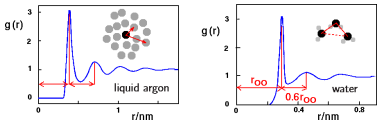
System size and potential range

Size of the simulated sample depends on:

- correlation length (property of the system)
- range of the potential (technical aspect)



Simulation **time** depends on:

- correlation time (property of the system)
- timestep and code efficiency (technical aspect: wall time)

liquid: hundreds of molecules, 10–100 ps, ionic liquids: > 10 ns
biomolecules: 10^4–10^6, ns (structure), μs (complex phenomena, bindung), ms (protein folding)
nanostructures, crystals (defects): billions, ns

problem: correlation times of many complex phenomena are long

Pair potential treatment:

number of operations needed for 1 MD step or 1 attempted move of every particle:

- loop over all pairs (nearest-image): $\sim N^2$
- short-range potential, optimum algorithm: $\sim N^1$

Short-range forces

- Potential cutoff

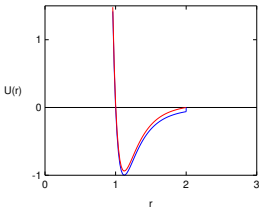
$$u_{\text{simul}}(r) = \begin{cases} u(r) & \text{for } r \le r_c, \\ 0 & \text{for } r > r_c, \end{cases}$$

Usually $r_c < L/2$ (L = box size, in the periodic b.c.)

- MD: continuous forces, or at least *cut-and-shift* potential:

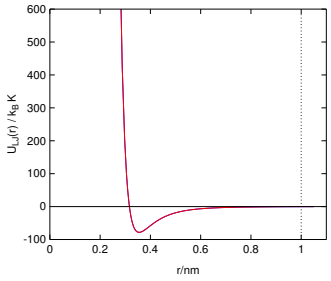
$$u_{\text{simul}}(r) = \begin{cases} u(r) - u(r_c) & \text{pro } r \le r_c, \\ 0 & \text{pro } r > r_c, \end{cases}$$

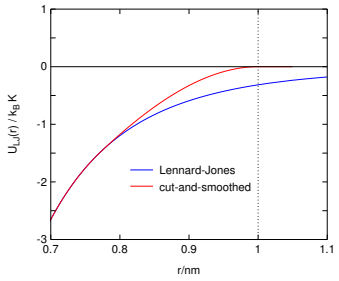
⇒ discontinuity (jump) in forces.
Better: smooth (depends on the integrator order)



- Nearest image boundary conditions

Smooth cutoff





Cutoff corrections

Correction of energy of a selected atom (assuming: $g(r) = 1$ for $r > r_c$):

$$\Delta U = \int_{r_c}^{\infty} u(r) \rho\, 4\pi r^2 \mathrm{d}r \qquad \text{for the whole box : } N\Delta U/2$$

Dispersion forces: $u(r) \propto r^{-6}$, $\Delta U \propto r_c^{-3}$; for $r_c = L/2$ we get error $\propto 1/N$

Typical values r_c: 2.5 to 4 LJ $\sigma \approx 8$ to 15 Å

Coulomb problem: dipole–dipole: r^{-3}, charge–charge: r^{-1} – ΔU diverges!

Methods:

- cut-and-shift, must be done smoothly – cheap, inaccurate, time $\sim N$
  ions: OK for $r_c \gg$ Debye screening length, dipoles: bad correlations
- Ewald summation – golden standard
  standard Ewald: computer time $\propto N^{3/2}$
  particle-mesh (FFT): computer time $\propto N \log N$
- tree-code (Greengard–Rokhlin)

a similar method for cut-off corrections exists for Lennard-Jones

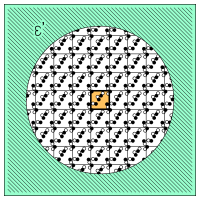
For dipolar systems only:

- reaction field: dielectric response beyond cutoff, computer time $\propto N$

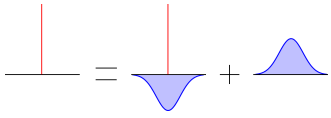
Ewald summation I

- Periodic boundary conditions surrounded "at infinity" by a dielectric or metal ($\varepsilon' = \infty$, *tin-foil*)
- sum of **all** periodic images:

$$U = \sum_{\vec{n}}{}' \sum_{1 \le j,l \le N} \frac{1}{4\pi\varepsilon_0} \frac{q_j q_l}{|\vec{r}_j - \vec{r}_l + \vec{n}L|}$$



Summation trick:
point charges screened by Gaussian charge distribution of opposite sign



- the screened charge interaction is short-ranged
- Gaussians are summed in the k-space

Ewald summation II

Oops! The infinite sum does not converge absolutely

$$U = \lim_{s \to 0} \sum_{\vec{n}}{}' \exp(-s\vec{n}^2) \sum_{1 \le j,l \le N} \frac{1}{4\pi\varepsilon_0} \frac{q_j q_l}{|\vec{r}_j - \vec{r}_l + \vec{n}L|}$$

Tricks used in the derivation:

$$\frac{1}{r} = \frac{2}{\sqrt{\pi}} \int_0^{\infty} \exp(-t^2 r^2) \mathrm{d}t = \frac{2}{\sqrt{\pi}} \int_0^{\alpha} \exp(-t^2 r^2) \mathrm{d}t + \frac{2}{\sqrt{\pi}} \int_{\alpha}^{\infty} \exp(-t^2 r^2) \mathrm{d}t$$

1st term: 3× the Poisson summation formula

$$\sum_{n=-\infty}^{\infty} f(x + nL) = \frac{1}{L} \sum_{k=-\infty}^{\infty} \hat{f}(k/L) \mathrm{e}^{2\pi i k x / L}$$

where

$$\hat{f}(k) = \int_{-\infty}^{\infty} f(x) \mathrm{e}^{-2\pi i k x / L} \mathrm{d}x$$

2nd term leads to the function

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) \mathrm{d}t$$

Ewald summation III

$$\begin{aligned} 4\pi\varepsilon_0 U &= \sum_{\vec{n}}{}' \sum_{1 \le j,l \le N} \frac{q_j q_l \operatorname{erfc}(\alpha |\vec{r}_j - \vec{r}_l + \vec{n}L|)}{|\vec{r}_j - \vec{r}_l + \vec{n}L|} \\ &+ \sum_{\vec{k}, \vec{k} \ne \vec{0}} \frac{\exp(-\pi^2 k^2 / \alpha^2 L^2)}{2L\pi k^2} |Q(\vec{k})|^2 + \frac{2\pi}{2\varepsilon_r' + 1} \frac{\vec{M}^2}{L^3} - \frac{\alpha}{\sqrt{\pi}} \sum_{j=1}^{N} q_j^2 \end{aligned}$$

$$\begin{aligned} Q(\vec{k}) &= \sum_{j=1}^{N} q_j \exp(2\pi i \vec{k} \cdot \vec{r}_j / L) \\ \vec{M} &= \sum_{j=1}^{N} \vec{r}_j q_j \quad \text{(watch point charges!)} \\ \operatorname{erfc}(x) &= \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) \mathrm{d}t \end{aligned}$$

with optimized parameters: computing cost $\sim N^{3/2}$
with *particle mesh* for the k-space part: computing cost $\sim N \log N$

Reaction field I

For dipolar systems without free charges: dipoles beyond spherical cutoff replaced by response of continuous dielectric

Neutral molecules with point partial charges:

$$u_{\text{RF}}(i,j) = \frac{1}{4\pi\varepsilon_0} \times \sum_{a \in \{i\}} \sum_{b \in \{j\}} \begin{cases} \dfrac{q_{i,a} q_{j,b}}{|\vec{r}_{i,a} - \vec{r}_{j,b}|} \left[1 + \dfrac{\varepsilon_r - 1}{2\varepsilon_r + 1} \left(\dfrac{|\vec{r}_{i,a} - \vec{r}_{j,b}|}{r_c} \right)^3 \right], & r_{ij} < r_c \\ 0, & r_{ij} > r_c \end{cases}$$

MD: needs smoothing!

Caveat: forces are not central

Reaction field II

Energy of dipole $\vec{\mu}_i$ with a dielectric outside an r_c-sphere:

$$-\frac{1}{4\pi\varepsilon_0} \vec{\mu}_i \cdot \frac{\varepsilon_r' - 1}{2\varepsilon_r' + 1} \frac{1}{r_c^3} \vec{M}_i'$$

where

$$\vec{M}_i' = \sum_{j, r_{ij} < r_c} \vec{\mu}_j, \qquad \vec{\mu}_i = \sum_{a \in \{i\}} q_{i,a} \vec{r}_{i,a}, \qquad \sum_{a \in \{i\}} q_{i,a} = 0$$

Trick:

$$\begin{aligned} -\vec{\mu}_i \cdot \vec{\mu}_j &= -\sum_{a \in \{i\}} q_{i,a} \vec{r}_{i,a} \cdot \sum_{b \in \{j\}} q_{j,b} \vec{r}_{j,b} + 0 + 0 \\ &= -\sum_{a \in \{i\}} q_{i,a} \vec{r}_{i,a} \cdot \sum_{b \in \{j\}} q_{j,b} \vec{r}_{j,b} \\ &\quad + \frac{1}{2} \sum_{a \in \{i\}} q_{i,a} \cdot \sum_{b \in \{j\}} q_{j,b} |\vec{r}_{j,b}|^2 + \frac{1}{2} \sum_{a \in \{i\}} q_{i,a} |\vec{r}_{i,a}|^2 \cdot \sum_{b \in \{j\}} q_{j,b} \\ &= \frac{1}{2} \sum_{a \in \{i\}} \sum_{b \in \{j\}} q_{i,a} q_{j,b} |\vec{r}_{i,a} - \vec{r}_{j,b}|^2 \end{aligned}$$