Answers to Practice Test Questions 11
Nonmetals Part 2 (Groups 14-17 and Boron)

1.
(a)   F, fluorine *or* Cl, chlorine *or* Br, bromine *or* I, iodine *or* At, astatine
(b) HNO_3, nitric acid *or* HNO_2, nitrous acid *or* H_2SO_4, sulfuric acid *or* H_2SO_3, sulfurous acid
       or H_2CO_3, carbonic acid *or* H_3PO_4, phosphoric acid *or* $HClO_4$, perchloric acid
       or $HClO_3$, chloric acid *or* $HClO_2$, chlorous acid *or* $HOCl$, hypochlorous acid, *etc.*
(c) NO_3^-, nitrate *or* NO_2^-, nitrite *or* SO_4^{2-}, sulfate *or* SO_3^{2-}, sulfite *or* CO_3^{2-}, carbonate
       or PO_4^{3-}, phosphate *or* ClO_4^-, perchlorate *or* ClO_3^-, chlorate *or* ClO_2^-, chlorite *or* ClO^-,
       hypochlorite, *etc.*
(d) Br_2
(e)   Te

2.

Formula	Name
$CrPO_3$	chromium(III) phosphite
$Cu(NO_2)_2$	copper(II) nitrite
$Fe_2(SO_4)_3$	iron(III) sulfate
HNO_3	nitric acid
$Cu(ClO_4)_2$	copper(II) perchlorate
Li_3PO_4	lithium phosphate
$Ca(HCO_3)_2$	calcium hydrogen carbonate
$Ca(NO_3)_2$	calcium nitrate
Na_2SO_3	sodium sulfite
$HClO_4$	perchloric acid
H_2SO_3	sulfurous acid

3.

(a) $P_4(s) + 6Cl_2(g) \rightarrow 4PCl_3(l)$

(b) $SO_2(g) + H_2O(g) \rightarrow H_2SO_3(g)$
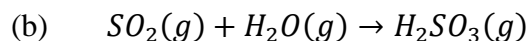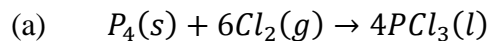
If this reaction had been done in solution instead of the upper atmosphere, it would have been $H_2O(l)$ and $H_2SO_3(aq)$.

(c) $NH_3(g) + H^+(aq) \rightarrow NH_4^+(aq)$

or $NH_3(g) + H_3O^+(aq) \rightarrow NH_4^+(aq) + H_2O(l)$

(d) $NH_3(g) + BF_3(g) \rightarrow H_3N \cdot BF_3(s)$
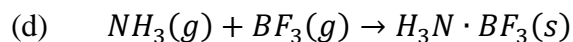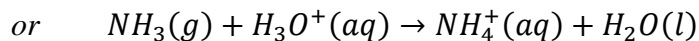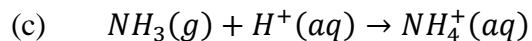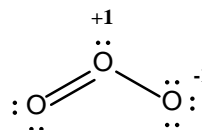
As a Lewis acid-base reaction, you may find it easier to see/show what is happening by drawing Lewis diagrams (instead of writing chemical formulas).

(e) $P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$

(f) $2O_3(g) \rightarrow 3O_2(g)$

4.

$$\ddot{O} = \ddot{O}$$
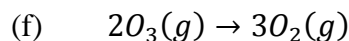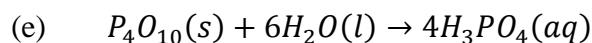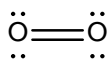
linear

bent

It is somewhat redundant to say that a diatomic molecule (like O_2) is linear since two points, by definition, form a line.

