Lecture VII: Spectra, Lensing, Output

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Where are we?

```
int main() {
 # done:
 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);
 # to be done:
 spectra_init(ppr,pba,ppt,ppm,pnl,ptr,psp);
 lensing_init(ppr,ppt,psp,pnl,ple);
 output_init(pba,pth,ppt,ppm,ptr,psp,pnl,ple,pop);
}
```

The spectra module

`source/spectra.c`

The function spectra_init()

The function `spectra_init()` calls (at most) three functions:

- `spectra_pk` computes the linear and non-linear matter power spectrum

$$P_L(k, z) = (\delta_m(k, \tau(z)))^2 \, \mathcal{P}(k)$$

  or in the case of several initial conditions,

$$P_L(k, z) = \sum_{ij} \delta^i_m(k, \tau(z)) \, \delta^j_m(k, \tau(z)) \mathcal{P}_{ij}(k)$$

  (same for $P_{NL}(k, z)$ with extra factor R^2_{NL}). Result stored in `psp->ln_pk` and `psp->ln_pk_nl`.

- `spectra_sigma()` computes mean variance in sphere of radius R. By default, code calls it to get $\sigma_8(z = 0)$ and stores it in `psp->sigma8`

The function spectra_init()

- `spectra_cl` computes the harmonic power spectra (formulae below holds in flat space)

$$C_l^{XY} = 4\pi \sum_{ij} \int \frac{dk}{k} \Delta_l^X(k) \Delta_l^Y(k) \mathcal{P}(k)$$

or in the case of several initial conditions,

$$C_l^{XY} = 4\pi \sum_{ij} \int \frac{dk}{k} \frac{1}{2} \left[\Delta_l^{iX}(k) \Delta_l^{jY}(k) + \Delta_l^{iX}(k) \Delta_l^{iY}(k) \right] \mathcal{P}_{ij}(k)$$

for $XY \in \{TT, TE, EE, BB, PP, TP, EP, N_iN_j, TN_i, PN_i, L_iL_j, TL_i, N_iL_j\}$ where $P \equiv$ CMB lensing, $N_i \equiv$ galaxy number count in i-th bin, and $L_i \equiv$ galaxy lensing in i-th bin.
Calculation takes place only for few values of l, later result can be interpolated at any l.

The result is stored in `psp->cl`.

External functions in spectra

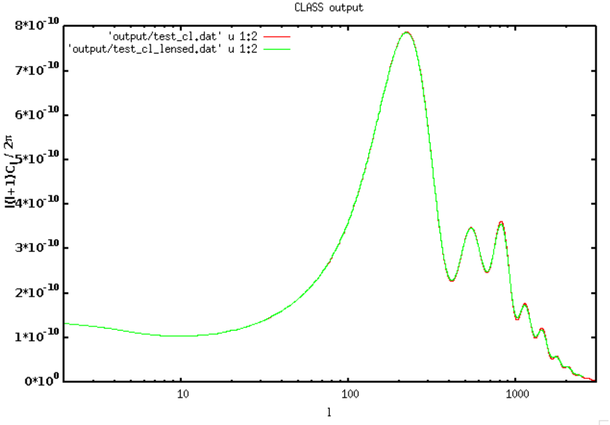
Functions called later by `output` module, but you might need to use them directly when embedding CLASS in your own code or when writing your own `main` function.

- `spectra_cl_at_l()` returns C_l's (either linear or non-linear) at a given l. Result can be a big array because returns result for each type, each i.c., each mode, and the total for each type.
- `spectra_pk_at_z()` returns $P_L(k, z)$ at given z for all k's.
- `spectra_pk_at_k_and_z()` returns $P_L(k, z)$ at given z and k.
- `spectra_pk_nl_at_z()` returns $P_{NL}(k, z)$ at given z for all k's.
- `spectra_pk_nl_at_k_and_z()` returns $P_{NL}(k, z)$ at given z and k.
- `spectra_sigma()` returns σ_R, i.e. the variance of matter fluctuations in a sphere of radius R, like the usual σ_8.
- `spectra_bandpower(l_1,l_2)` returns the bandpower $\sum_{l_1<l<l_2}(2l+1)C_l$

The lensing module

`source/lensing.c`

Given the unlensed CMB spectra $C_l^{TT,TE,EE,BB}$ and the spectrum of the lensing potential C_l^{PP}, the goal is to compute the lensed spectra $\tilde{C}_l^{TT,TE,EE,BB}$.



The function lensing_init()

- follows the all-sky method of A. Challinor and A. Lewis.
- implemented in CLASS by S. Prunet.
- differs from CAMB only through numerical implementation (quadrature weights, etc.), not methodology. Results agree very well.
- module is switched on/off with `lensing = yes, no`. But it also requires at least `output= tCl, lCl` or `output= pCl, lCl` or `output= tCl, pCl, lCl` to output lensed spectra.

At the end of `lensing_init()`, `ple->cl_lens` contains a replica of tables in `psp->cl`, excepted that $C_l^{TT,TE,EE,BB}$ are replaced by their lensed counterpart.

External function: `lensing_cl_at_l()`, works like `spectra_cl_at_l()`, but returns only total lensed spectra (individual lensed spectra make no sense).

Called by `output` module or by external code. Contains really observable quantities: called by `classy.pyx` and Monte Python.

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

Exemple of wrappers in `test/test_loops.c`, `python/classy.pyx`, `cpp/ClassEngine.cc`

Exercises

Exercise III

Compare the evolution of $\phi(k,\tau)$ and $\psi(k,\tau)$ for $k = 0.01, 0.1/\text{Mpc}$. Check that they are not equal on super-Hubble scales. To understand why, plot $a^2(\bar{\rho}_\nu + \bar{p}_\nu)\sigma_\nu$ versus time and check that the results are consistent with the Einstein equation $k^2(\phi - \psi) = 12\pi G a^2(\bar{\rho} + \bar{p})\sigma_{\rm tot}$.

Exercise IV

Modify the first Einstein equation in the synchronous gauge like:

$$k^2\eta - \frac{1}{2}\frac{a'}{a}h' = -\mu(k,\tau)\; 4\pi G a^2 \bar{\rho}_{\rm tot}\delta_{\rm tot}\;.$$

Localise the above equation and implement, for instance, $\mu = 1 + a^3$. Print the evolution of ϕ and ψ in the standard and modified models, and conclude that the C_l^{TT}'s should be affected only through the late ISW effect. Get a confirmation by comparing directly the C_l's.

Exercise V

By doing small modifications of `perturb_sources()`, check whether the tensor temperature spectrum $C_l^{TT,\rm tens.}$ comes mainly from photon perturbations on the last scattering surface, or from an integrated Sachs-Wolfe effect.

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- more detailed python wrapper of all existing external functions: CLASS will become a python module with library of functions

CLASS Bibliography

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- The CLASSgal code for Relativistic Cosmological Large Scale Structure, by E. Di Dio, F. Montanari, J. Lesgourgues and R. Durrer, JCAP 1311 (2013) 044