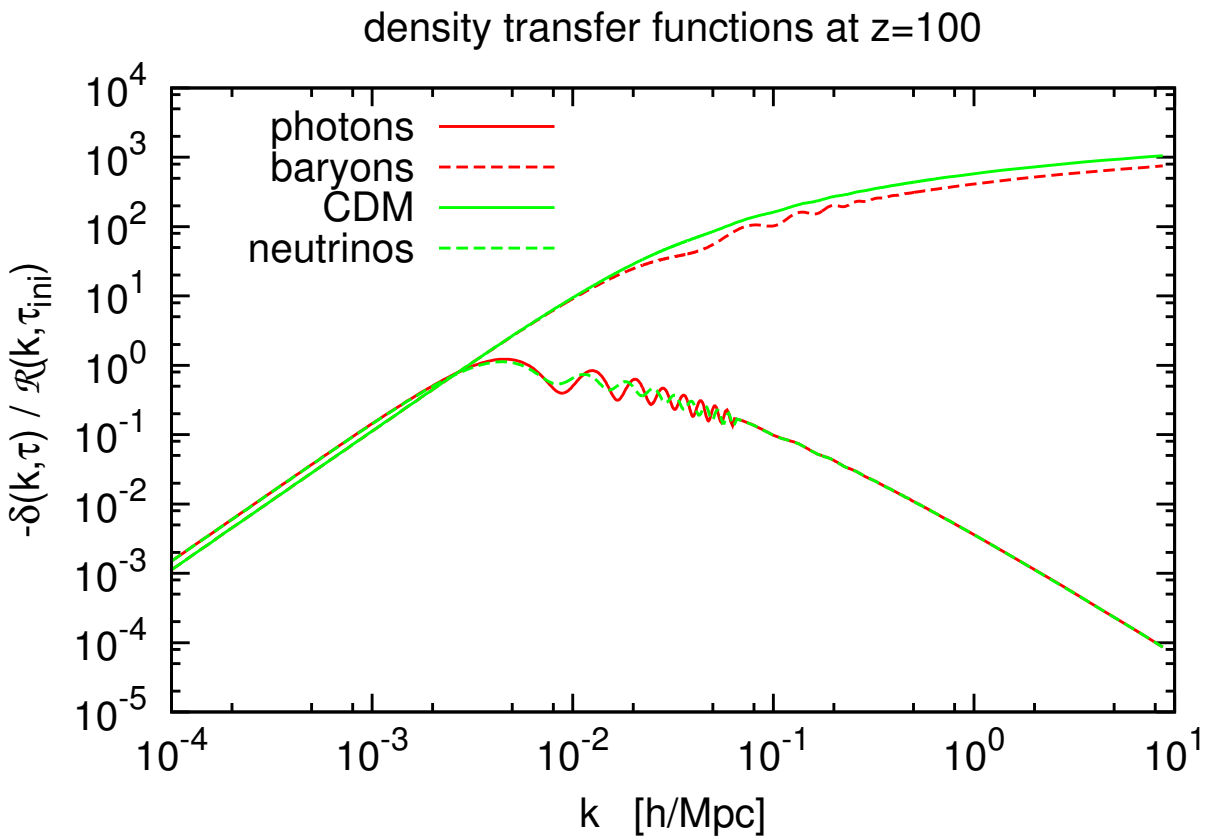
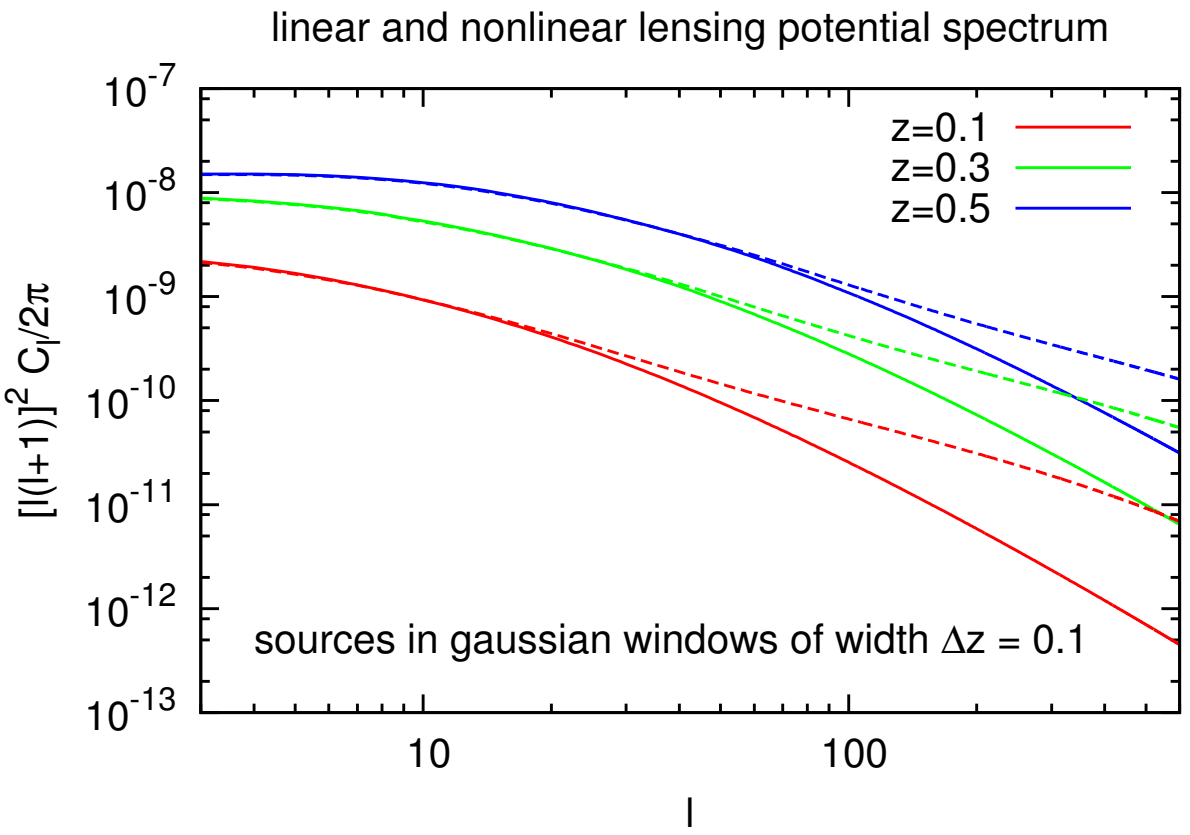
Computing transfer functions (e.g. initial conditions for N-body):