5.   Diamond: a covalently bonded three dimensional network of tetrahedral carbon atoms

Graphite: a layered structure; each layer consists of strongly bonded trigonal planar carbon atoms; layers are weakly attracted to each other; conducts electricity

Graphene: a single layer of strongly bonded trigonal planar carbon atoms; conducts electricity

Nanotube: a single layer of strongly bonded carbon atoms; instead of being a flat sheet (like graphene), the overall structure is tubular

Fullerenes: hollow molecules consisting solely of carbon atoms (e.g. C_{60}); shaped somewhat like soccer balls (fused pentagons and hexagons with carbon atoms at each corner)

Remember that if you have trouble finding the right words to describe something, a diagram can be a good way to convey your thoughts.

6.   Nitrogen does not exhibit allotropy.

Phosphorus has several allotropes including:

white phosphorus (P_4) consists of distinct pyramid-shaped molecules

red phosphorus (P) is a network solid; this means that it does not contain distinct molecues; rather, the atoms form one extended network; red phosphorus is used on the tips of match sticks

Black phosphorus and violet phosphorus also exist. Like red phosphorus, they are network solids; however, the arrangement of the atoms is different in these allotropes. These allotropes would only be testable if discussed in lecture.

7.   Diborane (B_2H_6) contains two three-atom two-electron bonds in which a single pair of electrons is shared by three atoms (both boron atoms and one hydrogen atom):

or
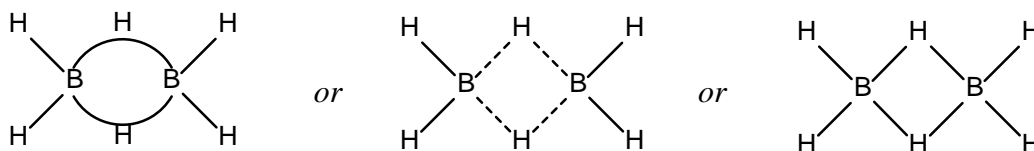
The leftmost diagram is the only one that clearly shows which three atoms share each pair of electrons in the three-atom two-electron bonds. The rightmost diagram is how you will usually see diborane drawn in textbooks and papers but it is misleading because it implies that there are two more electron pairs than diborane actually has. The middle picture is a compromise, showing that there are only 12 electron pairs (with each dashed line suggesting half a bond) but it is still not clear which are the "sets" of atoms in each three-atom two-electron bond.

8.

(a)
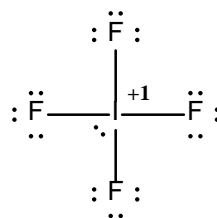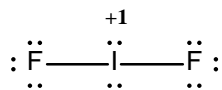
(b)   bent   see saw
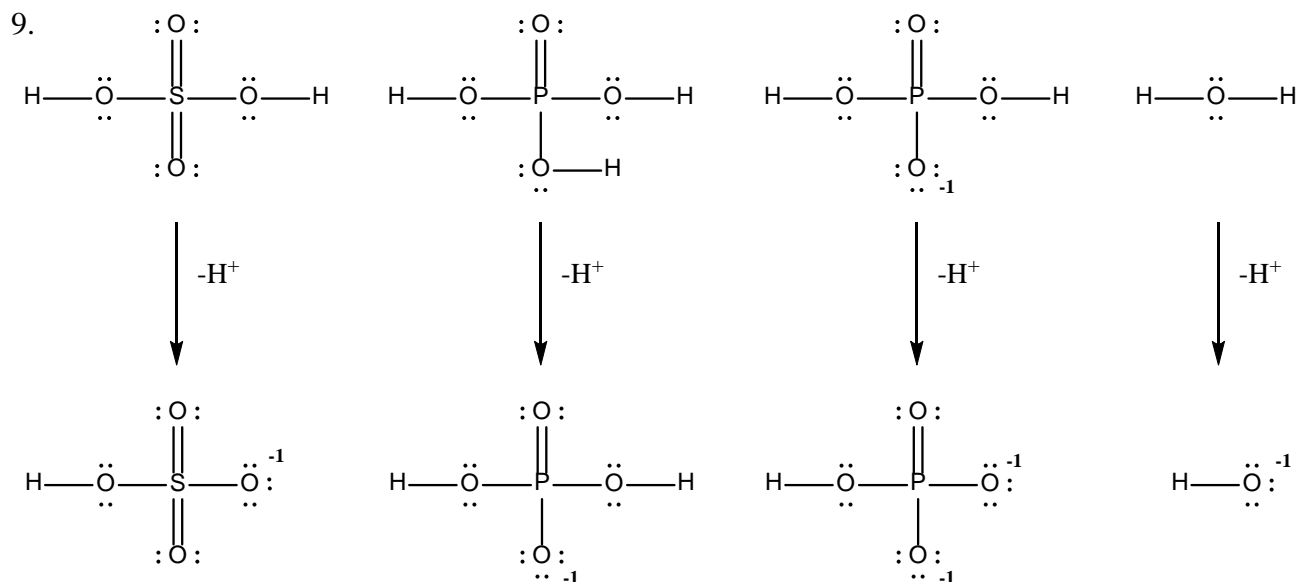
(c)   +3   +5

