Optimal ciliary beating patterns ANDREJ VILFAN, NATAN OSTERMAN, J. Stefan Institute, Ljubljana, Slovenia — We introduce a measure for energetic efficiency of single or collective biological cilia. We define the efficiency of a single cilium as $Q^2/P$, where $Q$ is the volume flow rate of the pumped fluid and $P$ is the dissipated power. For ciliary arrays, we define it as $(\rho Q)^2/(\rho P)$, with $\rho$ denoting the surface density of cilia. We then numerically determine the optimal beating patterns according to this criterion. For a single cilium optimization leads to curly, somewhat counterintuitive patterns. But when looking at a densely ciliated surface, the optimal patterns become remarkably similar to what is observed in microorganisms like *Paramecium*. The optimal beating pattern then consists of a fast effective stroke and a slow sweeping recovery stroke. Metachronal waves lead to a significantly higher efficiency than synchronous beating. Efficiency also increases with an increasing density of cilia up to the point where crowding becomes a problem. We finally relate the pumping efficiency of cilia to the swimming efficiency of a spherical microorganism and show that the experimentally estimated efficiency of *Paramecium* is surprisingly close to the theoretically possible optimum.