Targets

Computing matter density (number count) spectra, or lensing angular spectra:



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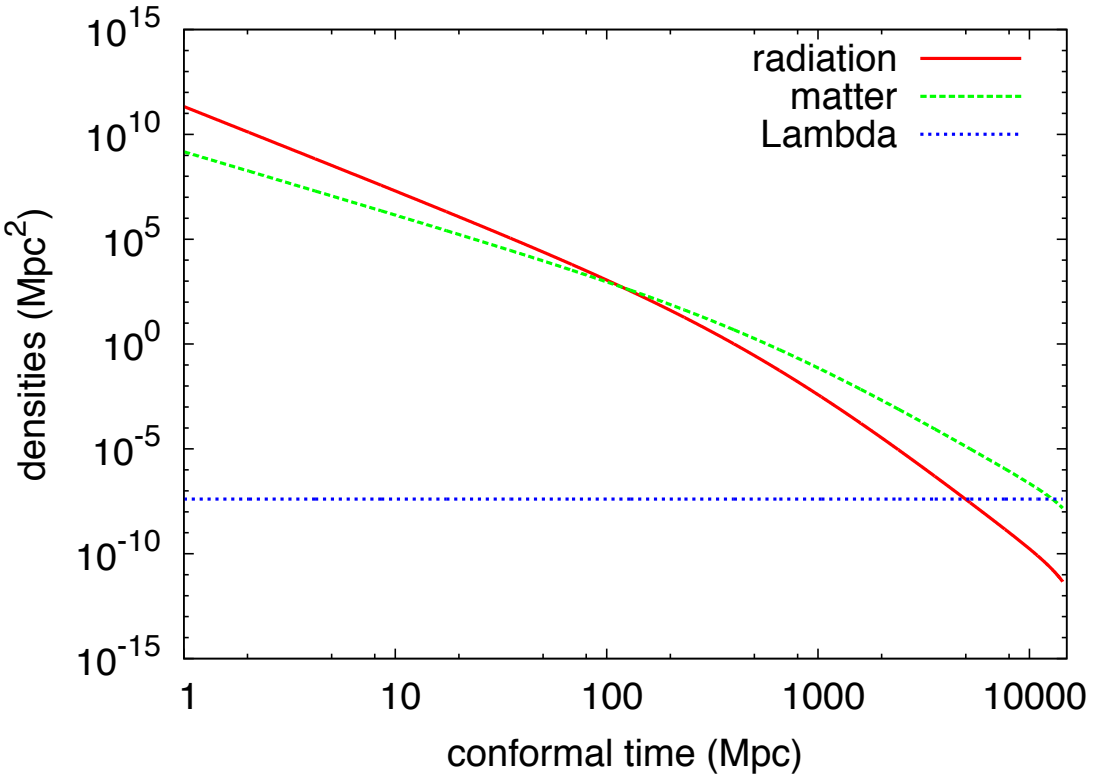
Computing background evolution in a given cosmological model:



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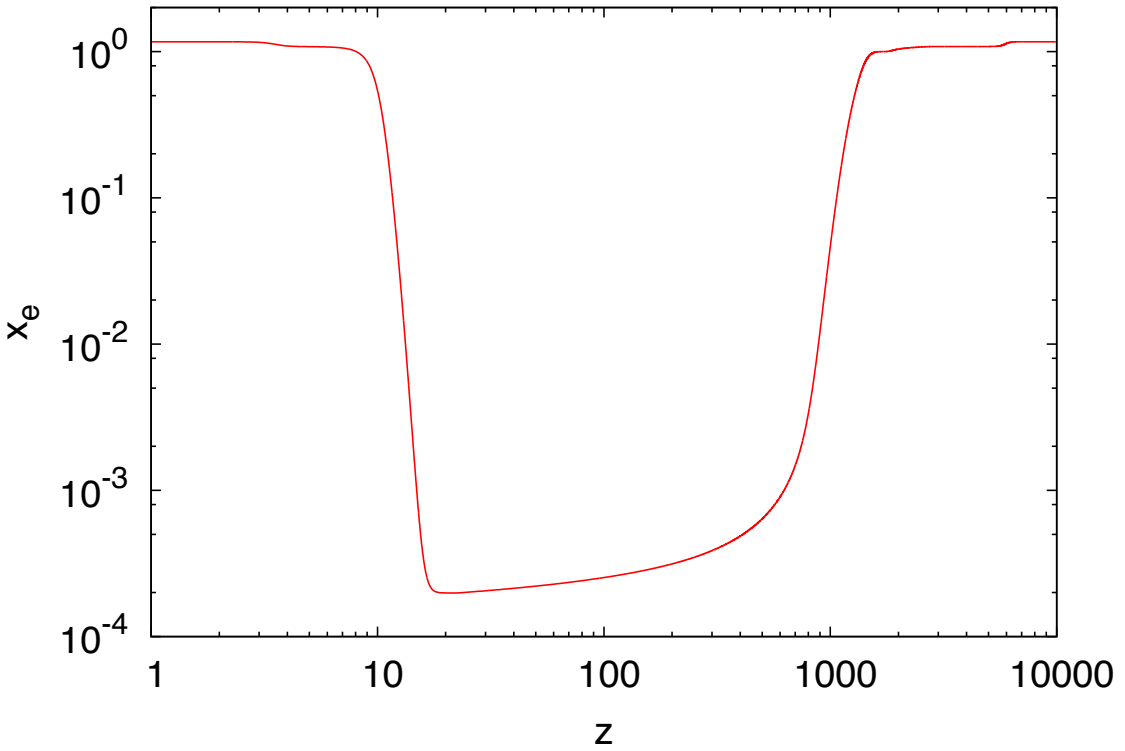
Computing thermal history in a given cosmological model:



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As both...

... you want to infer constraints on cosmological parameters from a new dataset
... you want to test your own favorite model, given existing data
... you want to predict the sensitivity of a future experiment to a given parameter

Targets

- we will see how to reach the first two targets with the Cosmic Linear Anisotropy Solving System (CLASS)
- we will see how to reach the third target with a Monte Carlo code in Python, Monte Python
- good occasion to refresh our mind or understand better the underlying theory! We will do that on-the-fly, since the structure of the CLASS code is the same as the sections of a cosmology text book.

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So there will be:

1. lectures on CLASS (numerics + underlying physics) by JL, some aspects will be developed by JT & TT
2. lectures on Monte Pyhton (underlying statistics + use of the code) by BA
3. exercise sessions on both codes, tutored by BA, JL, JT

Targets

Not difficult from numerical point of view.
Ideally, basic knowledge of C and Python required.
If not, no problem: for the exercises, we will mainly copy existing structures in the code.
Moreover C is very similar to fortran, and Python has similarities with Matlab, Mathematica or IDL.