(d) IF_4^+

The iodine atom in IF_4^+ is more electron deficient (has a higher oxidation state) therefore it gains electrons more readily, making it a better oxidizing agent.

9.

H_2SO_4 is the only strong acid, so it has the lowest pK_a. (Strong acids have negative pK_a values. Weak acids have positive pK_a values.)

H_3PO_4 is a stronger acid than $H_2PO_4^-$ or H_2O, so it has the next lowest pK_a. It is easier to remove the first H^+ from H_3PO_4 than it is to remove the second H^+ (which comes off the now-anionic $H_2PO_4^-$). In both acids, the oxygen atoms pull electron density away from phosphorus (and hydrogen) toward themselves. In the case of $H_2PO_4^-$, there is a net negative charge, so more electron density remains at phosphorus and in the O-H bonds. Therefore, it requires a stronger base to remove H^+ from $H_2PO_4^-$ than to remove H^+ from H_3PO_4.

$H_2PO_4^-$ is a stronger acid than H_2O, so is has the third lowest pK_a (leaving H_2O with the highest). While less acidic than H_3PO_4, $H_2PO_4^-$ still has two terminal oxygen atoms, pulling electron density toward themselves (and therefore away from the O-H bonds). The O-H bonds in water do not experience the same effect, so it requires a stronger base to remove H^+ from water than from $H_2PO_4^-$.

or

We can calculate the approximate pK_a values of each oxoacid, and we know that the pK_a of water is about 14.

$pK_a(H_2SO_4) \approx 8 - 5(2) = -2$

$pK_a(H_3PO_4) \approx 8 - 5(1) = 3$

$pK_a(H_2PO_4^-) \approx 3 + 5 = 8$ *(removing one H^+ raises pK_a by ~5)*

$pK_a(H_2O) \approx 14$

The strength of an acid is measured by its pK_a value. A lower pK_a value corresponds to a stronger acid so the acids are listed from strongest to weakest in the list above.

For questions of this type, drawing the Lewis structures of the species involved is generally the best way to see/explain what's going on. An answer containing correct Lewis structures will typically get a better mark than an equivalent answer trying to explain everything verbally. If you take the calculation approach, you still need to draw the Lewis structures to show where you're getting the value for p from (see formula sheet).

10.

(a) i.

ii.

or

iii.

