2 The purpose of these notes

The format of this activity is somewhat different from the others. The challenges are not described in this Handbook but will be presented to you at the Residential School on a series of Challenge Sheets. The notes in this Handbook contain background information and resources that will provide you with a theoretical understanding of the practical principles that you will be applying in Robotics Activity and that will help you complete the challenges. At the Residential School itself you will have an opportunity to complete several hands-on exercises that illustrate the principles described in the background resource information.

The notes also include several short exercises for you to check your understanding of the material. You are strongly encouraged to read through these notes before attending the Residential School.

3 The challenge-based approach

Throughout this activity, you will be set several challenges. For example, one challenge might be to program your robot to drive between various checkmarks placed on the ground, or to use a light sensor to track a moving infrared light source.

The tasks are defined as challenges for various reasons:

• there may be several ways of achieving a solution to the task, rather than a single best approach;

• it may be possible to refine any particular solution and improve its performance against some measure (such as time taken to complete the task, or precision achieved while completing the task).

Challenges implicitly incorporate some performance measure that you can use to rate the effectiveness of your solution, such as the time taken for the robot to complete a task, or the accuracy with which it does so.

There is thus a mildly competitive element to the activity – both against oneself (trying to improve the quality of one’s own solution) and against other groups. There is little point simply copying someone else’s work especially if you don’t refine it – your solution is unlikely to be better than theirs and you may not fully understand how it was arrived at.

4 Mechanical considerations

One of the most important mechanical components is a gear wheel. A gear wheel is a wheel with teeth that can mesh or engage with the teeth of another gear wheel. When gears are meshed together, we say we have a gear train (Figure 1).

Gears can be used to change the speed or direction of a turning motion, as well as the amount of turning force, or torque, that is available.

When two gears are meshed together properly, turning one gear will turn the other in the opposite direction. You probably also noticed from Figure 1 that with the correct arrangement gears can be used to rotate shafts that are at right angles to each other. Furthermore, the number of times the second gear turns relative to the first is determined by the number of teeth on each gear, in particular on the ratio of the number of teeth on one gear to the number of teeth on the other.
If you are not familiar with gears, you may find it difficult to visualise just how one gear turns with respect to another. In Figure 1, the gears are firmly attached to the black shaft running through the centre of the gear. Each shaft is capable of turning freely in the hole through the black beam. If you have access to a suitable construction set, you may like to try and build similar models to the ones shown here and see how real gears work. Don’t worry if you do not have access to such a resource – you will have an opportunity to experiment with a variety of gear assemblies at the Residential School.

4.1 Gearing up and gearing down

Suppose I have a gear with 20 teeth (which I shall refer to as a 20t gear) and mesh it with a 10t gear (that is, a gear with 10 teeth). Every time the first, 20t gear turns a single complete turn, the second gear will rotate completely twice. Can you work out why?

*Hint:* because the teeth of gear are meshed together, each gear turns the same number of ‘teeth steps’. Correspondingly, each complete revolution of the second, 10t gear moves it 10 ‘teeth steps’. As the first 20t gear turns the same number of ‘teeth steps’ it will only rotate half a turn.

Connecting gears of different sizes allows us to modify the speed, or more accurately, the *rate* at which the gears, and the shafts they are connected to, turn. This is necessary because motors or engines often work at very high rates of rotation, far too fast to drive a wheel directly, for instance. The rate is measured in revolutions per unit time, such as revolutions per minute (rpm) or revolutions per second (rps). The following relationship governs the speed at which the gears turn relative to each other:

\[
\text{Number of teeth of first gear} \times \text{Rate at which first gear turns} = \text{Number of teeth on second gear} \times \text{Rate at which second gear turns}
\]

While increasing speed by using gears may be useful, it comes at a cost. In particular, there is a *trade-off* of turning force, or *torque*, available in exchange for speed. That is – more speed comes at the cost of less torque. You might be familiar with the idea of moving up or down gears from driving a car, or riding a bicycle. In order to get moving from a standing start, you need a large force to overcome friction and inertia and accelerate away. The answer is to gear down and start off in a low gear. It doesn’t matter that the gear is turning slowly – it is a large amount of torque, or rotational force, that you need. Once you are travelling at a cruising speed, you don’t need the large torque required for acceleration, but you do need the speed, so going up to a high gear is the best option.
Using gears also introduces friction into the system at the points where the teeth mesh. Overcoming these frictional forces requires energy, which would otherwise be available to the output gear.

