

Organofluorine chemistry

Graham Sandford

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Organofluorine chemistry By G ra h a m Sand ford

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The fascination of organofluorine chemistry stems from the fact that, apart from a few exceptions, molecules containing carbon-fluorine bonds do not occur in nature The fascination of organofluorine chemistry stems from the fact that, apart from a few exceptions, molecules containing carbon-fluorine bonds do not occur in nature and so the field is entirely 'man-made'. The fascination of organofluorine chemis
few exceptions, molecules containing car
and so the field is entirely 'man-made'.
Many fluoro-organic molecules are enc few exceptions, molecules containing carbon-fluorine bonds do not occur in nature
and so the field is entirely 'man-made'.
Many fluoro-organic molecules are encountered by the general public on a daily

basis, but this is probably not widely recognized even by the scientific commu-Many fluoro-organic molecules are encountered by the general public on a daily
basis, but this is probably not widely recognized even by the scientific commu-
nity. For example, the chlorofluorocarbon (CFC) refrigerants, n basis, but this is probably not widely recognized even by the scientific community. For example, the chlorofluorocarbon (CFC) refrigerants, now being replaced by the ozone-friendly hydrofluorocarbons (HFC), are present in the ozone-friendly hydrofluorocarbons (HFC), are present in everybody's kitchens.
Anaesthesia has been revolutionized by fluorinated anaesthetics, and many pharthe ozone-friendly hydrofluorocarbons (HFC), are present in everybody's kitchens.
Anaesthesia has been revolutionized by fluorinated anaesthetics, and many phar-
maceuticals, including the well-known antidepressant Prozac Anaesthesia has been revolutionized by fluorinated anaesthetics, and many phar-
maceuticals, including the well-known antidepressant $Prozac^{\circledR}$, owe their enhanced
biological activity to the presence of fluorine atoms in maceuticals, including the well-known antidepressant Prozac[®], owe their enhanced
biological activity to the presence of fluorine atoms in their structures. Fluoropoly-
mers have found widespread use in applications rang biological activity to the presence of fluorine atoms in their structures. Fluoropoly-
mers have found widespread use in applications ranging from non-stick coatings on
cookware (Teflon®, Du Pont), waterproof clothing (Go cookware (Teflon[®], Du Pont), waterproof clothing (Goretex[®], W. L. Gore), and as high-performance lubricants. In fact, supersonic flight and space travel would probably not have been possible without the use of perfluorinated materials that can
withstand such harsh operating environments. Fluorinated materials prepared many
years ago continue to find new applications: for instance, p with stand such harsh operating environments. Fluorinated materials prepared many
years ago continue to find new applications: for instance, perfluorocarbon fluids, orig-
inally prepared in the 1930s, are being developed a withstand such harsh operating environments. Fluorinated materials prepared many
years ago continue to find new applications: for instance, perfluorocarbon fluids, orig-
inally prepared in the 1930s, are being developed as years ago continue to find new applications: for instance, perfluidly prepared in the 1930s, are being developed as imaging ε of heart disease and as oxygen-carrying 'blood substitutes'.
Given the success of organoflu ally prepared in the 1930s, are being developed as imaging agents for the diagnosis
heart disease and as oxygen-carrying 'blood substitutes'.
Given the success of organofluorine chemistry in such a wide variety of applicat

of heart disease and as oxygen-carrying 'blood substitutes'.
Given the success of organofluorine chemistry in such a wide variety of applications,
the future of the subject is very bright. This essay outlines some of the f Given the success of organofluorine chemistry in such a wide variety of applications,
the future of the subject is very bright. This essay outlines some of the fascination
of studying the chemistry of fluoro-organic molecu the future of the subject is very bright. This essay outlines some of the fascination
of studying the chemistry of fluoro-organic molecules, gives a brief overview of how
organofluorine chemistry has helped shape some of t of studying the chemistry of fluoro-organic molecules, gives a brief overview of how
organofluorine chemistry has helped shape some of the remarkable developments of
the 20th century, and provides a personal view of the ro

organofluorine chemistry has helped shape
the 20th century, and provides a personal
the initial stages of the new millennium.