or
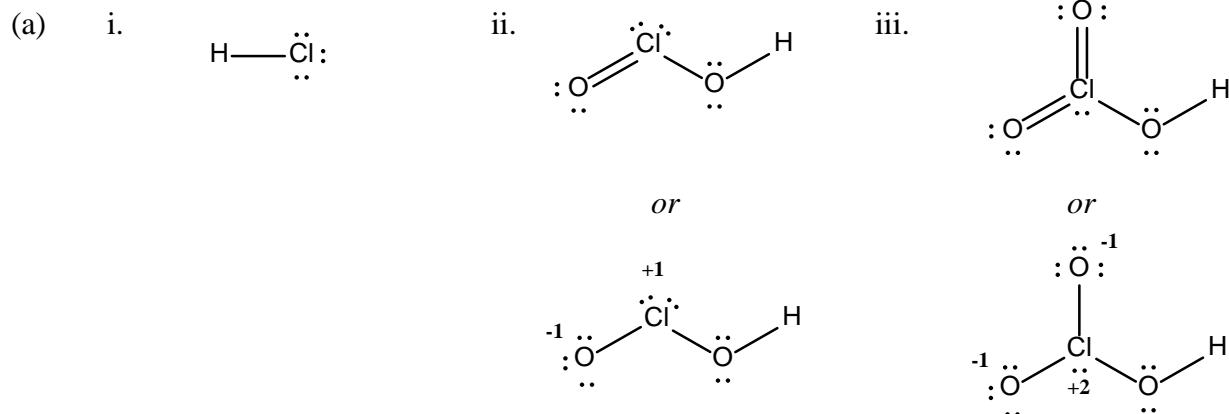
(b) i. -1   ii. +3   iii. +5

(c) i. $pK_a \approx 8 - 5(1) \approx 3$ ii. $pK_a \approx 8 - 5(2) \approx -2$

(d) HCl *(strongest)*, $HClO_3$, $HClO_2$ *(weakest)*

Stronger acids have lower pK_a values. (Negative pK_a is always lower than positive pK_a.)

(e) chloric acid = $HClO_3$ chlorous acid = $HClO_2$ hydrochloric acid = HCl

11.

(a) nitric acid = HNO_3 sulfuric acid = H_2SO_4 hydrobromic acid = HBr

perchloric acid = $HClO_4$ carbonic acid = H_2CO_3

(b) N is +5   S is +6   no central atom in HBr

Cl is +7   C is +4

(c) In the "common oxoacids", the oxidation state of the central atom is equal to the group number minus ten.

12.

(a) *most acidic* Cl_2O_7 SO_3 CO_2 Al_2O_3 BaO   *most basic*

acid   acid   acid   amphoteric   base

(b) In each of these compounds, O has an oxidation state of -2. Since the sum of the oxidation states must equal the overall charge of the molecule, the remaining oxidation states can be calculated:

Cl has an oxidation state of +7 in Cl_2O_7

S has an oxidation state of +6 in SO_3
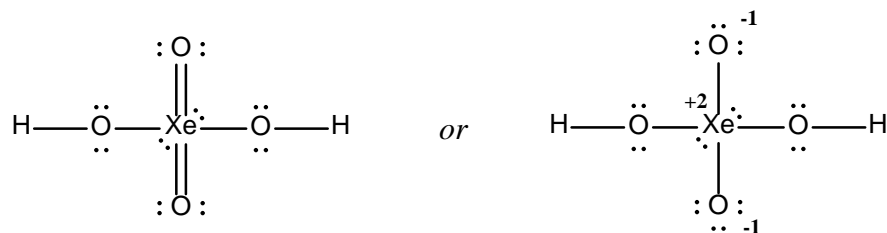
C has an oxidation state of +4 in CO_2

Al has an oxidation state of +3 in Al_2O_3

Ba has an oxidation state of +2 in BaO

(c)   Oxides in which the central atom(s) has/have a more positive oxidation state are more strongly acidic than those which in which the central atom(a) has/have a less positive oxidation state.

13

(a)

(b)   trigonal bipyramidal

(c)   seesaw

(d)   +6

(e)   oxidizing agent

(f) H_2XeO_4 $pK_a \approx 8 - 5(2) \approx -2$

        $HXeO_4^-$ $pK_a \approx -2 + 5 \approx 3$

(g)   strong acid

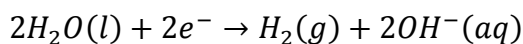14.   A solution of NaCl(aq) is electrolyzed in an electrolytic cell.

        The cell contains an ion-permeable membrane separating two chambers. This allows separation of the Na^+(aq) cations and the Cl^-(aq) anions.

        The Cl^-(aq) anions are oxidized at the anode to Cl_2(g) which is piped out of the cell.