When talking about gear trains, we say that we are gearing up when a large gear drives a smaller one, and gearing down when a small gear drives a larger one. In the first case, of gearing up, the second, smaller gear rotates faster than the first gear but delivers less force. In the second case, gearing down, the second, larger gear rotates more slowly than the first but can deliver larger torque.

4.2 Gear ratios

When gears are connected together, it is common to talk about the corresponding gear ratio. The ratio of one gear to another is usually given in terms of the ratio of the number of teeth on the first gear to the number of teeth on the second. Conventionally, the ratio is written in the order: driver gear: follower gear.

That is, the motor (or pedals, on a bike) turns the shaft that the driver gear is attached to. Gears that are meshed with a driver gear are driven by it. The follower gear is the gear at the other end of the gear train to the driver gear. It is convenient to write down a gear ratio in the following way:

Number of teeth on first, driver gear : Number of teeth on second, driven gear

So for example, the ratio of a 20t gear connected to a 10t gear is written as 20:10 (which reads as ‘20 to 10’).

Ratios can be simplified in a similar way to how we simplify fractions, by dividing through each side of the ratio by the same number. So for example, we would commonly write the fraction 10/20 as \( \frac{1}{2} \), by dividing through both the numerator (the top bit, i.e. 10) and the denominator (that is, the bottom bit – 20 in this case) by 10. Similarly, dividing 5/15 through by 5 gives us the fraction 1/3. In the case of our 20:10 ratio, this means we can divide through by 10 and simplify it to the ratio 2:1.

\[
\frac{20}{10} = \frac{2}{1} = \frac{\frac{1}{5}}{\frac{1}{2}} = \frac{20:1}{10:5} = 2:1
\]

In a similar way, the ratio of a 12t gear driving a 48t gear is a ratio of 1:4, since we can divide through both sides of the original 12:48 ratio by 12.

You can also use this resemblance between ratios and fractions to help you identify whether you are gearing up into a high gear, or gearing down into a low gear. For example, if you regard the gear ratio 1:4 as the fraction 1/4, you can immediately see that this is less than 1. Hence, you are gearing down and using a low gear.

In contrast, viewing the ratio 10:1 as the fraction 10/1 (that is, 10), this is greater than 1 and hence you are gearing up into a high gear where the driven gear is rotating faster than the driver gear.

The gear ratio expresses in a straightforward way the relative torque (or turning force) and speed of the gears too, so a 2:1 (gearing up) ratio tells you that the second gear will deliver twice the speed but half the torque of the first. A 1:4 (gearing down) ratio tells you that the second gear will deliver four times the force of the first but will rotate at a quarter of the speed.
Hence, it is possible to also describe the gear ratio as:

Rate at which second gear turns : Rate at which first gear turns

or

Torque of first gear: Torque of second gear

Try and work through each of the exercises given below before referring to the answer.

**Exercise 1**

For the following combinations of gears, how fast will the second gear turn relative to the first:

(a) a 10t gear is meshed to a 40t gear
(b) a 40t gear is meshed to a 20t gear

**Exercise 2**

If a 20t gear turning at 400 rpm is meshed with a 10t gear, how quickly will the 10t gear turn?

**Exercise 3**

What size gear must a 20t gear turning at 100 rpm be meshed with for the second gear to turn at 50 rpm?

**Exercise 4**

If I place a 20t gear on the axle of a wheel and connect it to a 100t driver gear connected to a motor:

(a) Am I gearing up or down?
(b) What is the gear ratio?
(c) With what speed and torque will the wheel turn relative to the motor?