the new millennium.
Keywords: organic chemistry; organofluorine;
elemental fluorine: selective fluorination elemental chemistry; organofluorine;
elemental fluorine; selective fluorination

1. Introduction

Organic molecules containing fluorine atoms are used on a daily basis by everybody If the developed containing fluorine atoms are used on a daily basis by everybody
in the developed world. Many of the astonishing scientific developments of the past
50 years have been made possible by organofluorine compo Organic molecules containing fluorine atoms are used on a daily basis by everybody
in the developed world. Many of the astonishing scientific developments of the past
50 years have been made possible by organofluorine comp in the developed world. Many of the astonishing scientific developments of the past 50 years have been made possible by organofluorine compounds, although this is probably not widely recognized even by the scientific commu 50 years have been made possible by organofluorine compounds, although this is
probably not widely recognized even by the scientific community, and, in fact, it is
unusual for even a university chemistry degree course to i $\frac{1}{2}$ chemistry on its syllabus.
Naturally occurring molecules largely consist of carbon, hydrogen, nitrogen and unusual for even a university chemistry degree course to include any organofluorine

oxygen atoms, and all molecules containing carbon frameworks possess many carbon

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Figure 1. Fluorinated analogues of some hydrocarbon systems.

atoms that are attached to hydrogen atoms. Of the countless naturally occurring atoms that are attached to hydrogen atoms. Of the countless naturally occurring
molecules, only a handful of systems have carbon atoms that are attached to fluorine
atoms, and most of these are metabolites in tropical plan atoms that are attached to hydrogen atoms. Of the countless naturally occurring
molecules, only a handful of systems have carbon atoms that are attached to fluorine
atoms, and most of these are metabolites in tropical pla molecules, only a handful of systems have carbon atoms that are attached to fluorine
atoms, and most of these are metabolites in tropical plants found in the South-
ern Hemisphere (Harper & O'Hagan 1994). The existence of atoms, and most of these are metabolites in tropical plants found in the South-
ern Hemisphere (Harper & O'Hagan 1994). The existence of molecules containing
carbon-fluorine bonds is due almost entirely to human efforts i ern Hemisphere (Harper & O'Hagan 1994). The existence of molecules containing
carbon–fluorine bonds is due almost entirely to human efforts in the 20th century
because nature, after billions of years, has never found a ge carbon–fluorine bonds is due almost entirely to human efforts in the 20th century
because nature, after billions of years, has never found a generally effective method
of introducing fluorine atoms into organic systems, ev because nature, after billions of years, has never found a generally effective method
of introducing fluorine atoms into organic systems, even though she has had plenty of
raw material with which to experiment (fluorine is of introducing fluorine a
raw material with whic
in the Earth's crust).
Fluorine is not signiraw material with which to experiment (fluorine is the 13th most abundant element
in the Earth's crust).
Fluorine is not significantly different in size to hydrogen, and, in principle, it is

in the Earth's crust).
Fluorine is not significantly different in size to hydrogen, and, in principle, it is
possible to take any of nature's molecules and replace either one hydrogen atom
with fluorine to give a selective Fluorine is not significantly different in size to hydrogen, and, in principle, it is
possible to take any of nature's molecules and replace either one hydrogen atom
with fluorine, to give a selectively fluorinated derivat possible to take any of nature's molecules and replace either on
with fluorine, to give a selectively fluorinated derivative, or all the
by fluorine, to create a fully fluorinated (perfluorinated) system.
The introduction th fluorine, to give a selectively fluorinated derivative, or all the hydrogen atoms fluorine, to create a fully fluorinated (perfluorinated) system.
The introduction of one or more fluorine atoms into a naturally occurrin