Program: Day 1

	DAY I : Monday 12th May	
9:30-10:30	Introduction to CLASS I. *Brief history of Boltzmann codes.* *Goals and philosophy of CLASS.* *Structure of the code.*	JL
10:30-11:00	Coffee	
11:00-11:30	Introduction to CLASS II. *Basic input and output.* *Plotting facilities.*	JL
11:30-12:00	CLASS Exercises I. *Looking at all possible outputs of CLASS.* *Vizualizing them using the CLASS Plotting Unit, Gnuplot, Matlab, or one's own favorite plotting software.*	BA, JL
12:00-13:30	Lunch break	
13:30-15:00	Cosmological parameter extraction from data. *Overview of the main methods and existing codes.*	BA
15:00-15:30	CLASS Exercises I. *Continuation of the morning session.*	BA, JL

CLASS: Lecture I

Introduction to CLASS

- Motivations and goals of CLASS
- The philosophy of CLASS: how to achieve friendliness and flexibility
- Overall structure of the code
- Input file/parameters
- Output files

Next lectures will describe the modules one-by-one: background, thermodynamics, perturbations, etc.

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- 2003: Doran does a similar work of reorganization in C++: CMBEASY
- later: CAMB maintained and improved over the years; others not.

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2. Accurate: need more and more precision. Analyzing Planck and WMAP data required very different accuracy settings. Before, CAMB precision could only be calibrated w.r.t itself. CLASS played important role in pushing precision to Planck level. Similar efforts in the future (LSS, next CMB satellite, 21cm, etc.)

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3. Fast: for parameter extraction (Metropolis-Hastings, Multinest, Cosmo Hammer, grid-base methods). Typical project: 10'000 to 1'000'000 executions

The philosophy of `class`

Our efforts for ensuring flexibility and friendliness in CLASS, summarised in 14 key points

Friendliness and flexibility in 14 points

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Examples:
- expects only one out of $\{H_0,\, h,\, 100 \times \theta_s\}$, otherwise complains;
- missing ones inferred from given one
- same with $\{T_{\rm cmb}$ or $\Omega_\gamma,\, \omega_\gamma\}$, or with $\{\Omega_{\rm cdm},\, \omega_{\rm cdm}\}$, $\{\Omega_{\rm b},\, \omega_{\rm b}\}$...

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3. Perturbation equations and notations taken literally from well-known Ma & Bertschinger (`astro-ph/9506072`) paper ...

... rather than specific notations of one given group, or mixed notations from various origins.

For non-flat universes we found and published the simplest possible generalisation of Ma & Bertschinger notations, (`arXiv:1305.3261`).

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As many comment lines as C lines

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- Never write the index of an array as an integer; indexing down automatically and internally by the code; use symbolic index names;

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7. No global variables

All variables passed as arguments of functions. Important for readability and parallelisation.

Friendliness and flexibility in 14 points

8. Clear modular structure

Dinstinct modules with separate physical tasks. No duplicate equations.

E.g.: Friedmann equation appears in one single place. Same for linearised Einstein equations. Ideal for implementing modified gravity theories.

```
 1. input.c
 2. background.c
 3. thermodynamics.c
 4. perturbations.c
 5. primordial.c
 6. nonlinear.c
 7. transfer.c
 8. spectra.c
 9. lensing.c
10. output.c
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9. All precision variables grouped in one single place (`input.c`), and even inside a single structure 'precision'

There are... many. True for any code, but they are usually hidden and spread!

Friendliness and flexibility in 14 points

10. Given "ingredient" always implemented between brackets, in zone switched by a flag

- adding new physics does not slow down the code or compromise its readability.
- incentive to add lots of new things even if rarely used, with no drawback.
- with a search, one can localise all the parts of the code related to a given ingredient.

Examples:

```
if (has_fld == TRUE) {...}
if (has_cmb_lensing == TRUE) {...}
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if (has_cmb_lensing == TRUE) {...}
```

11. Adding new ingredient...

... can be done by searching for occurrence of another similar ingredient, copy/pasting, and adapting the new lines.

Example: if you want to add a new Dark Energy component, you may search for '_fld', duplicate all corresponding lines, change '_fld' into e.g. '_myde', and adapt the physical equations.

Friendliness and flexibility in 14 points

12. Error management

In principle CLASS never crashes. In case of problem, it returns an error message, with a well-documented error (line, function, what caused the crash, suggestions on how to avoid it). Most of this message is generated automatically by the code.

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13. Version history

Old versions can always be downloaded. In most cases, new versions feature new ingredients and avoid (whenever possible) to modify or erase the old ones. Try to develop in such way that modifications to an old version can still be pasted in a new version (as much as possible).

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14. Git repository and GitHub website.

The code can be downloaded as a `.tar.gz`, or as a git repository. Then, user can develop his own modification with the advantage of git (branching, memory of changes...); or merge his changes with a newer version almost automatically; or submit his modifications to the CLASS team in view of an easy merging with the public version.

Structure of the code

The directory `class/` contains subdirectories:

```
include/  # header files (*.h) containing declarations
source/   # the 10 important modules of CLASS
main/     # main CLASS function: short, just calls 10 modules
test/     # other main functions for testing part of the code
tools/    # auxiliary pieces of codes (numerical methods)
output/   # output files
python/   # python wrapper of CLASS
cpp/      # C++ wrapper of CLASS
build/    # binary files created at compilation
```

plus examples of input files, `README`, `Makefile`, and few other directories containing ancillary data or external code

Structure of the code

In CLASS, what is a module?

- a file `include/xxx.h` containing some declarations
- a file `source/xxx.c` containing some functions
- each module is a associated with a structure `xx`, containing all what other modules need to know, and nothing else
- some fields in this structure are filled in the `input.c` module (input parameters relevant for this module)
- all other fields are filled by a function `xxx_init(...)`
- "executing a module" $\equiv$ calling `xxx_init(...)`

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List of structures associated to modules:

module	structure	ab.	*	main content

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lensing.c	lensing	le	ple	lensed C_ℓ's
output.c	output	op	pop	description of output format

Structure of the code

Each module contains:

- a function `xxx_init(...)` filling the structure `xx`
- a function `xxx_free(...)` freeing all the memory allocated to this structure
- some functions `xxx_external_1(...)`, ..., `xxx_external_n(...)` that can be called from other modules (e.g. to read correctly or interpolate the content of the structure `xx`)
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Following order always respected in `xxx.c`:

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...
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...
xxx_internal_m(...)
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xxx_free(...)
xxx_internal_1(...)
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xxx_internal_m(...)
```

Remark: a module in the CLASS code is very similar to a "class" in C++. We enjoy the structure of C++ and the speed of C.

Structure of the code

The `main()` function of CLASS located in `main/class.c` only contains:

```
int main() {
 input_init(pfc,ppr,pba,pth,ppt,ptr,ppm,psp,pnl,ple,pop);
 background_init(ppr,pba);
 thermodynamics_init(ppr,pba,pth);
 perturb_init(ppr,pba,pth,ppt);
 primordial_init(ppr,ppt,ppm);
 nonlinear_init(ppr,pba,pth,ppt,ppm,pnl);
 transfer_init(ppr,pba,pth,ppt,pnl,ptr);
 spectra_init(ppr,pba,ppt,ppm,pnl,ptr,psp);
 lensing_init(ppr,ppt,psp,pnl,ple);
 /* all calculations done, free the structures */
 lensing_free(ple);
 spectra_free(psp);
 transfer_free(ptr);
 nonlinear_free(pnl);
 primordial_free(ppm);
 perturb_free(ppt);
 thermodynamics_free(pth);
 background_free(pba);
}
```

The input module

source/input.c

Input

./class can take two input files *.ini and *.pre:

```
>./class my_model.ini some_precision.pre
```

But one is enough. Syntax:

```
h = 0.7
T_cmb = 2.726 # comment
output = tCl, pCl
more comments, ignored because there is no equal sign
# comment with an =, still ignored thanks to the sharp
```

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>./class my_model.ini some_precision.pre
```

But one is enough. Syntax:

```
h = 0.7
T_cmb = 2.726 # comment
output = tCl, pCl
more comments, ignored because there is no equal sign
# comment with an =, still ignored thanks to the sharp
```

- Order of lines doesn't matter at all.
- All parameters not passed fixed to default, i.e. the most reasonable or minimalistic choice
- All possible input parameters and details on the syntax explained in `explanatory.ini`
- This is only a reference file; we advise you *never* to modify it, but rather to copy it and reduce it to a shorter and more friendly file.
- For *basic* usage: `explanatory.ini` $\equiv$ full documentation of the code

Input

For instance, we can create a very short file `lcdm.ini`:

```
******************************
* CLASS input parameter file *
******************************
----> background parameters:
H0 = 72.
omega_b = 0.0266691
omega_cdm = 0.110616
----> thermodynamics parameters:
z_reio = 10.
----> define primordial perturbation spectra:
A_s = 2.3e-9
n_s = 1.
----> define which perturbations should be computed:
output = tCl, pCl
----> parameters for the output spectra:
l_scalar_max = 2500
```

Input

How does the input module works?
Three essential functions:

```
input_init_from_arguments()

input_init()

input_read_parameters()
```

Input

(1) `input_init_from_arguments(argc,argv,...)`

- reads the input file(s) `*.ini`, (`*.pre`)
- identifies known names associated with values, and store them in a structure called `file_content` with fields `name`, `value`, e.g.:

```
struct file_content fc;
fc.name[0] = "h";           fc.value[0] = "0.68";
fc.name[1] = "Omega_b";     fc.value[1] = "0.04";
fc.name[2] = "omega_cdm";   fc.value[2] = "0.12";
fc.name[3] = "modes";       fc.value[3] = "s,t";
...
```

- calls `input_init(&fc,...)`
  or equivalently:

```
struct file_content * pfc;
pfc = &fc;
input_init(pfc,...)
```

Input

(2) `input_init(pfc,...)`

- eventually runs a shooting algorithm, as will be explained in two slides.
- calls `input_read_parameters(pfc, ...)`, the function in charge of defining all input parameters.

These are located in:

- precision structure (`pr`) for precision parameters
- beginning of each structure (`ba, th, pt, ...`) for cosmological parameters and parameters describing what needs to be computed

Hence the full list of arguments is

```
input_read_parameters(pfc,ppr,pba,pth,ppt,ptr,ppm,psp,pnl,ple,pop,errmsg)
```

Input

(3) `input_read_parameters(pfc,...)`

- initialises all parameters with default values with `input_default_params()` and `input_default_precision()`
- tries to read all existing parameters in the file content
- check if it can make sense of them (e.g. no redundant information)
- eventually overwrites default values

Contains some basic logic, and a few simple analytical formula, e.g. $\Omega_i = \omega_i / h^2$

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This is not enough for parameters which cannot be treated with analytic formulas! E.g. $100 \times \theta_s$ cannot be converted analytically into h! Other examples:

target parameter	unknown parameter
$100 \times \theta_s$	h
$\Omega_{\rm dcdm}$	$\rho^{\rm ini}_{\rm dcdm}$
σ_8	A_s

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target parameter	unknown parameter
$100 \times \theta_s$	h
$\Omega_{\rm dcdm}$	$\rho^{\rm ini}_{\rm dcdm}$
σ_8	A_s

Requires a shooting method !

Input

Full sequence when CLASS called with input files:

1. `input_init_from_argument(..)` : reads file, and fills `fc`
2. `input_init(pfc,...)` :
3. check if there are target/unknow parameters
4. if yes, shooting: several attempts for "unknown parameters" followed by a mini-run of beginning of CLASS, until "target parameters" are reached
5. now, all parameters are known
6. calls `input_read_parameters(..)`

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5. now, all parameters are known
6. calls `input_read_parameters(..)`

Full sequence when CLASS is called inside another code (wrapper):

Same except first step:

1. create and fill a structure `fc`
2. then call normally `input_init(plc,...)`

...

Hence the same logic is used in wrappers and on-line executions!!

Input

Essential input parameters controlling the output (see details in `explanatory.ini`):

```
modes = s,t
ic = ad, cdi, bi, nid, niv
lensing = yes
nonlinear = halofit
output = tCl, pCl, lCl, mPk, mTk, vTk, nCl, sCl

l_max_scalars=2500
l_max_tensors=500
l_max_lss = 1000
P_k_max_h/Mpc = 0.2
#P_k_max_1/Mpc =
z_pk = 0 #or 1,2,10

root = output/test_ #default: output/<ini_file>##_

headers = yes, no
format = class, camb
write parameters = yes, no
write warnings = no

verbose_xxx = 1
```

The output module

source/output.c

The output module

Called in the last place by `main/class.c` to write all requested output in files. Only writing, no physics, no manipulation of tables stored in other modules. Uses external interpolation functions of other modules, e.g.

```
spectra_cl_at_l(...);
lensing_cl_at_l(...);
spectra_pk_at_z(...);
spectra_pk_nl_at_z(...);
...
```

If CLASS embedded in another code, same information is obtained by directly calling such functions.

The output module

Following files created (or not) automatically (here we assume that `root=test_`):

- `test_cl.dat` total unlensed C_l's

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- `test_cl_lensed.dat` total lensed C_l's

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Following files created (or not) automatically (here we assume that `root=test_`):

- `test_cl.dat` total unlensed C_l's
- `test_cl_lensed.dat` total lensed C_l's
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- `test_pk_nl.dat` non-linear matter power spectrum

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- `test_pk.dat` matter power spectrum
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- `test_cl_ad.dat`, `test_cl_cdi.dat`, `test_cl_ad_cdi.dat` etc. when different i.c. requested

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- `test_cl_ad.dat`, `test_cl_cdi.dat`, `test_cl_ad_cdi.dat` etc. when different i.c. requested
- `test_pk_ad.dat`, `test_pk_cdi.dat`, `test_pk_ad_cdi.dat` etc. when different i.c. requested
- `test_tk.dat` density and/or velocity transfer functions

The output module

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- `test_cl_lensed.dat` total lensed C_l's
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- `test_cl_ad.dat`, `test_cl_cdi.dat`, `test_cl_ad_cdi.dat` etc. when different i.c. requested
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- `test_tk.dat` density and/or velocity transfer functions
- `test_tk_ad.dat`, `test_tk_cdi.dat`, `test_tk_ad_cdi.dat` etc. when different i.c. requested
- if `pk` or `tk` requested at different redhsift, several files, with extra suffix `_z0`, `_z1`, etc.

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- `test_tk.dat` density and/or velocity transfer functions
- `test_tk_ad.dat`, `test_tk_cdi.dat`, `test_tk_ad_cdi.dat` etc. when different i.c. requested
- if `pk` or `tk` requested at different redhsift, several files, with extra suffix `_z0`, `_z1`, etc.

Number of columns in these files can vary a lot depending on input parameters. Always indicated in the header.

Plotting

Whatever software is fine: `gnuplot`, `python`, `matlab`, `IDL`...

We provide scripts:

- in `python` using `gnuplot`: the old Class Plotting Unit `CPU`
- in `python` using `matplotlib`: the new Class Plotting Unit `CPU.py`
- in `matlab`: the new `plot_CLASS_output.m`

Plotting

E.g. to plot total E-mode C_l^{EE} polarisation in `output/test_cl_lensed.dat`:

```
# dimensionless total [l(l+1)/2pi] C_l's
# for l=2 to 3000, i.e. number of multipoles equal to 2999
#
# -> if you prefer output in CAMB/HealPix/LensPix units/
    order, set 'format' to 'camb' in input file
# -> if you don't want to see such a header, set 'headers'
    to 'no' in input file
#
#  l TT     EE       TE       BB      phiphi      Tphi     Ephi
```

you could do:

```
python CPU.py -h
python CPU.py output/test_cl_lensed.dat -s 'EE'
```

or inside matlab:

```
plot_CLASS_output('output/test_cl_lensed.dat','EE')
```

Exercises I

All these exercises consist in running CLASS with the correct set of input parameters (cosmological parameters are unimportant), and plotting its different outputs with `CPU.py`, or `plot_CLASS_output.m`, or with your own favorite software.

Ia

Check the difference between the lensed and unlensed C_l^{TT} of scalars, to see effect of smoothing of the peak contrast, and extra damping.

Ib

Check the difference between the lensed and unlensed C_l^{BB} of tensors, to see that B modes are dominated by lensing at least on small scales. Use $r = 0.2$ and like in BICEP results!

Exercises I

Ic

Check the difference between the unlensed C_l^{TT} of scalar modes for adiabatic and CDM isocurvature (CDI) initial conditions (with index $n_{\rm cdi} = 1$) , to check that peaks are suppressed in amplitude and shifted in scale. Do the same with NID isocurvature modes (with index $n_{\rm nid} = 1$) to check that the suppression in amplitude is less pronounced and the phase of NID and CDI are different.

Id

Check the difference between the linear and non-linear matter power spectrum at $z = 0$ and $z = 2$, to see that at low redshift non-linear corrections are present on larger scales.