VALVE TIMING

This note explains the valve timing (for inlet and exhaust valves) of the four-stroke engine (intake, compression, power or combustion, exhaust).

Four-stroke cycle

Short explanation

Engines do the same things over and over again. Therefore, we concentrate on one series of events – a cycle – until they begin to repeat themselves. Most internal combustion engines are four-stroke engines, implying four strokes of the piston, two up and two down, in each cycle. The crankshaft makes two revolutions during every cycle.

The piston starts at the top of the cylinder (TDC, top dead center). On the first stroke – *intake* – the piston moves down and an air-fuel mixture is drawn into the cylinder through the inlet port. When the piston is at the bottom of the cylinder (BDC, bottom dead center), the cylinder is full of air-fuel mixture.

Then, the inlet valve is closed and the piston goes up again. This second stroke – *compression* – squeezes up the content of the cylinder into a small space at the top of the cylinder. The piston is back where it started from, and the crankshaft has gone all the way around once.

About the time the piston reaches the top of its second stroke, the mixture is ignited. It starts burning and expands. The pressure forces the piston down to its bottom position again. This third stroke – *power* or *combustion* – makes the engine run.

The fourth stroke is the *exhaust* stroke. The exhaust valve has opened and the exhaust gases, the result of burning the air-fuel mixture, start escaping through it. As the piston rises it pushes them out the valve port. At the end of this stroke the cylinder is practically clear of the burned gases, and the piston is back in its top position.

There is only one power stroke every second revolution of the engine.