        In the other chamber, H^+(aq) cations in the water are reduced at the cathode to give H_2(g) which is also piped out of the cell. As H^+(aq) cations are consumed, more H^+(aq) and OH^-(aq) are produced from the water. *Recall Le Châtelier's principle and what happens when a product is removed from a system at equilibrium.* This results in a build-up of OH^-(aq) anions which are pumped away along with the spectator Na^+(aq) cations as NaOH(aq).

        At cathode: $2H^+(aq) + 2e^- \rightarrow H_2(g)$ *and* $2H_2O(l) \rightleftharpoons 2H^+(aq) + 2OH^-(aq)$
                        gives an overall reaction of:
                            $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$
        At anode: $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$

        Overall: $2H_2O(l) + 2Cl^-(aq) \rightarrow H_2(g) + 2OH^-(aq) + Cl_2(g)$
                        or $2H_2O(l) + 2NaCl(aq) \rightarrow H_2(g) + 2NaOH(aq) + Cl_2(g)$

15. Haber-Bosch process:
- $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$
- Requires a catalyst (also heat and high pressure)
- Reaction does *not* go to completion
- Mixture of N_2, H_2 and NH_3 is cooled to condense the ammonia out of the mixture of gases
- Remaining N_2 and H_2 are recycled so that eventual yield (after many cycles) approaches 100%

Why special conditions are necessary:
- The bonds in N_2 and H_2 are very strong. (N_2 bond energy is 946 kJ/mol and H_2 bond energy is 436 kJ/mol according to the table on the data sheet.) A catalyst allows these bonds to be broken without forming free H and N atoms. Therefore, less energy input is necessary for the reaction to proceed.
- Increasing the pressure forces the hydrogen and nitrogen molecules into closer proximity therefore promoting reaction.
- Adding heat to the reaction chamber provides the energy necessary for the reaction to proceed in a forward direction (even though it shifts the equilibrium back toward starting materials).

16. Frasch process: Deposits of fairly pure sulfur ($S_{8(s)}$) exist underground.

Superheated water is injected to melt the sulfur. ($S_{8(s)} \rightarrow S_{8(l)}$)

Hot compressed air is injected through a separate pipe a pushes the molten sulfur out of the ground.

The sulfur is poured into molds and solidifies as it cools.

Claus process: Sulfur ($S_{8(s)}$) is generated from hydrogen sulfide ($H_2S_{(g)}$).

Hydrogen sulfide is combusted to give sulfur dioxide.
$$(2H_2S_{(g)} + 3O_{2(g)} \rightarrow 2SO_{2(g)} + 2H_2O_{(g)})$$
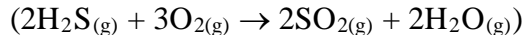
Sulfur dioxide reacts with the remaining hydrogen sulfide to give sulfur and water. $(16H_2S_{(g)} + 8SO_{2(g)} \rightarrow 3S_{8(s)} + 16H_2O_{(g)})$

This allows fabrication of a useful product (sulfur) and safe by-product (water) from an environmentally unfriendly by-product of the oil industry.

17.
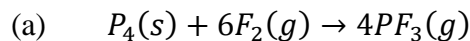
(a) $P_4(s) + 6F_2(g) \rightarrow 4PF_3(g)$

(b)

	P$_4$(s)	+	6 F$_2$(g)	$\rightarrow$	4 PF$_3$(g)
M	123.8952g/mol		37.9968 g/mol		87.9690 g/mol
m$_{initial}$	6.58 g				
P$_{initial}$			3.15 bar = 315 kPa = 315000 Pa		0 bar
V			750 mL = 0.750 L		
T			19.65 °C = 292.80 K		
n$_{initial}$	0.0531 mol		0.0970 mol		0 mol
n$_{change}$	-0.0162 mol		-0.0970 mol		+0.0647 mol
n$_{final}$	0.0369 mol		0 mol		0.0647 mol
m$_{final}$					5.69 g