by fluorine, to create a fully fluorinated (perfluorinated) system.
The introduction of one or more fluorine atoms into a naturally occurring molecule
can have a profound effect on its physical, chemical and biological pro The introduction of one or more fluorine atoms into a naturally occurring molecule
can have a profound effect on its physical, chemical and biological properties. For
example, the replacement of one hydrogen in acetic acid can have a profound effect on its physical, chemical and biological properties. For
example, the replacement of one hydrogen in acetic acid (used as vinegar to flavour
food) by fluorine gives highly poisonous fluoro-acetic example, the replacement of one hydrogen in acetic acid (used as vinegar to flavour
food) by fluorine gives highly poisonous fluoro-acetic acid (figure 1), which is present
in gifblaar (*Dichapetalum cymosum*), a plant tha food) by fluorine gives highly poisonous fluoro-acetic acid (figure 1), which is present
in gifblaar (*Dichapetalum cymosum*), a plant that has caused many livestock fatalities
on the South African veld. In another exampl in gifblaar (*Dichapetalum cymosum*), a plant that has caused many livestock fatalities
on the South African veld. In another example, the fully fluorinated (perfluorinated)
polymer, polytetrafluoroethylene (figure 1) is on the South African veld. In another example, the fully fluorinated (perfluorinated) polymer, polytetrafluoroethylene (figure 1) is far more thermally and chemically resistant than the non-fluorinated compound polyethylene.
There is the possibility of creating an infinite number of new organic systems that

There is the possibility of creating an infinite number of new organic systems that There is the possibility of creating an infinite number of new organic systems that contain fluorine atoms, with each new molecule having its own distinct properties and chemical reactivity. Organofluorine chemistry, there contain fluorine atoms, with each new
and chemical reactivity. Organofluorine
vast extension to organic chemistry. vast extension to organic chemistry.

2. Why fluorine?

Why do fluorine atoms give rise to molecules with such different properties to analogous non-fluorinated molecules? There are two main reasons (Chambers 1973) as follows.

(1) Fluorine is the most electronegative element, which means that a fluorine atom
can attract the negatively charged electrons present in a chemical bond towards Fluorine is the most electronegative element, which means that a fluorine atom
can attract the negatively charged electrons present in a chemical bond towards
itself a property that can completely change the electronic env Fluorine is the most electronegative element, which means that a fluorine atom
can attract the negatively charged electrons present in a chemical bond towards
itself, a property that can completely change the electronic en can attract the negatively charged electrons present in a chemical bond towards
itself, a property that can completely change the electronic environment and,
therefore, affect the chemical reactivity of an organic molecule itself, a property that can completely change the electronic environment and, therefore, affect the chemical reactivity of an organic molecule. For example,
in hydrocarbon systems such as benzene, the presence of negatively charged
electrons on the aromatic ring makes the molecule reactive towards in hydrocarbon systems such as benzene, the presence of negatively charged
electrons on the aromatic ring makes the molecule reactive towards positively
charged reagents called electrophiles (E^+ , figure 2). In contrast electrons on the aromatic ring makes the molecule reactive towards positively
charged reagents called electrophiles $(E^+, \text{figure 2})$. In contrast, electronegative
fluorine atoms 'suck' the electrons out of the hexafluorobenze charged reagents called electrophiles $(E^+, \text{figure 2})$. In contrast, electronegative fluorine atoms 'suck' the electrons out of the hexafluorobenzene ring, making the carbon atoms slightly positively charged and, therefore, r the carbon atoms slightly positively charged and, therefore, reactive towards
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Figure 2. Fluorocarbon chemistry can 'mirror' hydrocarbon chemistry. (a) Naturally occurring
hydrocarbon systems (b) 'Man-made' fluorocarbon systems %;
arbon chemistry can 'mirror' hydrocarbon chemistry. (a) Nat
hydrocarbon systems. (b) 'Man-made' fluorocarbon systems.

Figure 3. The perfluorinated radical is much more stable than the hydrocarbon radical.

negatively charged reagents (nucleophiles, Nuc⁻). Similarly, positively charged hydrocarbon systems (nucleophiles, Nuc⁻). Similarly, positively charged
hydrocarbon systems (Olah *et al.* 1985) (carbocations) are 'mirrored' by the
existence of negatively charged fluorocarbon derivatives (Bavliff & Ch negatively charged reagents (nucleophiles, Nuc⁻). Similarly, positively charged
hydrocarbon systems (Olah *et al.* 1985) (carbocations) are 'mirrored' by the
existence of negatively charged fluorocarbon derivatives (Bay hydrocarbon systems (Olah *et al.* 198
existence of negatively charged fluoroot
1988) (see also figure 2, carbanions).

(2) α Buorine atom possesses three pairs of negatively charged electrons in its outer
electronic shell that are not involved in bonding with any other atoms. This electronic shell that are not involved in bonding with any other atoms. This

dought that are not involved in bonding with any other atoms. This

dought of non-bonding electrons surrounding each fluoring atom can in highly A fluorine atom possesses three pairs of negatively charged electrons in its outer
electronic shell that are not involved in bonding with any other atoms. This
'cloud' of non-bonding electrons surrounding each fluorine ato electronic shell that are not involved in bonding with any other atoms. This 'cloud' of non-bonding electrons surrounding each fluorine atom can, in highly fluorinated systems such as PTFE, be regarded as a 'protective she 'cloud' of non-bonding electrons surrounding each fluorine atom can, in highly
fluorinated systems such as PTFE, be regarded as a 'protective sheath' that
shields the carbon backbone of each molecule from chemical attack, fluorinated systems such as PTFE, be regarded as a 'protective sheath' that shields the carbon backbone of each molecule from chemical attack, providing many highly fluorinated systems with very high thermal and chemical shields the carbon backbone of each molecule from chemical attack, providing
many highly fluorinated systems with very high thermal and chemical stability.
The increased stability conferred upon molecules by the presence o

allows a number of unusual systems to be synthesized and studied that would oth-The increased stability conferred upon molecules by the presence of fluorine atoms
allows a number of unusual systems to be synthesized and studied that would otherwise be extremely reactive or unstable. Hydrocarbon radica allows a number of unusual systems to be synthesized and studied that would otherwise be extremely reactive or unstable. Hydrocarbon radicals are highly reactive transient species due to the presence of a free unpaired ele erwise be extremely reactive or unstable. Hydrocarbon radicals are highly reactive
transient species due to the presence of a free unpaired electron on a carbon atom
and have lifetimes that can only be measured in millisec transient species due to the presence of a free unpaired electron on a carbon atom
and have lifetimes that can only be measured in milliseconds (Fossey *et al.* 1995).
In contrast, some fully fluorinated radicals (figure 3 \simeq In contrast, some fully fluorinated radicals (figure 3) are stable (Scherer *et al.* 1985) \simeq even when heated for several hours! contrast, some fully fluorinated radicals (figure 3) are stable (Scherer *et al.* 1985) en when heated for several hours!
Pyridine derivatives, protected by several perfluoroalkyl groups, can be trans-
med by ultraviolet

Formed by several hours!
Formed by ultraviolet light into the Dewar and prismane valence bond isomers (fig-
formed by ultraviolet light into the Dewar and prismane valence bond isomers (fig-
q-
q-
q-
q-
q-
q-
q-
q-
q-
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 Pyridine derivatives, protected by several perfluoroalkyl groups, can be transformed by ultraviolet light into the Dewar and prismane valence bond isomers (figure 4; see also Chambers & Middleton (1977)), all of which can formed by ultraviolet light into the Dewar and prismane valence bond isomers (figure 4; see also Chambers & Middleton (1977)), all of which can be isolated and stored unchanged over long periods of time, unlike the non-fl e 4; see also Chambers & Middleton (1977)), all of which can be isolated and stored changed over long periods of time, unlike the non-fluorine-containing analogues.
These few examples illustrate how different the chemistry

 $\begin{array}{|c|c|c|}\n\hline\n\text{I} & \text{on} & \text{on$ These few examples illustrate how different the chemistry and properties of fluorinated molecules can be compared with analogous hydrocarbon systems, and, quite frequently, the chemistry of some fluorocarbon systems is so rinated molecules can be compared with analogous hydrocarbon systems, and, quite
frequently, the chemistry of some fluorocarbon systems is so unexpected that it places
quite a strenuous test on our theories and understandi frequently, the chemistry of some fluorocarbon systems is so unexpected that it places
quite a strenuous test on our theories and understanding of organic chemistry. As
Professor D. Seebach notes, '...a few personal experi quite a strenuous test on our theories and understanding of organic chemistry. As Professor D. Seebach notes, '... a few personal experiences [in organofluorine chemistry] would suggest that one should be prepared for any *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 4. Unusually stable valence isomers of fluorinated pyridine derivatives.

Figure 4. Unusually stable valence isomers of fluorinated pyridine derivatives.
reactions—a thrilling prospect' (Seebach 1990). This is the continuing fascination of
organofluorine chemistry reactions—a thrilling prosp
organofluorine chemistry. organofluorine chemistry.
3. Organofluorine chemistry, the 20th century

3. Organofluorine chemistry, the 20th century
The future of any scientific subject, and its impact upon the general public, must
have its roots in the achievements of the past, and in order to try to predict future The future of any scientific subject, and its impact upon the general public, must
have its roots in the achievements of the past, and in order to try to predict future
directions in organofluorine chemistry as we enter th The future of any scientific subject, and its impact upon the general public, must have its roots in the achievements of the past, and in order to try to predict future directions in organofluorine chemistry as we enter t have its roots in the achievements of the past, and in order to try to predict future directions in organofluorine chemistry as we enter the new millennium, we must first consider current knowledge (Banks *et al.* 1986).

consider current knowledge (Banks *et al.* 1986).
In the 1920s, the Belgian chemist Frederic Swarts began his seminal studies on halogen exchange reactions, which involved the replacement of chlorine atoms in organic mole In the 1920s, the Belgian chemist Frederic Swarts began his seminal studies on halogen exchange reactions, which involved the replacement of chlorine atoms in organic molecules by fluorine using hydrogen fluoride gas as t In the 1920s, the Belgian chemist Frederic Swarts began his seminal studies on organic molecules by fluorine using hydrogen fluoride gas as the fluorinating reagent.
His work prompted American scientists (Midgley $\&$ Henne 1930) to prepare the organic molecules by fluorine using hydrogen fluoride gas as the fluorinating reagent.
His work prompted American scientists (Midgley $\&$ Henne 1930) to prepare the
first chlorofluorocarbons (CFCs), which were immediatel His work prompted American scientists (Midgley & Henne 1930) to prepare the first chlorofluorocarbons (CFCs), which were immediately developed as safe non-
flammable refrigerants, as alternatives to liquid ammonia and sul **MATHEMATICAL,
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SCIENCES** first chlorofluorocarbons (CFCs), which were immediately developed as safe non-
flammable refrigerants, as alternatives to liquid ammonia and sulphur dioxide, which
were being used up to that time. CFC refrigerants were us flammable refrigerants, as alternatives to liquid ammonia and sulphur dioxide, which were being used up to that time. CFC refrigerants were used globally in everyone's kitchens and automobile air-conditioning systems until were being used up to that time. CFC refrigerants were used globally in everyone's kitchens and automobile air-conditioning systems until the deleterious impact of the CFCs on the ozone layer became fully apparent (Rowland 1996) in the mid-1980s, and the use of such materials for refrigeration was banned and the use of such materials for refrigeration was banned in developed countries
under the terms of the Montreal protocol. Since refrigeration is now an essential
part of modern life (indeed, in Paul Theroux's (1982) nove and the use of such materials for refrigeration was banned in developed countries under the terms of the Montreal protocol. Since refrigeration is now an essential
part of modern life (indeed, in Paul Theroux's (1982) novel *The mosquito coast*, the
chief protagonist invents a refrigeration system becau chief protagonist invents a refrigeration system because he argues that 'Ice is civil-
isation'), the global chemical industry responded to both social and environmental chief protagonist invents a refrigeration system because he argues that 'Ice *is* civilisation'), the global chemical industry responded to both social and environmental requirements in a very short time. A new range of h isation'), the global chemical industry responded to both social and environmental
requirements in a very short time. A new range of hydrofluorocarbons (HFCs) is
now available as 'drop-in' replacements to the harmful CFCs; requirements in a very short time. A new range of hydrofluorocarbons (HFCs) is
now available as 'drop-in' replacements to the harmful CFCs; it is perhaps worth
emphasizing here that it is the chlorine atoms, not the fluori now available as 'drop-in' replacements to the harmful CFCs; it is perhaps worth
emphasizing here that it is the chlorine atoms, not the fluorine, that are the root
cause of the ozone depletion problem!
Towards the end of emphasizing here that it is the chlorine atoms, not the fluorine, that are the root $\overline{5}$