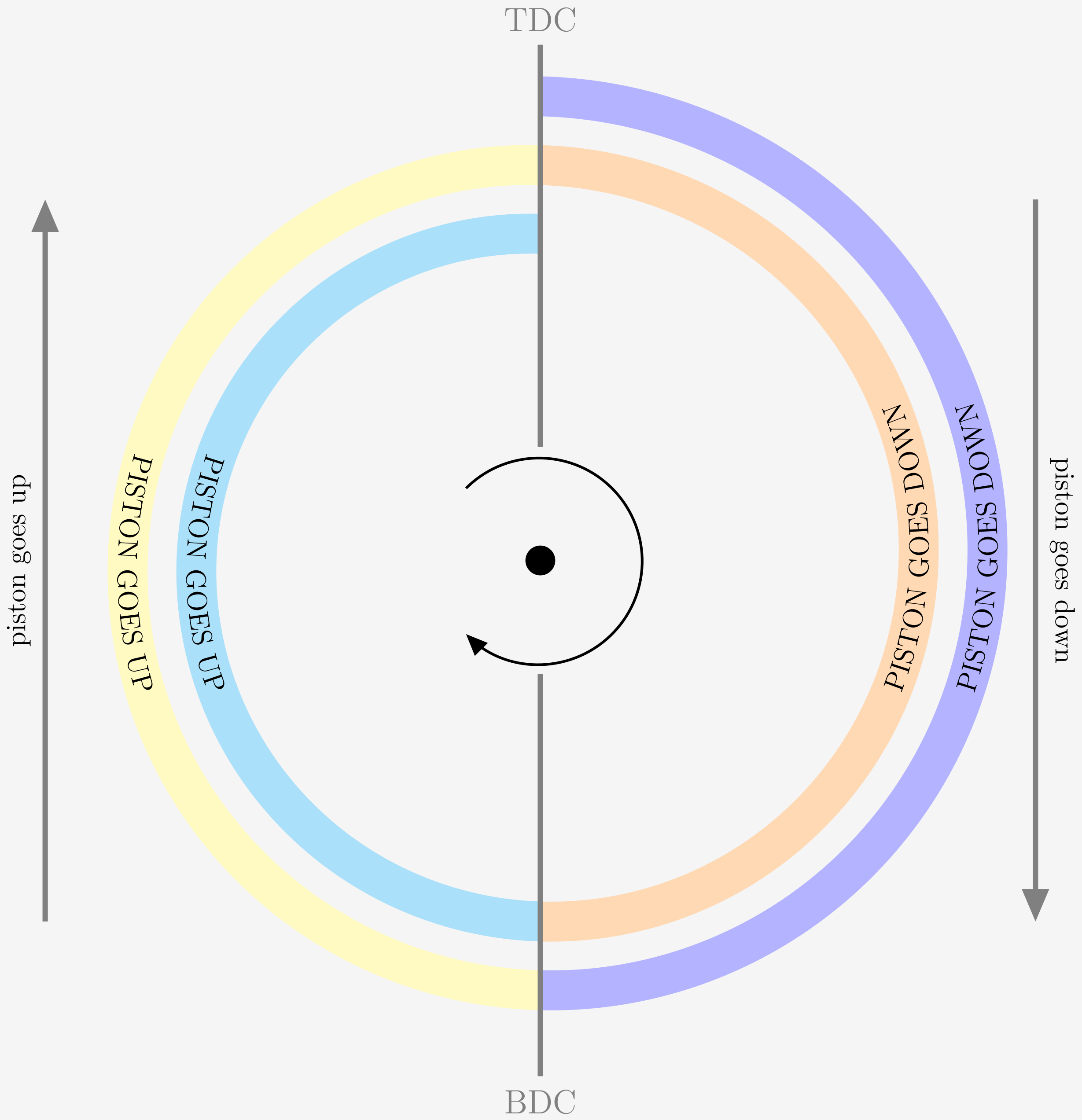

Figure 1: Four-stroke cycle, piston movements.

Graphical representation

The four strokes – a cycle – and its valve timing are graphically represented in a spiral of two circles showing the two crankshaft revolutions. For example, when the piston goes down from TDC to BTC, this corresponds to 180 degrees of crankshaft revolution, or put in other words half a revolution.

The first example (Figures 1, 2 and 3) is a fictive one, assuming that inlet and exhaust valves exactly open at TDC and BDC. Moreover, ignition is also assumed to take place at TDC. Such an engine could theoretically exist, but would poorly perform, as explained below.

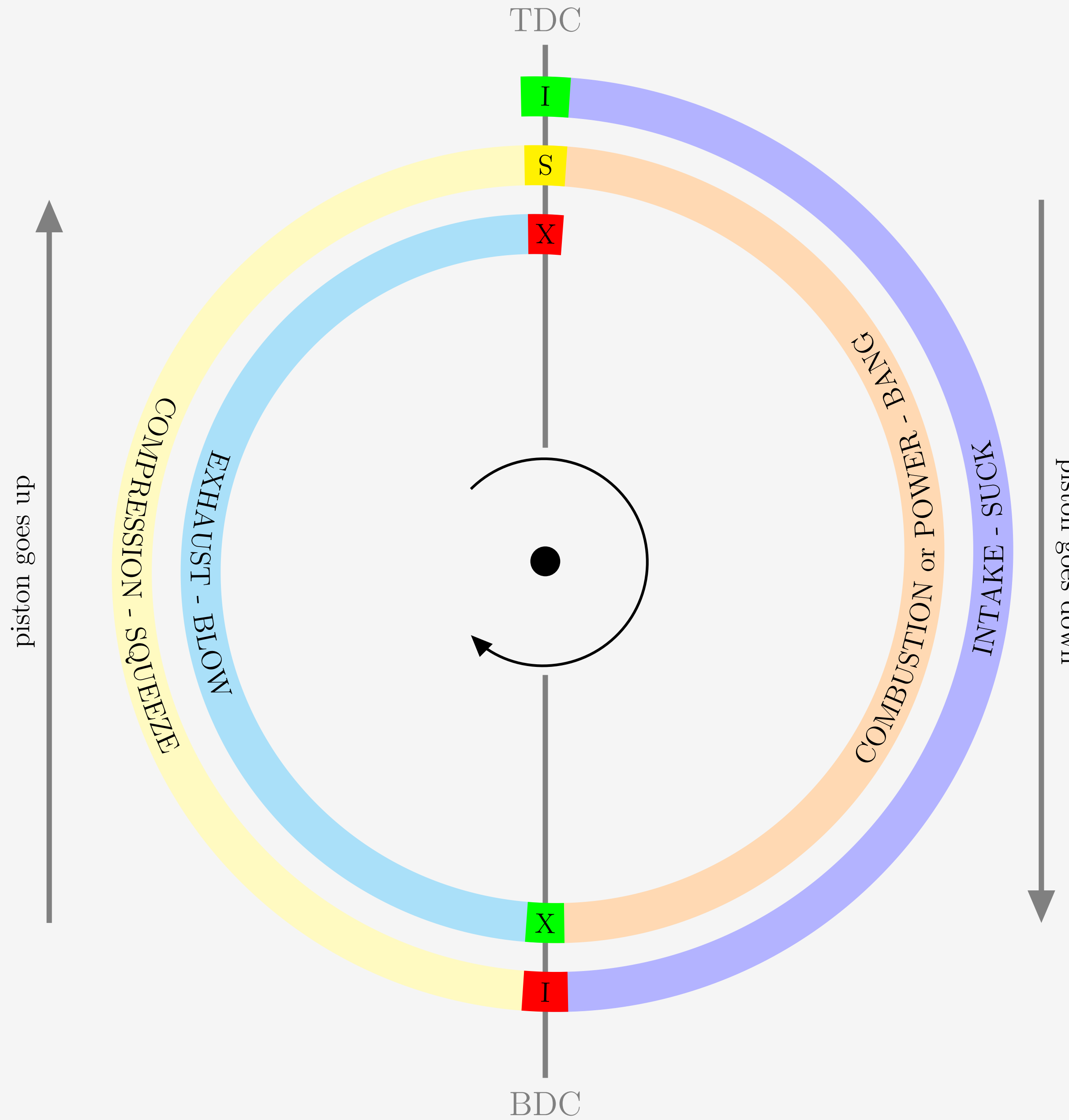

Figure 2: Fictive four-stroke cycle.

For the valve timing, we use the following acronyms: I, inlet valve, and X, exhaust valve. When a valve starts opening, it is green marked, when it is fully closed it is red marked. The ignition is represented with a yellow S.