### 4.3 Simple gear trains

On many occasions, the motor that will ultimately drive a wheel, for example, may be situated at some distance from the shaft the wheel is connected to. It is possible to build gears that mesh together in very long **simple gear trains**, such as the one in Figure 2.

![Figure 2  A simple gear train with four idler gears](image)
Exercise 5

You should recall that two gears meshed together will turn in opposite directions. Complete the following by deleting the statement that is incorrect.

(a) If there is an odd number of gears in a simple gear train, the gears at each end will turn in the same/opposite\* directions.
(b) If there is an even number of gears in a simple gear train, the gears at each end will turn in the same/opposite\* directions.

In a simple gear train, the ratio of the speed of the first driver gear to the speed of the last driven gear is given by:

\[
\text{Number of teeth of first gear } \times \text{ Rate at which first gear turns} = \text{Number of teeth on last gear } \times \text{ Rate at which last gear turns}
\]

It is worth remembering that the number and size of the intervening gears in a simple gear train does not affect the overall gear ratio, only the relative direction of the first and last gears. These intervening gears are referred to as idler gears. Idler gears are gears used to add spacing between other gears in a gear train without modifying the overall gear ratio, although they may modify the ultimate direction of rotation. Idler gears can be of any size and should be placed between the two gears that need spacing.

4.4 Compound gear trains

In order to get very high or very low gear ratios, a simple gear train is often inappropriate because we would need to combine very large and very small gears. For example, to produce a gear ratio of 1:20 from a 40t driver gear would require the driven gear to be 20 times larger than the driver gear. That is, we would require a \(40t \times 20 = 800t\) driven gear.

A compound gear train gets around this problem as shown in Figure 3.

Figure 3  Examples of compound gear trains
The compound gear train has two gears on some of the shafts. One of the gears acts as a driven ‘input’. The other, differently sized, gear is used to drive the next gear in the train. Of course, all the gears fixed onto the same shaft rotate at the same rate – the rate of rotation of the shaft.

The compound gear train allows you to multiply gear ratios together. Consequently, it is possible to create very large gear ratios and hence generate very large torque and low speeds from high-speed, low-torque motors, for example.

The overall gear ratio is found by multiplying all the individual gear ratios together. For example, in Figure 3, two gears are connected by a compound gear train with three stages. In the first stage, an 8t gear drives a 40t gear, giving a gear ratio of 1:5 for that stage. In the second stage, an 8t gear drives a 24t gear, for a ratio of 1:3. Finally, the third stage again has a ratio of 1:5. The overall gear ratio is found by multiplying the gear ratio of each stage together. If you treat each ratio as a fraction, these can be multiplied together and the overall gear ratio identified. That is, write the first ratio, 1:5, as the fraction 1/5; the second ratio, 1:3, as the fraction 1/3; and the third ratio, 1:5 again, as 1/5.

Multiplying the ‘rations as fractions’ of all three stages together gives the product:

$$(1/5) \times (1/3) \times (1/5) = 1/75$$

If we rewrite the resulting fraction back in the form of a ratio, we get the overall gear ratio as 1:75. What this tells us is that if the right-hand, 16t gear turns once a second, the left-hand 16t gear will not even have completed a single revolution after a minute (it takes 75 seconds to complete a single revolution). However, there will be a large amount of torque available from the left-hand gear; in fact 75 times more than was provided by the right-hand gear.

Additional gear pairs can be added to the compound gear train, introducing an additional multiplication step in the gear ratio calculation each time.

**Exercise 6**

What will the overall gear ratio be if a 40t gear drives a 10t gear, which is mounted on the same axle as another 40t gear driving a final 10t gear? Is this gearing up or gearing down?

**Exercise 7**

See Figure 4. How fast will the final 16t driven gear at the extreme left rotate in each of the compound gear trains if the right-hand 16t driver gear rotates at 20 rpm?

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*Figure 4*

*Compound gear trains for use with Exercise 7*