Step 1: Write a balanced chemical equation for the reaction

see above

Step 2: Organize all known information

see above; values in grey are not necessary for this calculation

Step 3: Calculate moles of P₄ and F₂ (n$_{initial}$)

$$n_{P_4-initial} = 6.58g \times \frac{1 mol}{123.8952g} = 0.0531 mol$$

$$PV = nRT$$

$$n_{F_2-initial} = \frac{PV}{RT} = \frac{(315000 Pa)(0.750 L)}{\left(8.3145 \frac{Pa \cdot m^3}{mol \cdot K}\right)(292.80 K)} \times \frac{1 m^3}{1000 L} = 0.0970 mol$$

Step 4: Identify the limiting reagent

Either calculate the amount of P$_4$ required to react with 0.0970 mol F$_2$ or calculate the amount of F$_2$ required to react with 0.0531 mol P$_4$:

$$n_{P_4-required} = 0.0970 \ mol \ F_2 \times \frac{1 \ mol \ P_4}{6 \ mol \ F_2} = 0.0162 \ mol \ P_4 \qquad \text{less than} \quad n_{P_4-initial}$$

or $\qquad n_{F_2-required} = 0.0531 \ mol \ P_4 \times \frac{6 \ mol \ F_2}{1 \ mol \ P_4} = 0.319 \ mol \ F_2 \qquad$ more than $n_{F_2-initial}$

There is not enough F$_2$ to react with all of the available P$_4$ so the F$_2$ will run out before the P$_4$. F$_2$ is therefore the limiting reagent.

Alternatively, you could calculate the moles of PF₃ produced if each is the limiting reagent. The one that produces fewer moles of PF₃ is the limiting reagent. (0.0970 mol F₂ gives 0.0647 mol PF₃ whereas 0.0531 mol P₄ gives 0.212 mol PF₃ therefore F₂ must run out before P₄. See Step 5 for sample calculation. The advantage of this approach is that you've already done Step 5!)

Step 5: Use mole ratio to calculate moles of PF₃ produced (n$_{final}$)

$$n_{PF_3-final} = 0.0970 \ mol \ F_2 \times \frac{4 \ mol \ PF_3}{6 \ mol \ F_2} = 0.0647 \ mol \ PF_3$$

Step 6: Calculate mass of PF₃ produced (m_final)

$$m_{PF_3-final} = 0.0647 \, mol \times \frac{87.9690 \, g}{1 \, mol} = 5.69 \, g$$

Step 7: Check your work

Does your answer seem reasonable? Are sig. fig. correct?

While the mass of product is lower than the mass of one of the reactants (P_4), we must remember that P_4 was not the limiting reagent. The same amount of F_2 could have reacted with a ton of P_4 and we would still get the same amount of PF_3! As long as the total mass of $P_4 + PF_3$ after the reaction is equal to the total mass of $P_4 + F_2$ before the reaction, the law of conservation of mass is obeyed.

18.

(a) $SO_2(g) + 2NaOH(aq) \rightarrow Na_2SO_3(aq) + H_2O(l)$

(b)
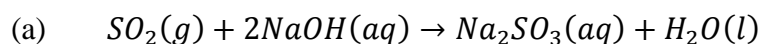
	$SO_2(g)$	+	$2\,NaOH(aq)$	$\rightarrow$	$Na_2SO_3(aq)$	+	$H_2O(l)$
M	64.065 g/mol		39.9971 g/mol		126.044 g/mol		18.0152 g/mol
$P_{initial}$	94 kPa = 94000 Pa						
V	0.75 L		0.100 L				
T	25 °C = 298.15 K *(only 3 sig. fig.)*						
$n_{initial}$	0.028 mol		0.057 mol				
n_{change}	-0.028 mol		-0.057 mol				
n_{final}	0 mol		0 mol				
$c_{initial}$			0.57 mol/L				