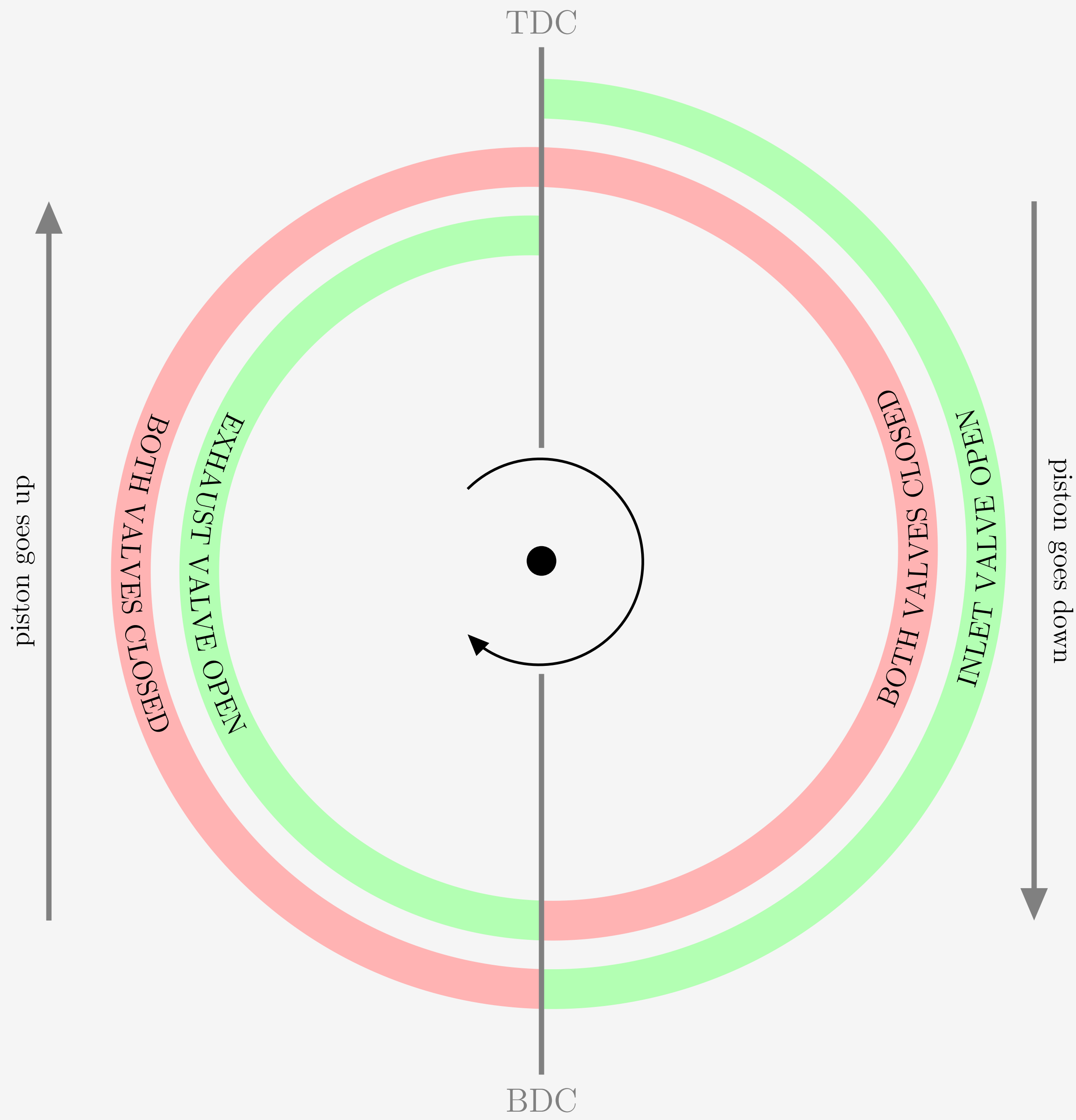

Figure 3: Fictive four-stroke cycle, valve timing.

Valve timing

Intuition

A valve cannot move from closed to fully open (or vice versa) instantaneously. The opening and the closing movements are each spread over a considerable angle of crankshaft rotation. Moreover, engines give their best performance when the greatest mass of air-fuel mixture is passed through the combustion chamber, burnt effectively, and its gases quickly eliminated. Therefore, valves have to open earlier and to close later than in the fictive example.

The same is true for the ignition timing. The ignition should happen before TDC, because the explosion of the mixture and the gas expansion take time.

Intake stroke

The downward movement of the piston reduces the pressure inside the cylinder so that the atmosphere pressure forces the air-fuel mixture along the inlet pipe. Moreover, the mixture flow along the pipe is accelerated. However, the resistance of the mixture causes it to lag behind the piston movement, so that by the time the piston reaches its maximum speed (about half-way down the stroke) the pressure inside the cylinder is well below atmospheric pressure. During the second half of the stroke, when the piston speed decreases, the mixture flow is able to catch up with the piston and the pressure inside the cylinder rises towards atmospheric pressure.

Compression stroke

At BDC the direction of piston movement reverses. However, the momentum of the mixture flow along the inlet pipe towards the cylinder causes it to continue entering the cylinder, until the piston has moved some way up – provided the inlet valve remains open. At some point during this stroke, the upward movement of the piston increases the pressure, the inlet valve closes and the greatest possible amount of mixture is trapped inside the cylinder. The inlet valve ideally closes just after BDC.

Power stroke

At about the end of the compression stroke, but before TDC, the compressed air-fuel mixture is ignited. The mixture burns once ignited, which increases the gas pressure even further and the piston is forced down the cylinder on its power stroke. During the downward movement of the piston, the increasing volume lowers the pressure of the gas within the cylinder, but as long as the exhaust valve remains closed the pressure is still well above atmospheric when the piston arrives at BDC.

Exhaust stroke

The pressure that exists at the bottom of the power stroke offers some resistance to the upward movement of the piston during the exhaust stroke, even though the exhaust valve may now be open. Moreover, as the piston approaches BDC in the power stroke, the leverage or effort exerted by the connecting rod on the crankshaft decreases rapidly because of the angle between the connecting rod and crankshaft. The pressure on top of the piston has a rapidly reducing effect on the rotation of the crankshaft. By opening the exhaust valve early, i.e. before BDC in the power stroke, a good deal of the burnt gas is allowed to escape before the piston begins its upward exhaust stroke. Therefore, the pressure remaining in the cylinder is much lower and consequently the opposition to the piston upward movement is very much reduced.

When the piston is actually on the exhaust stroke, the rising piston then increases the gas velocity along the exhaust pipe. As the piston approaches TDC and its upward velocity decreases, the pressure in the cylinder which is forcing out the exhaust gas progressively reduces. Additionally, the momentum of the gas that already rushes along the exhaust pipe actually creates a lower pressure inside the cylinder.

Because there is now a low pressure in the cylinder, if the inlet valve is now opened, fresh mixture begins moving into the cylinder. The opening of the inlet valve can usually occur before the piston has reached TDC on the exhaust stroke. So by opening the inlet port before the exhaust port has closed, the momentum of the exhaust gas is used to start the flow of fresh mixture into the cylinder without any help from the piston.

Fresh mixture entering the cylinder is drawn towards the exhaust port thus helping to displace the exhaust gas. Placing the valves on opposite sides of the combustion chamber makes the fresh mixture sweep right across the chamber on its way from inlet port to exhaust port. This ensures that the combustion chamber is thoroughly scavenged, or cleared of exhaust gas and filled with fresh mixture. The correct moment to close the exhaust port is the moment the fresh mixture reaches the exhaust port.

The inlet valve usually opens a little before TDC and the exhaust valve remains open a little after TDC. Thus, for some angle of crankshaft rotation around TDC both valves are open at the same time (valve overlap). While a large valve overlap may be beneficial at high engine speeds, it is difficult for the engine to idle or run slowly at light load. At low engine speeds and small throttle openings the pressure in the inlet manifold is well below atmospheric pressure. Under these conditions, opening the inlet valve before the exhaust valve closes results in a rush of exhaust gas into the inlet manifold. Therefore, on the following intake stroke the fresh charge drawn into the cylinder includes exhaust gas. This certainly results in a lower efficiency of the combustion process because a proportion of the charge has exhaust gas instead of the required air-fuel mixture. The ignition and burning of this contaminated mixture is difficult and results in loss of power and misfires.

The graphical representation can be found in Figures 4 and 5.

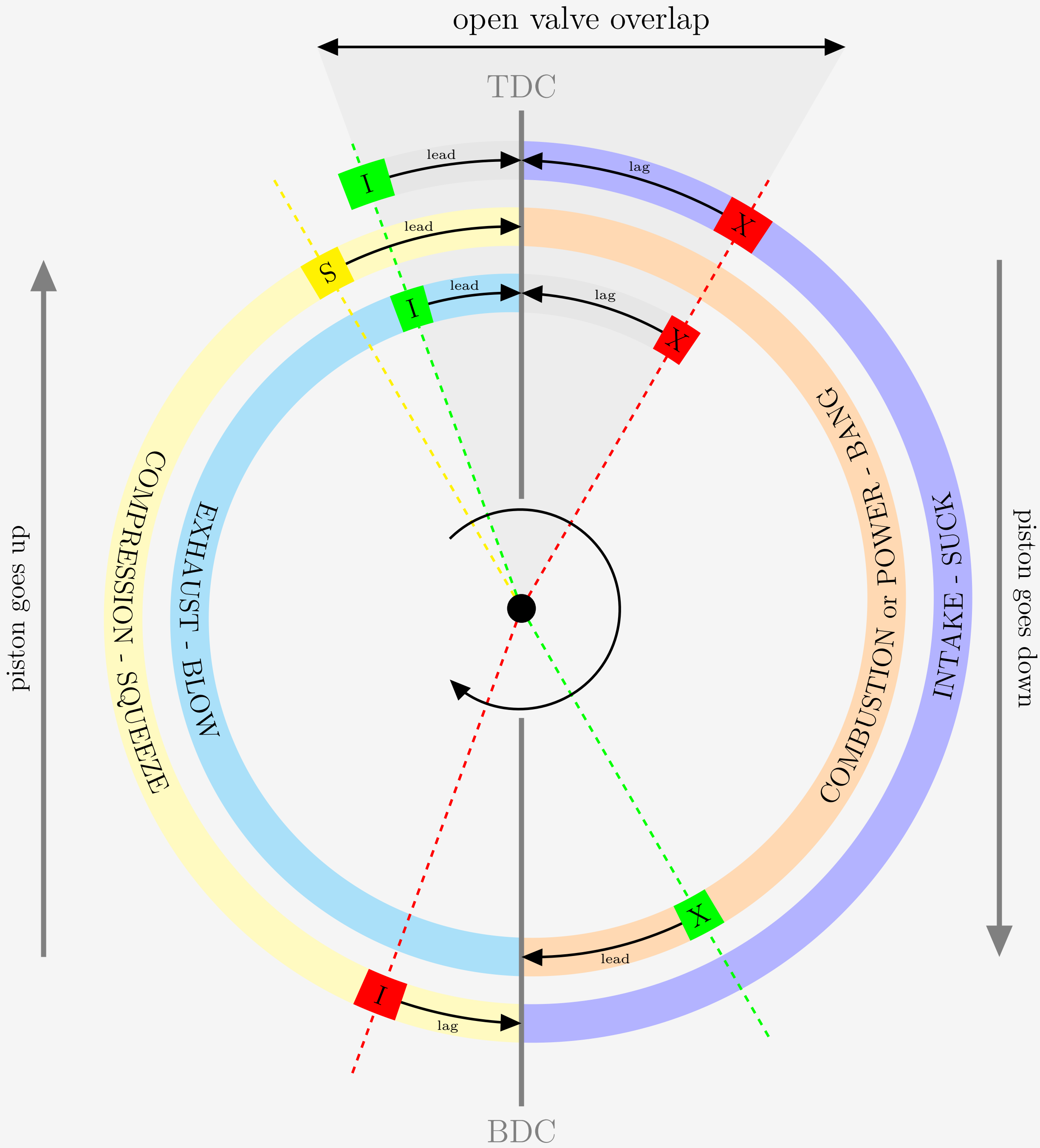

Figure 4: Realistic four-stroke cycle.

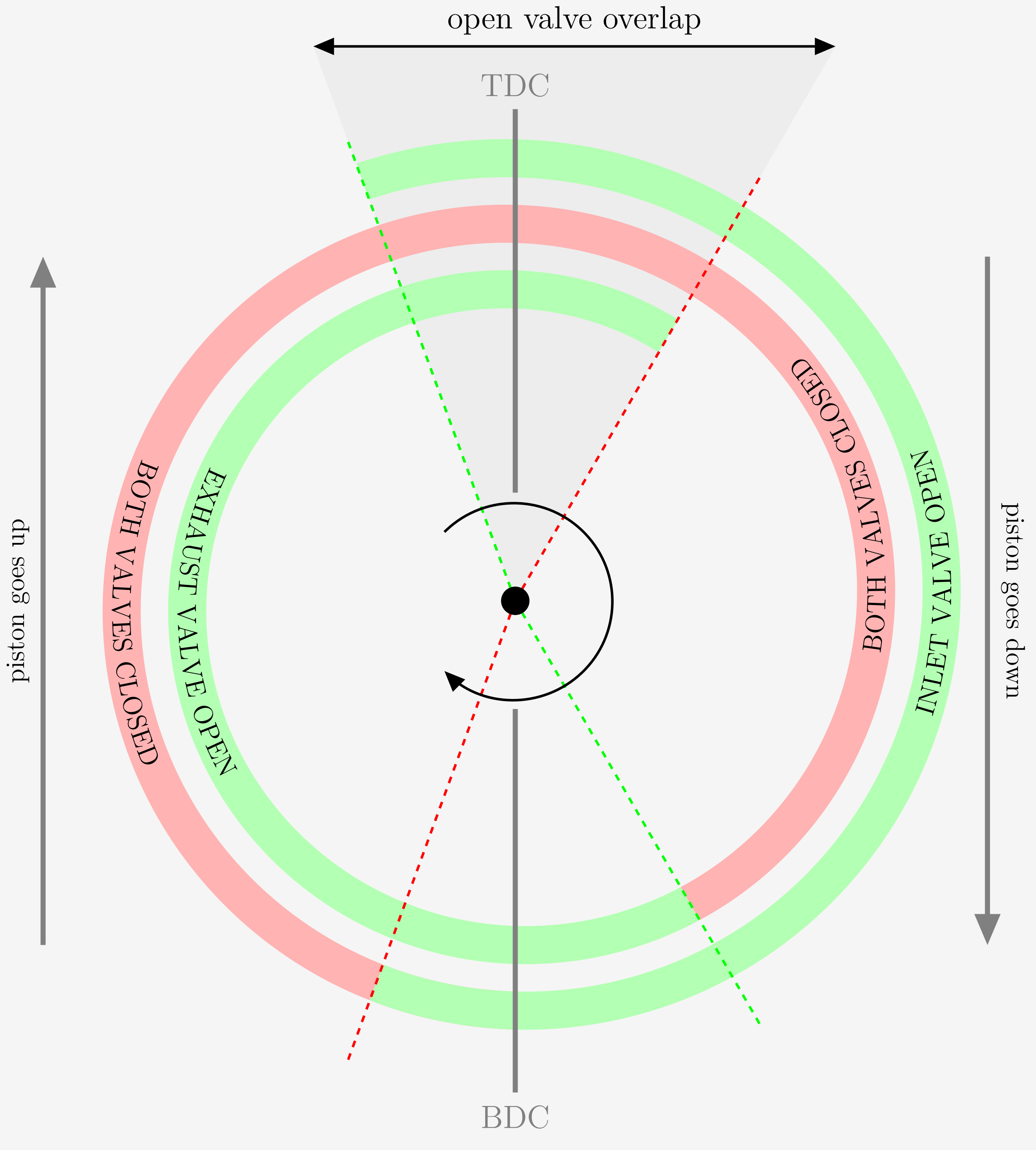

Figure 5: Realistic four-stroke cycle, valve timing.

Main messages

- ✓ **Inlet valve closing lag**. The inlet valve remains open after the piston has passed BDC at the end of the intake stroke.
- ✓ **Exhaust valve opening lead**. The exhaust valve opens before the piston reaches BDC at the end of the power stroke.
- ✓ **Exhaust valve closing lag**. The exhaust valve remains open after TDC at the end of the exhaust stroke.

- ✓ **Valve overlap** and **inlet valve opening lead**. The inlet valve opens before the exhaust valve has closed and usually before TDC.
- ✓ **Engine characteristics**. The amount of lead (or lag) of valve opening (or closing) points, and the amount of overlap depend upon the design of the engine and its performance characteristics.
- ✓ **Valve timing**. The opening and closing points of the valves in relation to piston and crankshaft position are called the 'valve timing'.

(compiled October 5, 2024)