# Traffic of Molecular Motors

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Molecular motors are proteins which catalyze a chemical reaction and use the free energy released from this reaction to generate directed movements and to perform work. Examples are the cytoskeletal motors which move in a directed fashion along cytoskeletal filaments, e.g. kinesins which move along microtubules. They consume adenosinetriphosphate (ATP) which represents their chemical 'fuel' and move in discrete steps in such a way that one molecule of ATP is used per step. Our understanding of molecular motors is based on biomimetic model systems which are rather simple compared to biological cells and consist of only a small number of components such as motors, filaments, and ATP. These systems allow us to study the transport properties of molecular motors systematically. A typical biomimetic experiment is shown in **Fig. 1**.

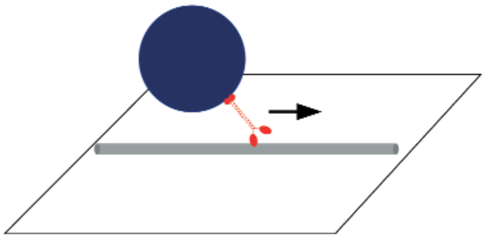

*Fig. 1: The bead assay provides an example for a biomimetic model experiment: A molecular motor transports a (glass or latex) bead along a filament which is immobilized on a surface.*

### Unbinding and Motor Walks

A molecular motor is called processive if it makes many steps while it is bound to the filament. However, even processive motors have only a finite walking distance, because the motor-filament binding energy can be overcome by thermal fluctuations. This walking distance is typically of the order of 1 µm for cytoskeletal motors. Unbound motors perform Brownian motion in the surrounding aqueous solution until they collide again with a filament and rebind to it.

Therefore, on large length and time scales which exceed a few microns and a few seconds, respectively, molecular motors perform peculiar motor walks as shown in **Fig. 2**. These motor walks consist of alternating sequences of active directed movements along filaments and passive non-directed diffusion **[1]**.

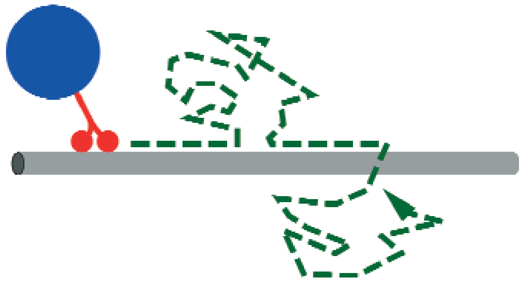

*Fig. 2: Motor walks: A molecular motor performs active directed movement along a filament and unbinds from it after a certain walking distance. The unbound motor diffuses passively in the surrounding fluid until it rebinds to the filament and resumes directed motion.*

We have studied these motor walks for various compartments with different geometries using both computer simulations and analytical techniques **[1, 2]**. The motor walks exhibit anomalous drift behaviour and strongly enhanced effective diffusion due to the repeated binding to the filament. The enhanced diffusion is particularly pronounced if the walking distance is large, which is the case for motor particles driven by several motor molecules.

### Exclusion and Jamming

If the concentration of molecular motors in a compartment is large, motor-motor interactions become important and lead to a variety of cooperative phenomena. In particular, motors interact via simple exclusion or hard core repulsion which implies that a motor bound to a binding site of the filament excludes other motors from this filament site. This type of motor-motor interaction leads to traffic jams on the filament and implies the existence of various kinds of phase transitions. In contrast to the traffic of cars and other vehicles, unbinding from the filament and diffusion of unbound motors play a role in the traffic of molecular motors. We have focussed on tube-like compartments as shown in **Fig. 3** with different kinds of boundary conditions. The tube geometry mimics the geometry of an axon, which provides the most prominent example for long-range motor traffic in vivo.

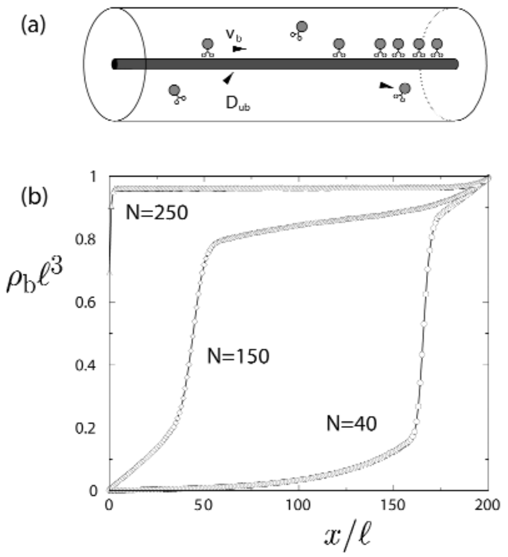


*Fig. 3: (a) Motors move in a closed tube system which contains one filament and build up a motor traffic jam at the right end of the system. (b) Profiles of the bound motor density along the filament for various total numbers N of motors within the tube. The jammed region becomes longer with increasing N.*

In closed tubes, the motors generate non-uniform density patterns and accumulate at the end of the tubes as shown in **Fig. 3**. The average bound motor current in these systems exhibits a maximum as a function of the motor concentration within the tube **[1]**.

Open tube systems, which are coupled to motor reservoirs at both ends, exhibit boundary-induced phase transitions **[3]**. The motor density within the tube is determined by the 'bottleneck' of the transport through the tube, which can be given by one of the boundaries or by the interior of the tube. Phase transitions occur if the position of the 'bottleneck' changes when the motor densities in the boundary reservoirs are changed.

**Bidirectional Motor Traffic**

Each molecular motor moves either towards the plus- or towards the minus-end of the corresponding filament, but different types of motors move into opposite directions along the same filament. In this situation, cooperative binding of the motors to the filament—in such a fashion that a motor is more likely to bind next to a bound motor moving in the same direction and less likely to bind next to a motor with opposite directionality—leads to spontaneous symmetry breaking **[4]**: For sufficiently strong motor-motor interactions, one motor species occupies the filament, while the other one is largely excluded from it as shown in **Fig. 4**. If several filaments are aligned in parallel and with the same orientation, this symmetry breaking leads to the spontaneous formation of traffic lanes for motor traffic with opposite directionality **[4]**.

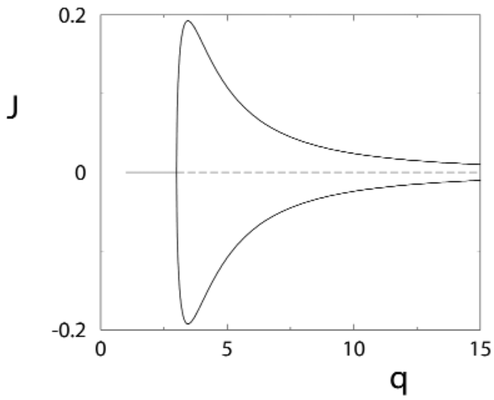


*Fig. 4: Spontaneous symmetry breaking in systems with two motor species moving into opposite directions along the same filament: The total motor current J is zero for weak interaction $q<q_c$, where the filament is equally populated by both motor species, but non-zero for sufficiently strong motor-motor interactions with $q>q_c$, where one motor species is essentially excluded from the filament. For very strong interaction, the current decreases because the filament becomes more and more crowded.*


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**References:**

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**[4]** Klumpp, S. and Lipowsky, R.: Phase transitions in systems with two species of molecular motors. Europhys. Lett. **66**, 90-96 (2004).