Step 1: Write a balanced chemical equation for the reaction

see above

Step 2: Organize all known information

see above; values in grey are not necessary for this calculation

Step 3: Calculate moles of SO₂ (n_initial)

$$PV = nRT$$

$$n_{SO_2-initial} = \frac{PV}{RT} = \frac{(94000Pa)(0.75L)}{\left(8.3145\frac{Pa \cdot m^3}{mol \cdot K}\right)(298.15K)} \times \frac{1m^3}{1000L} = 0.028 mol$$

Step 4: Use mole ratio to calculate moles of NaOH required (n_initial)

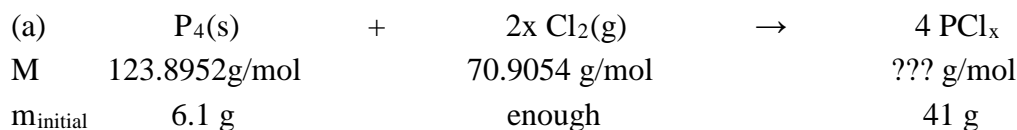$$n_{NaOH-initial} = 0.028 \, mol \, SO_2 \times \frac{2 \, mol \, NaOH}{1 \, mol \, SO_2} = 0.057 \, mol \, NaOH$$

Step 5: Calculate concentration of NaOH required (c_initial)

$$c_{NaOH-initial} = \frac{n_{NaOH-initial}}{V_{NaOH-initial}} = \frac{0.057 \, mol}{0.100 \, L} = 0.57 \, \frac{mol}{L}$$

Step 6: Check your work

Does your answer seem reasonable? Are sig. fig. correct?

19.

(a)

	P₄(s)	+	2x Cl₂(g)	→	4 PClₓ
M	123.8952g/mol		70.9054 g/mol		??? g/mol
$m_{initial}$	6.1 g		enough		41 g
$n_{initial}$	0.049 mol				0 mol
n_{change}	-0.049 mol				+0.20 mol
n_{final}	0 mol				0.20 mol
M					2.1×10^2 g/mol

Step 1: Write a balanced chemical equation for the reaction

see above; since you don't know the molecular formula for the product, write what you do know about it (that it contains P and Cl in some ratio); you also don't know how much Cl₂ is reacted, but you do know that it's not the limiting reagent

Step 2: Organize all known information

see above

Step 3: Calculate moles of P₄ ($n_{initial}$)

$$n_{P_4-initial} = 6.1g \times \frac{1 mol}{123.8952g} = 0.049 mol$$

Step 4: Use mole ratio to calculate moles of PClₓ produced (n_{final})

$$n_{PCl_x-final} = 0.049\ mol\ P_4 \times \frac{4\ mol\ PCl_x}{1\ mol\ P_4} = 0.20\ mol\ PCl_x$$

Step 5: Use mass and moles of PClₓ produced to calculate molar mass of PClₓ (M)

$$M_{PCl_x} = \frac{m_{PCl_x-final}}{n_{PCl_x-final}} = \frac{41\ g}{0.20\ mol} = 208\frac{g}{mol} = 2.1 \times 10^2 \frac{g}{mol}$$

Step 6: Calculate x

The molar mass of PClₓ will be equal to the molar mass of P added to the molar masses of the Cl atoms. Subtracting the molar mass of P from the molar mass of PClₓ then dividing by the molar mass of Cl should therefore give the number of Cl atoms (i.e. the value of x).

$$M_{Cl_x} = M_{PCl_x} - M_P = 208\frac{g}{mol} - 30.9738\frac{g}{mol} = 177\frac{g}{mol}$$

$$x = \frac{M_{Cl_x}}{M_{Cl}} = \frac{177\frac{g}{mol}}{35.4527\frac{g}{mol}} = 5.0$$

Therefore, the product is PCl₅.

Step 7: Check your work

Does your answer seem reasonable? Are sig. fig. correct?

The two most likely values for x were 3 and 5 (PCl₃ and PCl₅), so this answer makes sense.

The fact that it is easy to answer part (b) (even number of electrons; all atoms except P obey octet rule) should also be reassuring.

(b)   The product is trigonal bipyramidal: