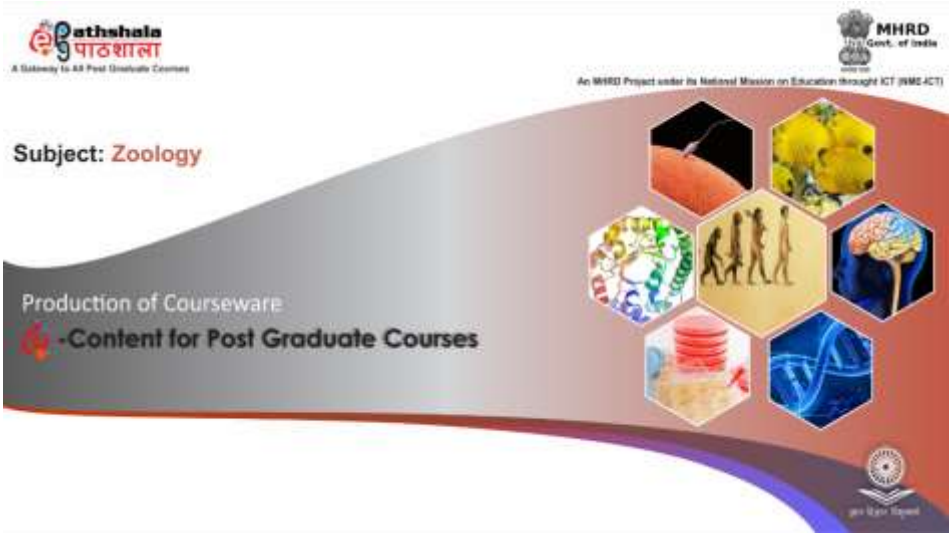

Paper : 15 Molecular Cell Biology
Module : 13 Cytoskeleton

Development Team

Principal Investigator:	Prof. Neeta Sehgal Department of Zoology, University of Delhi
Co-Principal Investigator:	Prof. D.K. Singh Department of Zoology, University of Delhi
Paper Coordinator:	Prof. Kuldeep K. Sharma Department of Zoology, University of Jammu
Content Writer:	Dr. Preeti Khandelwal, Sri Venkateswara College, DU Ms. Pooja Kumari, Department of Zoology, DU
Content Reviewer:	Prof. Rup Lal Department of Zoology, University of Delhi

Description of Module	
Subject Name	ZOOLOGY
Paper Name	Molecular Cell Biology; Zool 015
Module Name/Title	Cytoskeleton
Module Id	M13; Cytoskeleton
Keywords	Cytoskeleton, Microfilaments, Actin. Myosin, Microtubule, Dynein, Kinesin, Treadmilling

Contents

1. Learning Outcomes
2. Introduction
3. Microfilaments
   - 3.1. Structure of Actin molecule
   - 3.2. Dynamics of Actin Filaments
   - 3.3. Actin Filaments Grow Faster at (+) Ends than at (-) Ends
   - 3.4. Mechanism of Actin Filament Assembly
   - 3.5. Myosins
4. Intermediate filaments
5. Microtubules
   - 5,1. Mtocs (Microtubule-organizing centres)
   - 5.2. Microtubule dynamics
   - 5.3. Regulation of Microtubule Structure and Dynamics
   - 5.4. Microtubular motors and movements
   - 5.5. Kinesin is a highly processive motor protein
   - 5.6. Dynein
   - 5.7. Microtubule Dynamics in Mitosis
6. Summary

1. Learning Outcome

- What is cytoskeleton?
- Components of cytoskeleton
- Structure of actin molecules and their dynamics
- Functions of actin molecules
- Intermediate filaments and functions
- Structure of microtubules and their dynamics
- Motor proteins- kinesin and dynein
- Functions of microtubules

2. Introduction

A cell's shape and its functional polarity are provided by a three-dimensional filamentous protein network called the cytoskeleton. The cytoskeleton extends throughout the cell and is attached to the plasma membrane and internal organelles, so producing a framework for cellular organization. It can be very dynamic and have components capable of reorganization in less than a minute, or it can be quite stable for several hours. It is responsible for cell movements which includes not only the movements of entire cells, but also the internal transport of organelles and other structures (such as mitotic chromosomes) through the cytoplasm. The cytoskeleton is composed of three principal types of protein filaments: **microfilaments**, **microtubules** and **intermediate filaments** (Figure 1)

a. **Microfilaments** are polymers of the protein actin organized into functional bundles and networks by actin-binding proteins. Microfilaments are especially important in the organization of the plasma membrane, including surface structures such as microvilli. Microfilaments can function on their own or serve as tracks for ATP-powered myosin motor proteins, which provide a contractile function (as in muscle) or ferry cargo along microfilaments.
b. **Microtubules** are long tubes formed by the protein tubulin and organized by microtubule-associated proteins. They often extend throughout the cell, providing an organizational

framework for associated organelles and structural support to cilia and flagella. They also make up the structure of the mitotic spindle, the machine for separating duplicated chromosomes at mitosis. Molecular motors called kinesins and dyneins transport cargo along microtubules and are also powered by ATP hydrolysis.

c. **Intermediate filaments** are tissue specific filamentous structures providing a number of different functions, including structural support to the nuclear membrane, structural integrity to cells in tissues, and structural and barrier functions in skin, hair and nails.

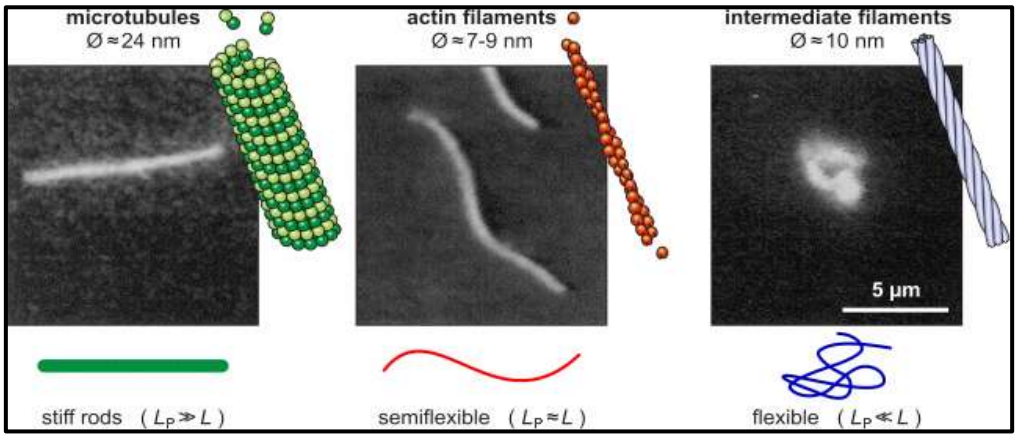

Figure 1: The components of the cytoskeleton
Source: http://www.uni-leipzig.de/~pwm/web/?section=introduction&page=cytoskeleton

3. Microfilaments

The major cytoskeletal protein of most cells is **actin**, which polymerizes to form actin filaments which are thin, flexible fibres approximately 7nm in diameter and up to several micrometres in length. Actin filaments are also called as microfilaments which are organised into higher-order structures, forming bundles or three-dimensional networks with the properties of semi-solid gels. The assembly and disassembly of actin filaments, their cross-linking into bundles and networks, and their association with other cell structures (such as the plasma membrane) are regulated by a variety of actin-binding proteins.

3.1. Structure of Actin molecule

Actin is the most abundant intracellular protein in most eukaryotic cells. In muscle cells, for example, actin comprises 10 percent by weight of the total cell protein; even in non-muscle

cells, actin makes up 1-5 percent of the cellular protein. The cytosolic concentration of actin in non-muscle cells ranges from 0.1 to 0.5 mM; in special structures such as microvilli, however, the local actin concentration can be 5 mM.

The three-dimensional structure of both individual actin molecules and actin filaments were determined in 1990 by Kenneth Holmes, Wolfgang Kabsch and their colleagues. Individual actin molecules (globular **[G] actin**) has tight binding sites that mediate head-to-tail interactions with two other actin monomers, so actin monomers polymerize to form filaments (filamentous **[F] actin**). Each actin molecule contains a magnesium ion complexed with either ATP or ADP. The conformation of the molecule is affected whether the ATP or ADP is attached. Addition of cations induce the polymerization of G-actin monomers into F-actin filaments and the process is reversible.

Each monomer of G-actin is rotated by 166° in the filaments, which therefore have the appearance of a double-stranded helix. Because all the actin monomers are oriented in the same direction, actin filaments have a distinct polarity and their ends (called barbed or plus ends, and pointed or minus ends) are distinguishable from one another. Addition of actin subunits is favoured at the (+) end whereas (-) end is favoured for the dissociation.

3.2. Dynamics of Actin filaments

The *in vitro* polymerization of G-actin to form F-actin filaments can be monitored by viscometry, sedimentation, fluorescence spectroscopy or fluorescence microscopy. The mechanism of actin assembly has been studied extensively. The polymerization of pure G-actin *in vitro* proceeds in three sequential phases (Figure 2):

i. The ***nucleation phase*** which is marked by a lag period in which G-actin subunits combine into short, unstable oligomers which reaches three subunits in length acting as a stable seed or nucleus.
ii. The ***elongation phase*** which is marked by a rapid increase in filament length by the addition of actin monomers to both of its ends. As F-actin filaments grow, the concentration of G-actin monomers decreases until equilibrium is reached between filaments and monomers.

iii. The ***steady-state phase*** in which G actin monomers exchange with subunits at the filament ends, but there is no net change in the total mass of filaments.

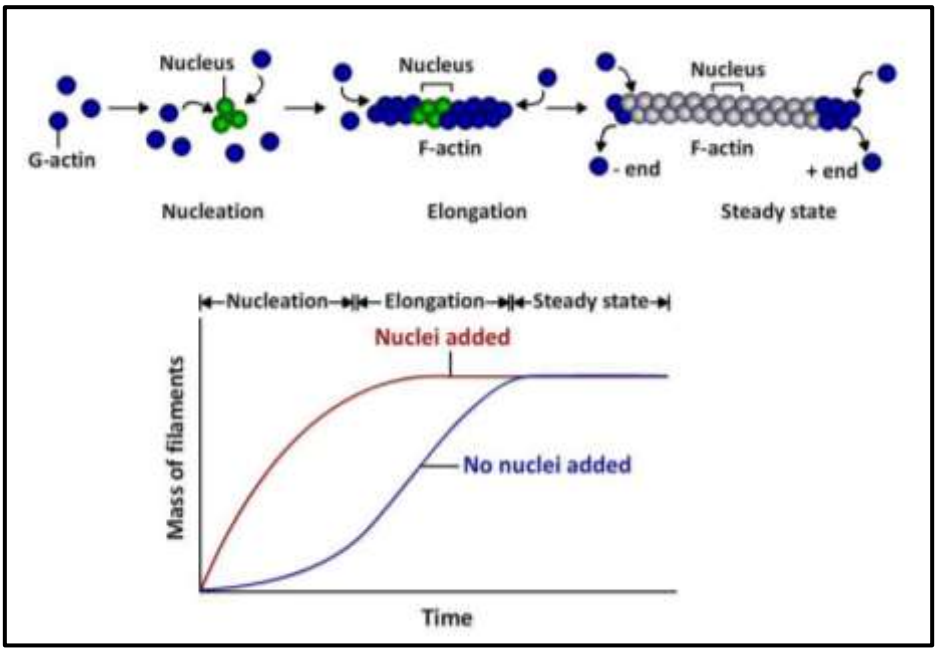

Figure 2: In-vitro polymerization of G-actin occurring in three phases: nucleation, elongation and steady statephase.

Source: http://pharmaceuticalintelligence.com/category/ionic-transporters-na/

The critical concentration is the concentration of G-actin monomers in equilibrium with actin filaments (Figure 3). At monomer concentrations below the critical concentration, no polymerization will take place. It occurs only when the monomer concentration is above the critical concentration and the filaments assemble until steady state is reached and the monomer concentration falls to critical concentration.

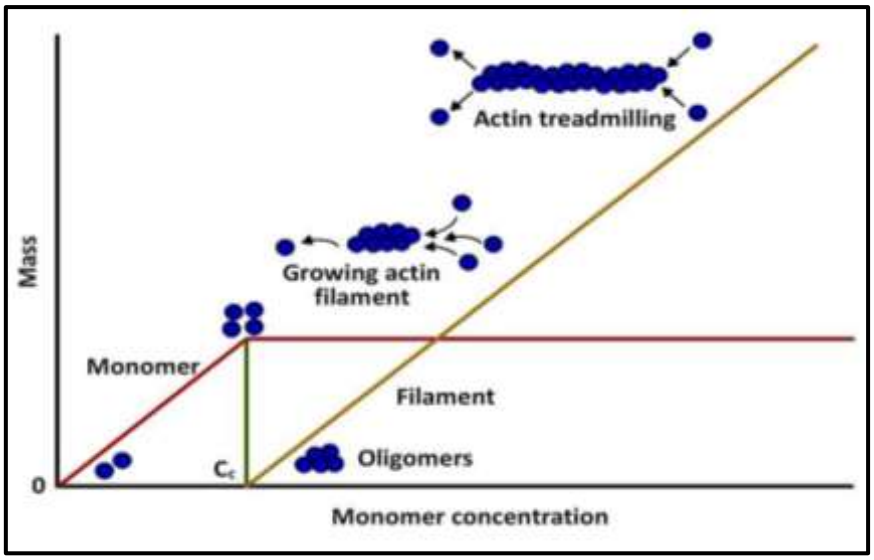

Figure 3: Concentration of actin determines filament assembly. C_c-critical concentration
Source:http://www.mechanobio.info/modules/go-0030041

3.3. Actin Filaments Grow Faster at (+) Ends than at (-) Ends

The rate of addition of ATP-G-actin is nearly 10-times faster at one end, the (+) end, than at the (-) end. The rate of addition is determined by the concentration of free ATP G-actin. It has been shown with the help of kinetic experiments that on average 12 subunits are added to the (+) end every second whereas only 1.3 will be added at the (-) end every second. In contrast, the rates of dissociation of ATP-G-actin subunits from the two ends are similar, about 1.4 per second from the (+) end and 0.8 per second from the (-) end (Figure 4). The rate of addition is dependent on the free ATP-G actin concentration, whereas the loss of subunits does not. The critical concentrations for both the ends are different, at the steady state the free ATP-G-actin concentration is between the C^{+}_{c} (C_c for plus end) and C^{-}_{c} (C_c for minus end), so the (+) end will grow and the (-) end will lose subunits. This process is called tread milling (Figure 5).

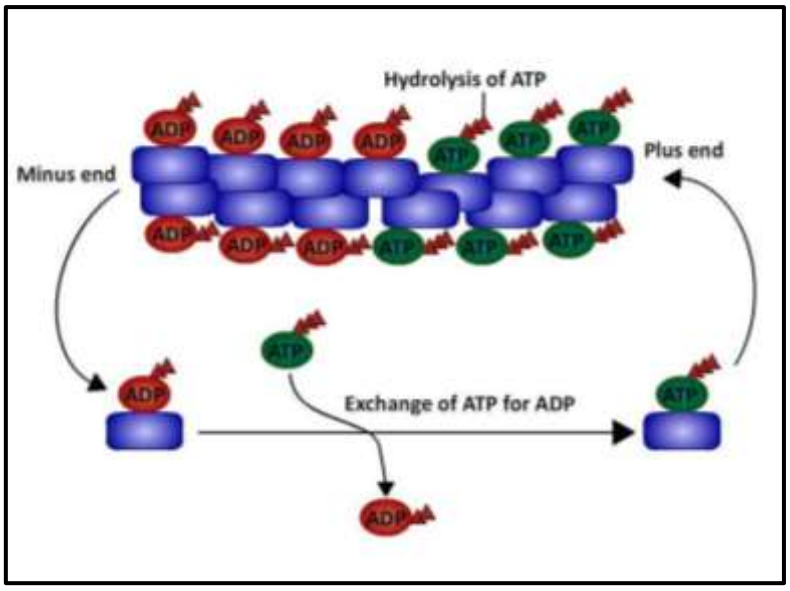

Figure 4: Treadmilling of actin filament at steady state
Source: http://www.ncbi.nlm.nih.gov/books/NBK9908/

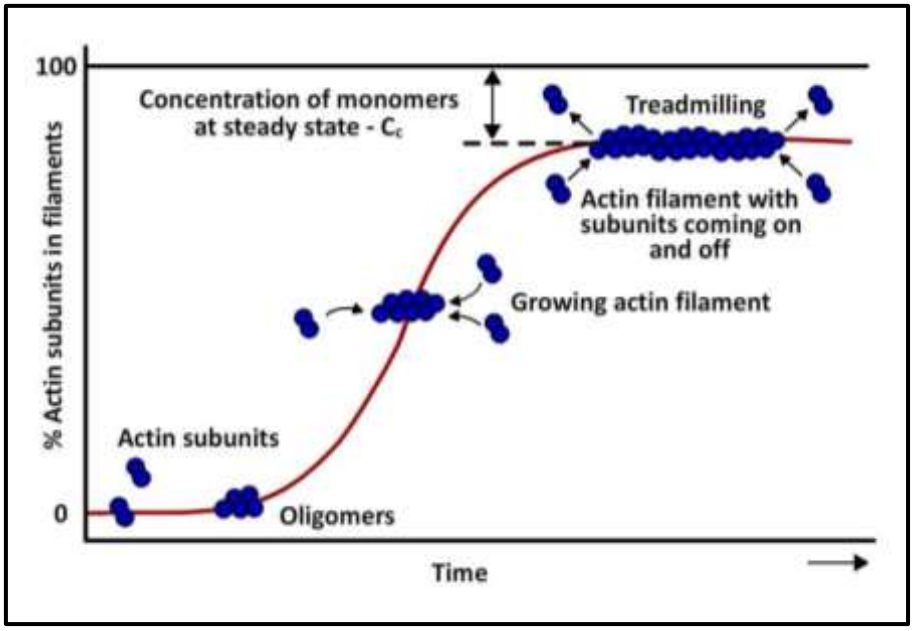

Figure 5: Phases of polymerization of G-actin
Source: https://www.studyblue.com/notes/note/n/2-microtubule-structure-and-dynamic-instability/deck/1615282

The mechanism of treadmilling is accelerated by two actin binding proteins- **profilin** and **cofilin**.

Profilin is a small protein which binds G-actin on the opposite side of the ATP binding site. When profilin is bound to G-actin, ADP is replaced by ATP which yields a profilin-ATP-actin complex. This complex can bind to the (+) end efficiently and profilin dissociate once action molecule is incorporated into the filament.

Cofilin is a small protein, binds F-actin in which the subunits contain ADP that are present toward the (-) end. It binds by interacting between two actin monomers and induces a change which destabilizes the filament, breaks into short pieces. In this way, it generates free (-) ends and the disassembly of the filament are enhanced.

3.4. Mechanism of Actin filament assembly

Assembly of actin filaments are controlled by diverse group of actin binding proteins (Figure 6).

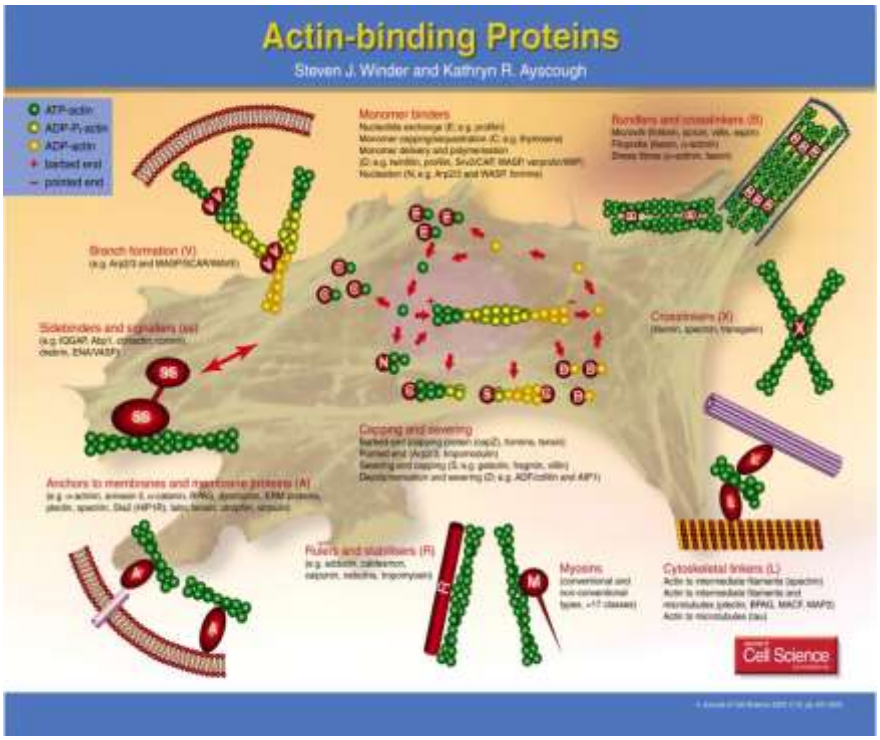

Figure 6: The diverse group of actin binding proteins with their functions.
Source: http://jcs.biologists.org/content/118/4/651.figures-only

The initial and rate limiting step in the assembly of the actin filaments is the nucleation of actin monomers. The nucleation step is co-ordinated by two classes of proteins- **formin** and **Arp2/3 (a**ctin-**r**elated **p**rotein**) complex**.

Formin protein family have two adjacent domains which are FH1 and FH2 domains, two FH2 domains associate to form a doughnut shaped complex which has the ability to nucleate actin assembly. The FH2 dimer binds two actin subunits and by rocking back and forth allows the insertion of additional subunits between the FH2 domain and the (+) end of the growing filament (Figure 7).

The FH1 domain is rich in proline residues which are the binding sites for the profilin molecules that exchange the ADP nucleotide on G actin to generate profilin-ATP-actin complexes. These complexes are provided to the FH2 domain for the assembly of actin to the (+) end of the filament. These proteins exist in a folded inactive conformation and are activated by membrane bound Rho-GTP, a Ras-related small GTPase. Thus, when Rho is switched from the inactive Rho-GDP form into its activated form Rho-GTP state, it can bind and activate the formin.

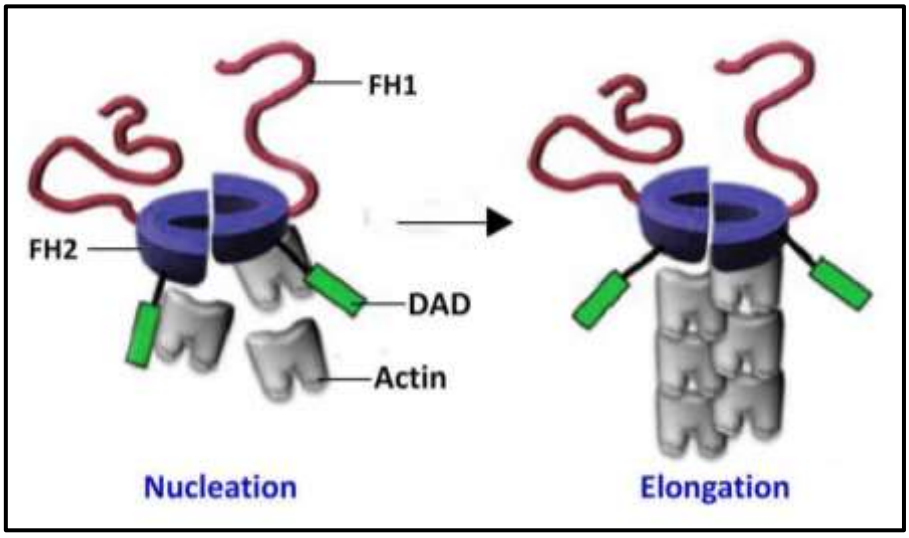

Figure 7: Actin nucleation by the formin FH2 domain
Source: http://www.cell.com/current-biology/abstract/S0960-9822 (11)00103-5

The **Arp2/3 complex** is a protein consisting of seven subunits, two of which are actin-related proteins (Arp). In its active state, it is bound with a regulatory protein, WASp and pre-formed

actin filament. When it binds to the side of F-actin in the presence of an activator, it changes conformation so that Arp-2 and Arp-3 resemble the (+) end of an actin filament which provides a template for the assembly of a new filament with a free (+) end (Figure 8). This new end grows until ATP-G actin is available or capped by a (+) end capping protein such as CapZ.

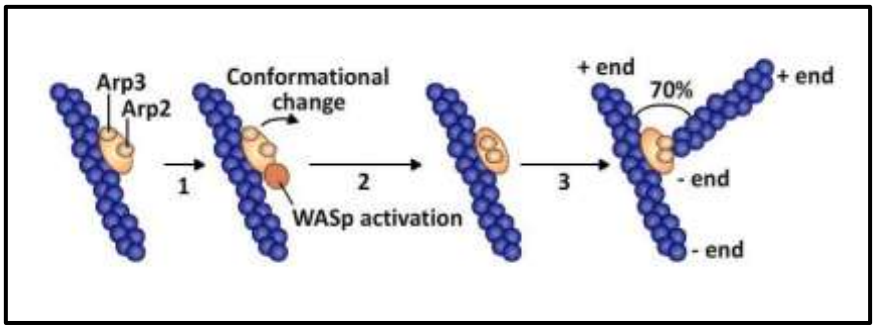

Figure 8: Actin nucleation by the Arp2/3 complex
Source: https://www.studyblue.com/notes/note/n/kollman-lecture-3-actin/deck/10763426

3.5. Myosins

Cells have another family of motor proteins called myosins which move along the actin filaments powered by ATP hydrolysis. Myosin II was the first myosin discovered from the skeletal muscle. Myosin II consists of two heavy chains and four light chains, tails of the heavy chains dimerize to form a coiled coil and light chains are associated with neck regions of heavy chains (Figure 9).

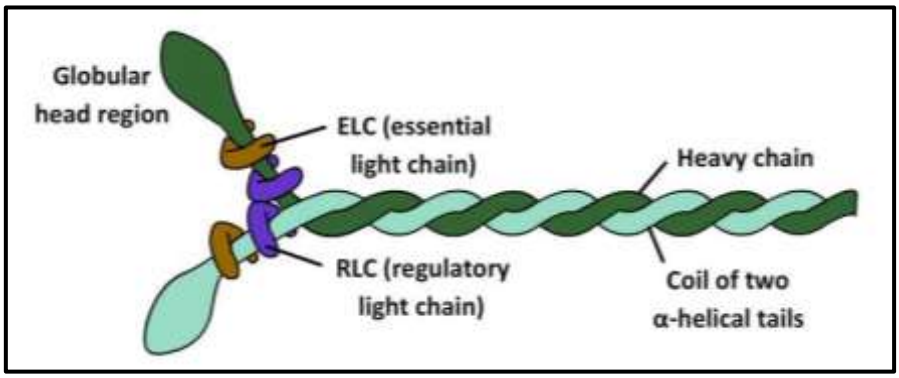

Figure 9: Structure of myosin II
Source: http://oregonstate.edu/instruction/bi314/summer09/cytoskel.html

For the movement to occur along the actin filament, myosin head requires binding of ATP which is hydrolysed to aid the movement. Myosin head has actin binding site also. Hence the myosin head uses ATP to pull on an actin filament.

There are about 40 myosin genes in the human genome which implies that these genes are paralogous in nature (Figure 10). These genes are responsible for the types of myosin present in the cell from which three classes of myosin are most studied ones. These three classes are commonly found in animals and fungi: myosin I, myosin II and myosin V.

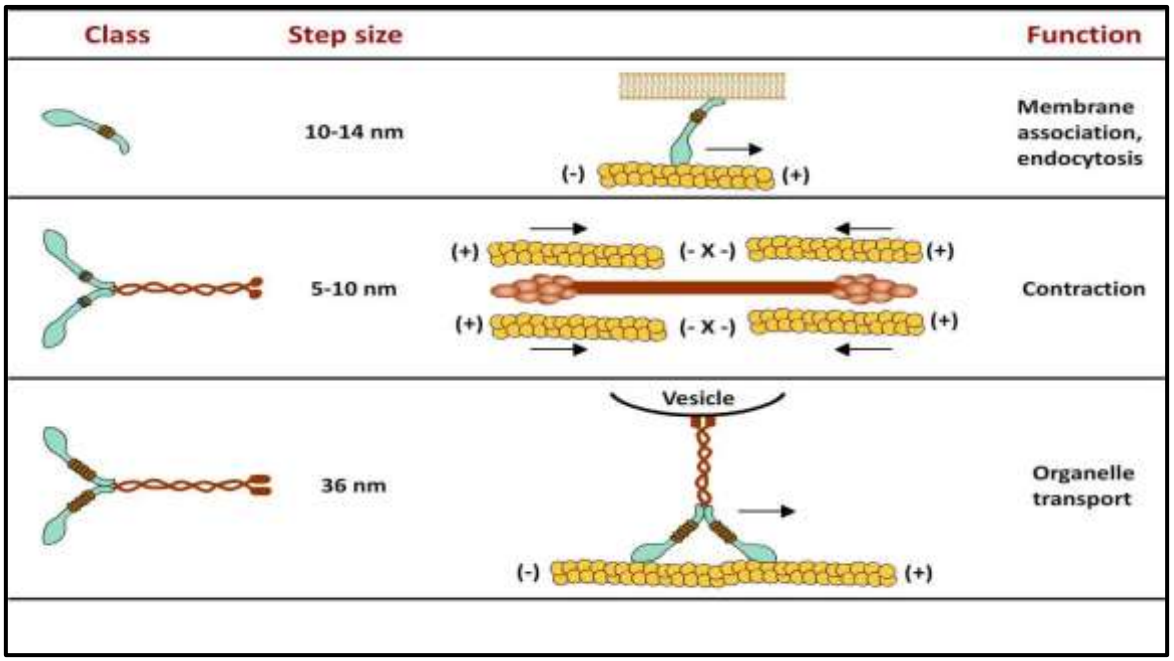

Figure 10: Three common classes of myosin
Source: Molecular Cell Biology, 6th Edition, Lodish (Figure 17-23)

4. Intermediate Filaments

These filaments are only present in cells that display a multicellular organization. They are assembled from a large number of different IF proteins. These proteins are divided into four major types based on their sequence and their tissue distribution (Table1).

Table1: Primary intermediate filaments in mammals

IF Protein	MW(10^{-3})*	Filament form	Tissue Distribution
Nuclear lamins			
Lamin A	70	Homopolymer	Nucleus
Lamin B	67	Homopolymer	Nucleus
Lamin C	67	Homopolymer	Nucleus
Keratins*			
Acidic keratins	40-57	Heteropolymers	Epithelia
Basic keratins	53-67	Heteropolymers	Epithelia
Type III Intermediate filaments			
Vimentin	57	Homo- and heteropolymers	Mesenchyme (fibroblasts)
Desmin	53	Homo- and heteropolymers	Muscle
Glial fibrillary acidic protein	50	Homo- and heteropolymers	Glial cells, astrocytes
Peripherin	57	Homo- and heteropolymers	Peripheral and central neurons
Neurofilaments			
NF-L	62	Homopolymers	Mature neurons
NF-M	102	Homopolymers	Mature neurons
NF-H	110	Homopolymers	Mature neurons
Internexin	66	-	Developing CNS

Source: Molecular Cell Biology, 5th Edition, Lodish (table19-4)

Intermediate filament–associated proteins (IFAPs) cross-link intermediate filaments with one another, forming a bundle or a network, and with other cell structures, including the plasma membrane. Only a few IFAPs have been identified, but many more will undoubtedly be discovered as researchers focus attention on the proteins that control IF organization and assembly. Unlike actin-binding proteins or microtubule-associated proteins, none of the known IFAPs sever or cap intermediate filaments, sequester IF proteins in a soluble pool, or act as a motor protein. Rather, IFAPs appear to play a role in organizing the IF cytoskeleton, integrating the IF cytoskeleton with both the microfilament and the microtubule cytoskeletons, and attaching the IF cytoskeleton to the nuclear membrane and plasma membrane, especially at cell junctions. An essential role of intermediate filaments is to distribute tensile forces across cells in a tissue. The organization of intermediate Filaments, into network and bundles, mediated by various IFAPs, provide structural stability to cells. Major degenerative diseases of skin, muscle and neurons are caused by disruption of IF cytoskeleton or its connections to other cell structures.

5. Microtubules

Structure of microtubules indicated that they are made up of 13 longitudinal repeating units which are called as protofilaments. Each protofilament consists of major protein tubulin and microtubule associated proteins, MAPs. Tubulin is a dimer consisting of α and β tubulin. Each subunit of the tubulin dimer can bind one molecule of GTP. The GTP in the α-subunit is non-hydrolyzable whereas of β-subunit is exchangeable with free GTP and hydrolysable. The protofilament have an intrinsic polarity as α-subunit is present at one end and β-subunit at the other. The end which is favourable for polymerization is the (+) end which is with exposed β subunits whereas the (-) end has exposed α-subunits (Figure 11). A singlet microtubule is built from the 13 protofilaments. In addition to the simple singlet structure, doublet microtubules are found in specialized structures such as cilia and flagella and triplet microtubules are found in centrioles and basal bodies (Figure 12).

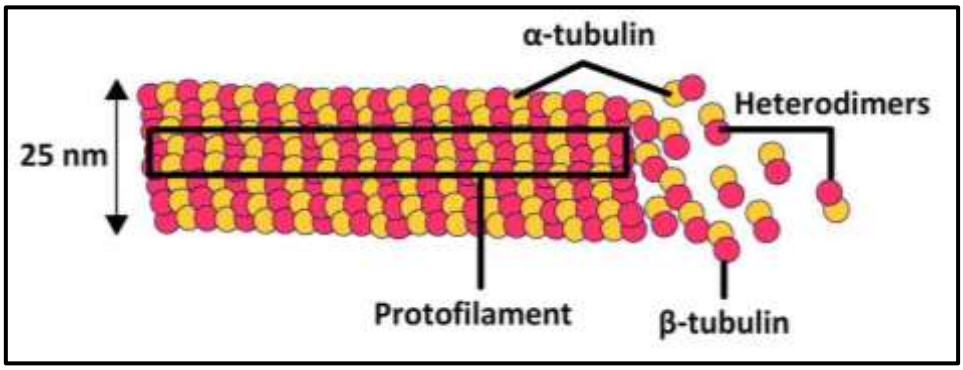

Figure 11: Structure of tubulin dimers and their organization into microtubules
Source: http://micro.magnet.fsu.edu/cells/microtubules/microtubules.html

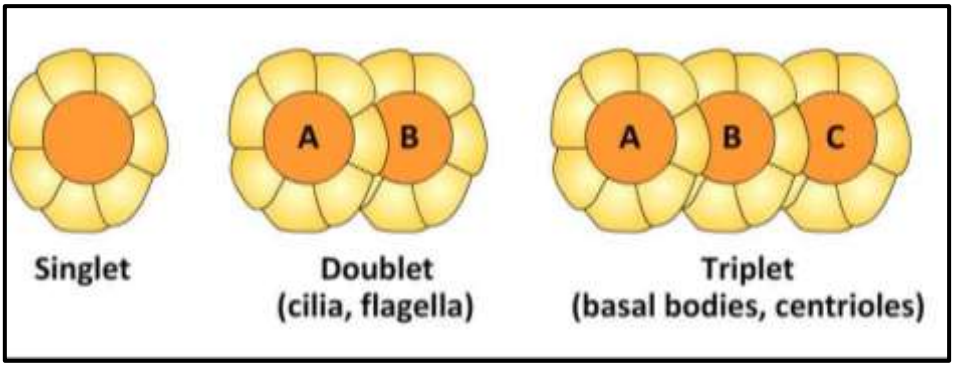

Figure 12: Singlet, doublet and triplet microtubules
Source: Molecular Cell Biology, 6th Edition, Lodish (Figure 18-4)

5.1. MTOCs (Microtubule-organizing centres)

All microtubules are nucleated from structures known as microtubule-organizing centres or MTOCs. The (-) end of the microtubule stays anchored in the MTOC. In interphase cells, the MTOC is known as the centrosome and located near the nucleus, producing a radial array of microtubules with their (+) end toward the cell periphery. During cell division, reorganization of microtubules occurs to form a bipolar spindle for the segregation of copies of the duplicated chromosomes. In cilia and flagella, microtubules are assembled from an MTOC called a basal body. Centrosomes in animal cells consist of a pair of orthogonally arranged cylindrical centrioles surrounded by apparently amorphous material called pericentriolar material. Y-tubulin ring complex present in the pericentriolar material is an important component for nucleating the cytoplasmic microtubule array (Figure 13).

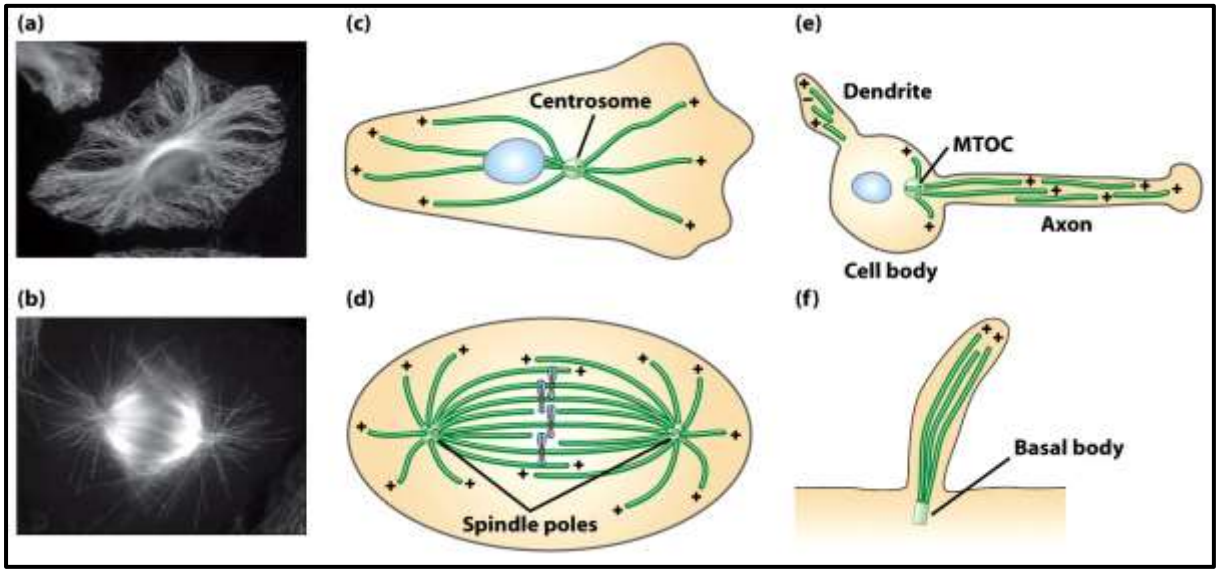

Figure 13: Microtubules are assembled from MTOCS
Molecular Cell Biology, 6th Edition, Lodish (Figure 18-5)

5.2. Microtubule dynamics

Assembly of microtubules is catalysed by the presence of microtubule-associated proteins (MAPs). The polymerization of microtubules involves three phases which are:

i. Slow nucleation phase
ii. Elongation phase

iii. Steady state phase

The assembly to occur, the αβ-tubulin concentration must be at the critical concentration.

Tubulin dimers add faster to one end which is the (+) end with exposed β-tubulin. The critical concentration is lower at the (+) end than at the (-) end. At steady state phase αβ-tubulin concentration is higher than the C_c for the (+) end whereas for the (-) end, it is lower. This condition results in the net addition to (+) end and loss from the (-) end, this process is known as **treadmilling** (Figure 14).

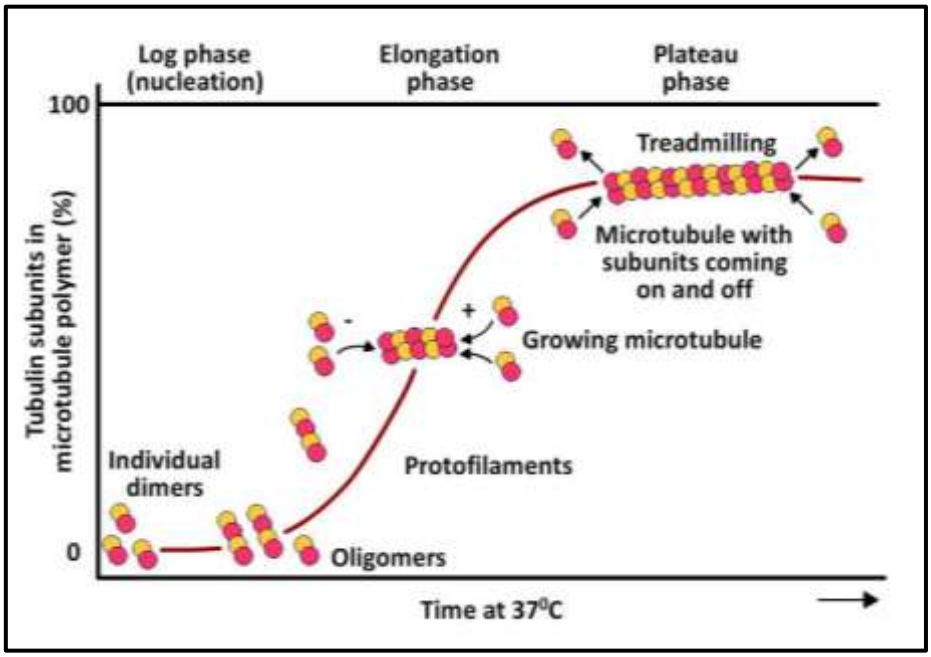

Figure 14: Phases of polymerization of tubulin dimers into microtubules

Microtubules also possess the ability to undergo dynamic instability which is distinct from the phenomenon of treadmilling. **Dynamic instability** is the process in which individual microtubule alternate between cycles of growth and shrinkage. The growth or shrinkage is determined in part by the rate of tubulin addition relative to the rate of GTP hydrolysis. As long as new GTP-bound tubulin molecules are added more rapidly than GTP is hydrolysed, the microtubule retains a GTP cap at its plus end and microtubule growth continues. Studies have shown that individual microtubules could grow and then suddenly undergo a *catastrophe* to a shrinking phase, but sometimes depolymerizing microtubule end go through a *rescue* and begin growing again (Figure 15). This process was observed in vitro by injecting

fluorescently labelled microtubules into live cells and named as *dynamic instability* of the microtubules. It is subjected to (+) end of the microtubule.

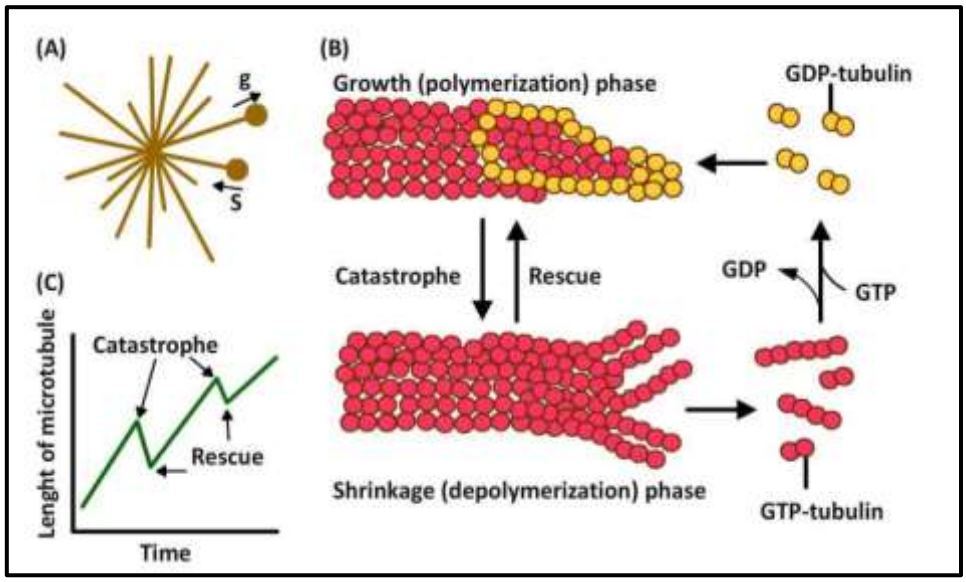

Figure 15: Dynamic instability of microtubules
Source: http://www.sciencedirect.com/science/article/pii/S096289240202295X

5.3. Regulation of Microtubule Structure and Dynamics

Microtubules are stabilized by the binding of microtubule-associated proteins (MAPs) and among these proteins are *tau* family of proteins (tau itself), MAP2 and MAP4.Tau proteins act as spacers between the microtubules and MAP2 forms fibrous cross bridges between microtubules and links them to intermediate filaments. Some of the MAPs associate with the (+) ends of microtubules and in some cases only the (+) ends of growing, not shrinking ones. This class of proteins is called +TIPs. Some of the TIPs stabilize the (+) end against a catastrophe or enhance the frequency of rescues, thus promotes the continued growth of the microtubule and others provide the aid for the attachment to the organelle.

Microtubules are disassembled also with the help of certain proteins such as Kinesin-13 family of proteins and oncoprotein 18 (Op18/stathmin). Kinesin-13 proteins bind and curve the end of the protofilaments into the GDP-β-tubulin conformation which facilitates the removal of terminal tubulin dimers and the rate of catastrophes is increased. Op18 also binds to two tubulin dimers in a curved, GDP-β-tubulin like conformation enhancing the rate of

catastrophes. It may also work by enhancing the hydrolysis of GTP in the terminal tubulin dimer and hence its dissociation is fastened.

5.4. Microtubular motors and movements

The major two motor proteins are responsible for powering the variety of movements which are- kinesins and dyneins. Kinesins and dyneins move along microtubule in opposite directions, kinesins move toward the plus end and dyneins toward the minus end.

Kinesin is a dimer of two heavy chains, each associated with a light chain (Figure 16). It comprises of the following domains:

i. a pair of globular head domains- binds microtubules and ATP
ii. short flexible linker domain- for forward motility
iii. a central stalk domain- dimerization of the two heavy chains
iv. a pair of small globular tail domain- binds to receptors on the membrane of cargoes

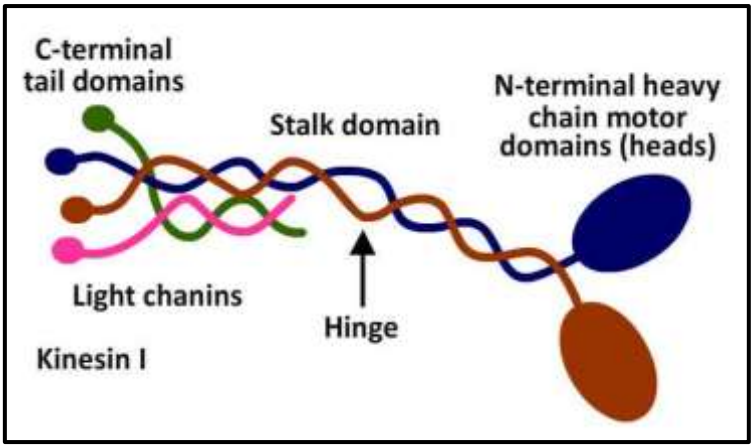

Figure 16: Structure of kinesin protein molecule
Source: https://www.rpi.edu/dept/bcbp/molbiochem/MBWeb/mb2/part1/kinesin.html

5.5. Kinesin is a highly processive motor protein

The double headed molecule of kinesin takes 8 nm step from one β-tubulin subunit to the next on the same protofilament in the microtubule (Figure 17). This entails each individual head taking 16 nm and two heads work in a highly co-ordinated manner along the microtubule.

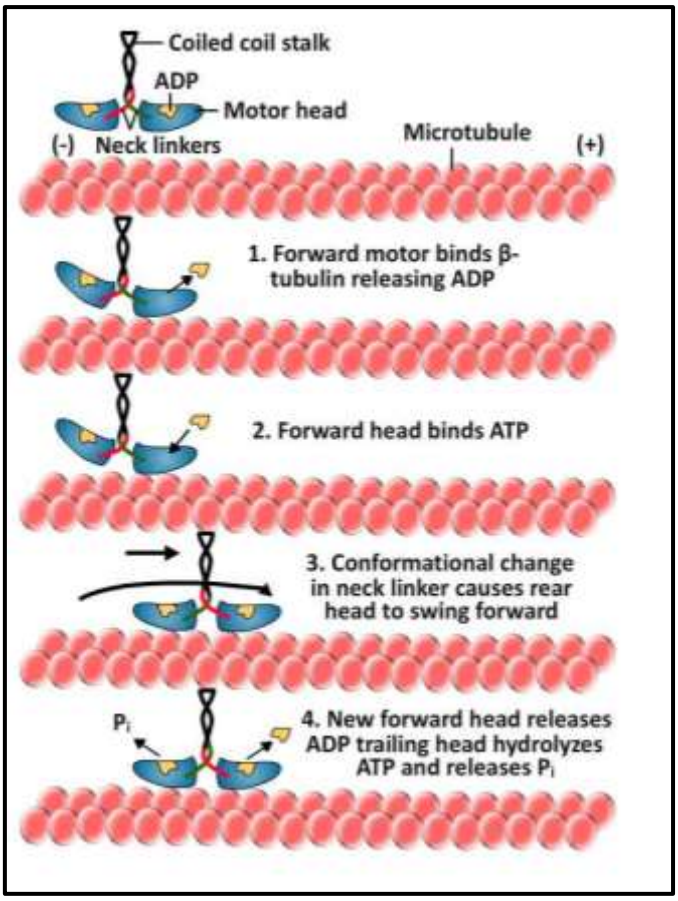

Figure 17: Kinesin uses ATP to walk down a microtubule
Source: Molecular Cell biology, 6th edition, Lodish (Figure 18-22)

i. ADP is bound to each kinesin heads, loss of ADP is induced when one head binds to the β-tubulin subunit giving rise to a nucleotide free state and strong binding of that head to the microtubule.
ii. The leading head then binds ATP which induces a conformational change causing the linker region to point forward, dock into the head domain and so thrust the trailing head forward.
iii. The leading head binds the microtubule and releases ADP, which induces the trailing head to hydrolyze ATP to ADP and $P_{i.}$
iv. P_i is released and the trailing head can now dissociate from the microtubule and the cycle is repeated.

5.6.Dynein

Dynein motor protein transports organelle towards the (-) end of the microtubules. This is a two-headed molecule built around two identical heavy chains (Figure 18). A single dynein heavy chain consists of a stem and around head domain containing the ATPase activity, from which protrudes a stalk having microtubule binding site.

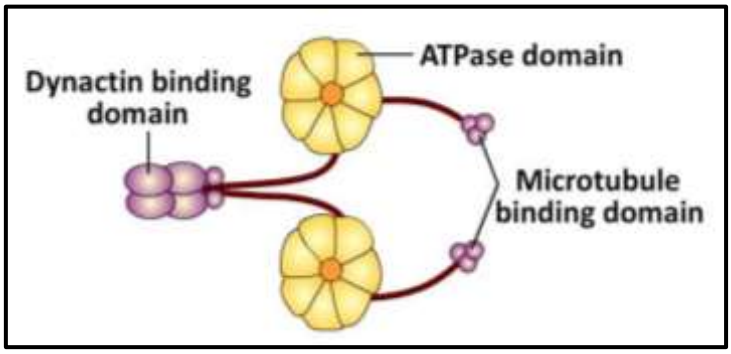

Figure 18: Structure of cytoplasmic dynein
Source: Molecular Cell biology, 6th edition, Lodish (Figure 18-24)

Dynein requires the **dynactin,** the protein complex which links dynein to the cargo and regulate its activity (Figure 19).

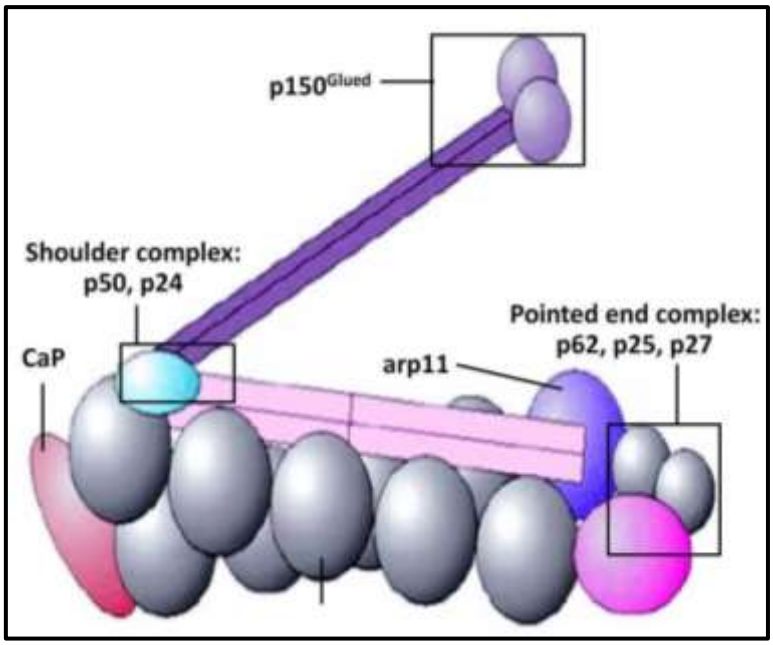

Figure 19: The Dynactin complex
Source: http://www.pnas.org/content/102/10/3667.figures-only

5.7. Microtubule Dynamics in Mitosis

Mitosis is the process that separates newly replicated chromosomes equally into daughter cells. Specialized microtubular structure called mitotic apparatus which undergoes cycle of assembly and disassembly during the course of mitosis.

At metaphase stage of mitosis, it is organized into two parts; a central mitotic spindle and a pair of asters (Figure 21). The spindle is a bilaterally symmetric bundle located at the opposite ends of the cell. An aster is a radial array of microtubules at each pole of the spindle. Formation of the mitotic spindle involves stabilization of microtubules radiating from the centrosome (Figure 20)

These microtubules are of four types:

i. **Kinetochore microtubules** attach to the centromeres of the condensed chromosomes. Centromeres are associated with specific proteins to form kinetochore, where these microtubules are attached.
ii. **Chromosomal microtubules** attach to the ends of the chromosomes via chromokinesin.
iii. **Polar microtubules** are not attached to the chromosomes, they overlap with each other and get stabilized.
iv. **Astral microtubules** are the ones which extend outward from the centrosomes to cell periphery and have exposed plus ends.

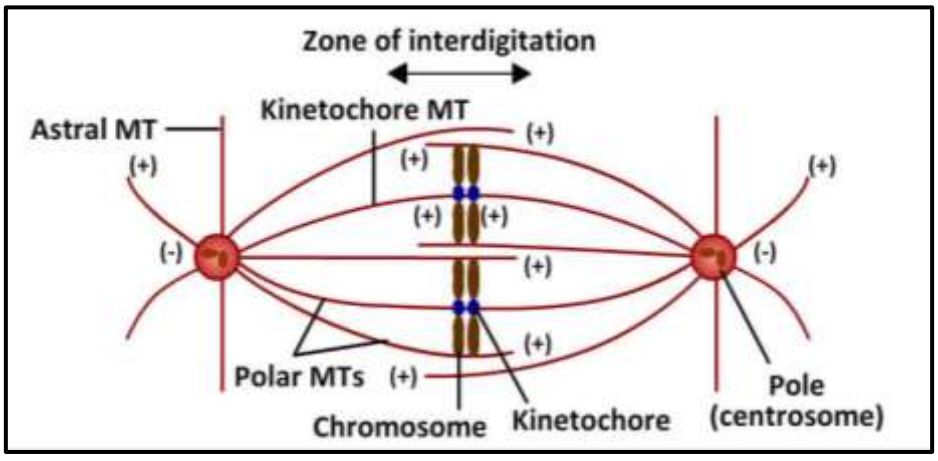

Figure 20: Types of microtubules
Molecular Cell biology, 6th edition, Lodish (Figure 18-36)

Mitosis can be divided into six phases:

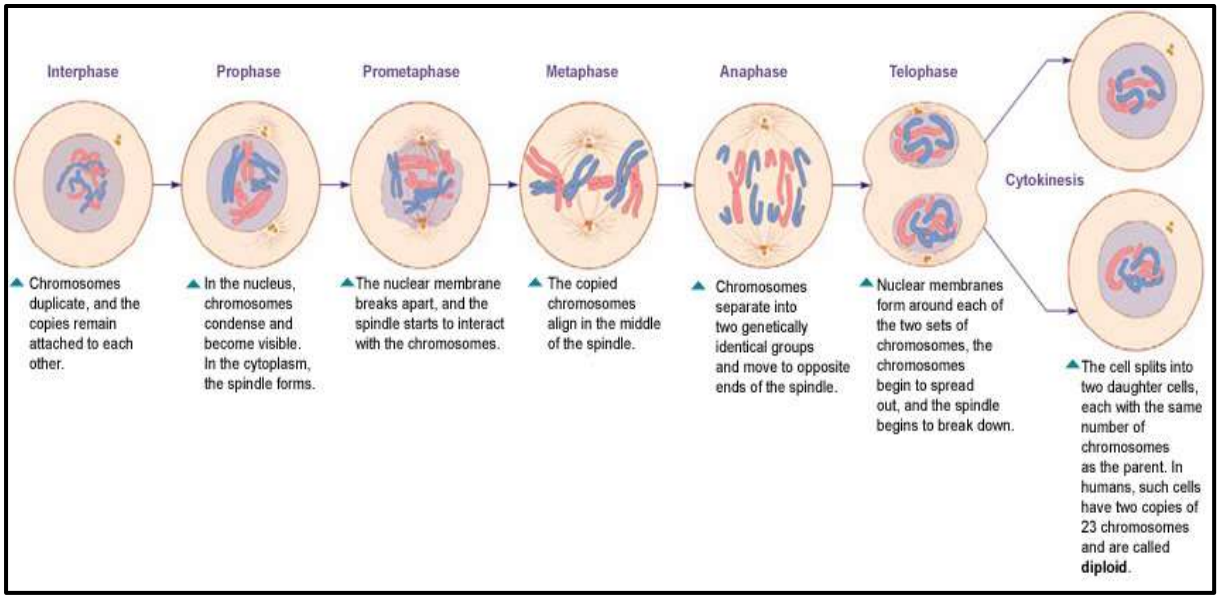

Figure 21: Stages of mitosis
Source: http://publications.nigms.nih.gov/insidethecell/ch4_phases_allbig.html

As cells enter mitosis, the activity of the two MTOCs increases greatly as they accumulate more pericentriolar material. Microtubules in the mitotic spindle treadmill constantly in addition to being highly dynamic.

Kinetochores help in the movement of chromosomes and contain many protein complexes to link the centromeric DNA to microtubules. In animal cells, the kinetochore consists of an inner centromeric and inner and outer kinetochore layers. Plus ends of the kinetochore microtubules terminating in the outer layer (Figure 22). Microtubules which are attached to the kinetochores do not undergo catastrophic phase which promotes the persistence of their attachment.

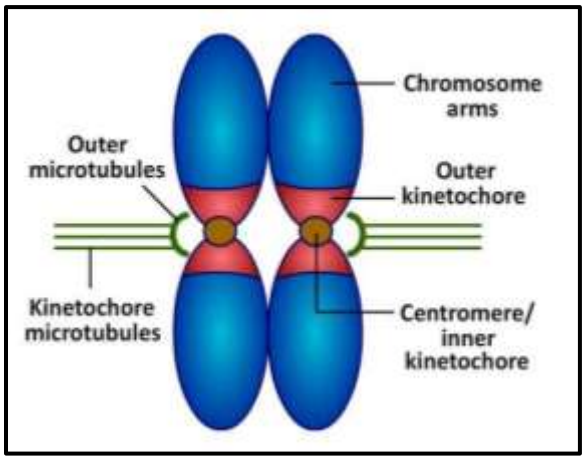

Figure 22: Structure of kinetochore
Source: http://www.nature.com/nrg/journal/v2/n8/fig_tab/nrg0801_584a_F1.html

Chromosomes become attached to any end of the microtubules, the duplicated chromosome is then drawn toward the spindle pole by kinetochore-associated dynein/dynactin as this motor moves towards the (-) end of a microtubule. Microtubule from the opposite pole finds and attached to the free kinetochore and the chromosome is said to be **bi-oriented**.

Bi-oriented chromosomes then move to a central point between the spindle poles in a process known as chromosome congression. During this process, chromosome pairs oscillate backward and forward before arriving at the mid-point (Figure 23). This oscillating behaviour involves lengthening of microtubules from one side and shortening from the other side.

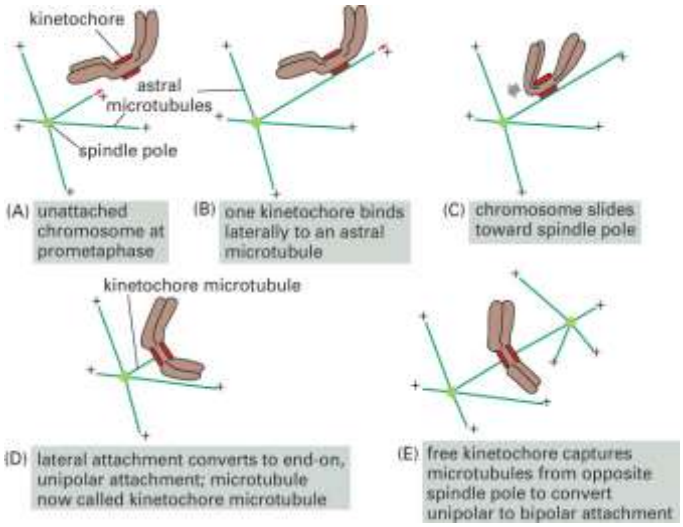

Figure 23: Kinetochore during prometaphase
Source: http://www.pha.jhu.edu/~ghzheng/old/webct/note7_5.files/Image4.jp

When chromosomes are brought to the metaphase plate successfully, the cell is ready to undergo anaphase. The first phase of the anaphase is the onset of anaphase A which is the stage when chromatids separate from each other and drawn to opposite poles and this movement is powered by microtubule shortening. The second phase of anaphase involves separation of the spindle poles which is called anaphase B (Figure 24). This movement is achieved with the help of kinesin and dynein proteins.

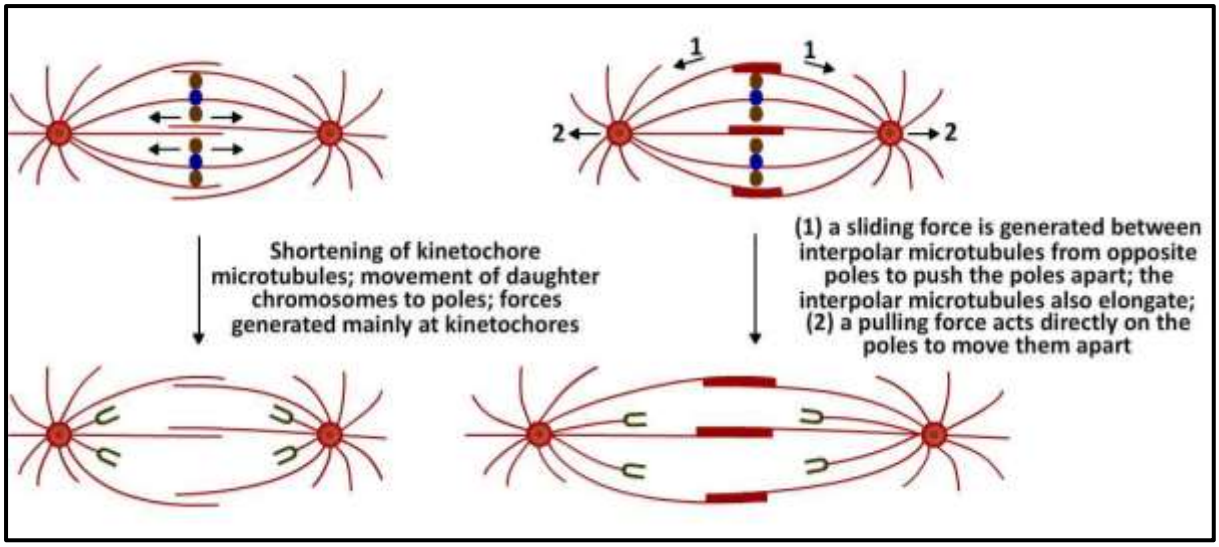

Figure 24: Kinetochore during anaphase
Source: http://www.pha.jhu.edu/~ghzheng/old/webct/note7_5.htm

Cytokinesis splits the daughter cells in two with the help of forming microtubule-based *contractile ring* which is attached to the plasma membrane that will eventually contract and pinch the cell into two.

6. Summary

Cytoskeleton is a cytoplasmic system of fibres which is critically involved in cell motility and cell support. Three types of fibres- Microfilaments, Intermediate filaments and microtubules comprise the complete cytoskeleton. They involved in movement of cell and its organelles. So, they play an important role in major cellular processes and ATP has also involved in their structural arrangements.