cause of the ozone depletion problem!
Towards the end of the Thirties, Dr R. J. Plunkett, a scientist at the Du Pont com-
pany, found that the contents of a cylinder containing tetrafluoroethylene, prepared
from one of the from one of the newly available CFCs, had solidified, and after sawing the cylinder in
the newly available CFCs, had solidified, and after sawing the cylinder in
half he obtained the first samples of solid polytetrafluoroe pany, found that the contents of a cylinder containing tetrafluoroethylene, prepared
from one of the newly available CFCs, had solidified, and after sawing the cylinder in
half, he obtained the first samples of solid polyt from one of the newly available CFCs, had solidified, and after sawing the cylinder in
half, he obtained the first samples of solid polytetrafluoroethylene (PTFE). Shortly
afterwards, Professor W. T. Miller (Cornell) prep afterwards, Professor W. T. Miller (Cornell) prepared polytrifluorochloroethylene (Kel-F^{\circledR}, 3M Co.), and, after the tremendous chemical and thermal stability of both materials had been recognized, these polymers became crucial in the successful fabri-

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of Everest in May 1999, wearing Gorstex[®] protective clothing. (Photograph: Popperfoto I.td.) Figure 5. Babu Chiri Sherpa, a Nepalese mountaineer, who spent a record 21 h on the summit of Everest in May 1999, wearing Goretex[®] protective clothing. (Photograph: Popperfoto Ltd.)

of Everest in May 1999, wearing Goretex^{or} protective clothing. (Photograph: Popperfoto Ltd.)
cation of the first atomic weapons (the US Manhattan project). The separation of the
fissionable uranium-235 isotope by gaseous cation of the first atomic weapons (the US Manhattan project). The separation of the fissionable uranium-235 isotope by gaseous diffusion of uranium hexafluoride (UF₆) through a permeable membrane to provide a U-235 enr cation of the first atomic weapons (the US Manhattan project). The separation of the
fissionable uranium-235 isotope by gaseous diffusion of uranium hexafluoride (UF₆)
through a permeable membrane to provide a U-235 enr fissionable uranium-235 isotope by gaseous diffusion of uranium hexafluoride (UF_6)
through a permeable membrane to provide a U-235 enriched sample of uranium was
made possible by the new fluorocarbon polymers, which cou \blacktriangleright made possible by the new fluorocarbon polymers, which could withstand the highly corrosive materials, such as elemental fluorine, required by the enrichment process.
 \blacktriangleright After the crucial role played by fluoro \blacksquare corrosive materials, such as elemental fluorine, required by the enrichment process. corrosive materials, such as elemental fluorine, required by the enrichment process.
After the crucial role played by fluorocarbon materials in the Manhattan project
was published (Goldwhite 1986), a number of groups aroun After the crucial role played by fluorocarbon materials in the Manhattan project
was published (Goldwhite 1986), a number of groups around the world took up the
challenge of exploring the chemistry of fluorinated molecules **∽**rapidly. challenge of exploring the chemistry of fluorinated molecules and the field developed rapidly.
PTFE is now used by humankind for many applications, such as waterproof cloth-

rapidly.
PTFE is now used by humankind for many applications, such as waterproof cloth-
ing (figure 5), gaskets, artificial veins, and as non-stick coatings for kitchenware
 $(e \circ \text{Teflon} @\text{-coated frvin } \sigma$ pans) Indeed, the roof o PTFE is now used by humankind for many applications, such as waterproof clothing (figure 5), gaskets, artificial veins, and as non-stick coatings for kitchenware (e.g. Teflon[®]-coated frying pans). Indeed, the roof of th ing (figure 5), gaskets, artificial veins, and as non-stick coatings for kitchenware (e.g. Teflon[®]-coated frying pans). Indeed, the roof of the Millennium Dome (figure 6), perhaps the most visible symbol of the millenni (e.g. Teflon[®]-coated frying pans). Indeed, the roof of the Millennium Dome (figure 6), perhaps the most visible symbol of the millennium celebrations in the UK, is fabricated from panels containing PTFE. Many other perf ure 6), perhaps the most visible symbol of the millennium celebrations in the UK, is
fabricated from panels containing PTFE. Many other perfluorinated polymers con-
tinue to find new uses; for instance, in the aerospace in *Phil. Trans. R. Soc. Lond.* A (2000) *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 6. The Millennium Dome, Greenwich, London. (Photograph: Popperfoto Ltd.)

Figure 6. The Millennium Dome, Greenwich, London. (Photograph: Popperfoto Ltd.)
flight and space travel would probably have not been possible without the use of per-
fluorinated materials that could withstand such demandin flight and space travel would probably have not been possible without the use of per-
fluorinated materials that could withstand such demanding operating conditions. For
example, perfluoropolyethers are used as lubricants flight and space travel would probably have not been possible without the use of per-
fluorinated materials that could withstand such demanding operating conditions. For
example, perfluoropolyethers are used as lubricants fluorinated materials that could withstand such demanding operating conditions. For example, perfluoropolyethers are used as lubricants on orbiting spacecraft because such materials are chemically inert to liquid propellan example, perfluoropolyethers are used as lubricants on orbiting spacecraft because
such materials are chemically inert to liquid propellants and remain as fluids over
a wide temperature range (from -90 °C to $+250$ °C), such materials are chemically inert to liquid propellants and remain as fluids over
a wide temperature range (from $-90\,^{\circ}\text{C}$ to $+250\,^{\circ}\text{C}$), essential for lubrication of
spacecraft that must cope with the high spacecraft that must cope with the high temperatures of take-off and the extreme cold of a space orbit. Consequently, the US Space Shuttle (figure 7) and the international space station presently under construction make fu spacecraft that must cope with the high temperatures of take-off and the extreme
cold of a space orbit. Consequently, the US Space Shuttle (figure 7) and the interna-
tional space station presently under construction make cold of a space orbit. Consequently, the US Space Shuttle (figure 7) and the interna-
tional space station presently under construction make full use of a variety of highly
fluorinated materials. However, the failure of a tional space station presently under construction make full use of a variety of highly
fluorinated materials. However, the failure of a fluorocarbon O-ring seal on the solid
rocket booster of the space shuttle was found to fluorinated materials. However, the failure of a fluorocarbon O-ring seal on the solid
rocket booster of the space shuttle was found to be responsible for the explosion that
led to the destruction of the Challenger spacec rocket booster of the space shuttle was found to be responsible for the explosion that
led to the destruction of the Challenger spacecraft and the tragic loss of seven US
astronauts in 1986. The unusual cold (29 °F) o led to the destruction of the Challenger spacecraft and the tragic loss of seven US astronauts in 1986. The unusual cold $(29 \degree F)$ of the morning of the launch caused the crucial O-ring seals to become brittle and fail, a astronauts in 1986. The unusual cold (29 °F) of the morning of the launch caused
the crucial O-ring seals to become brittle and fail, a property that was illustrated
by Professor Richard Feynman, using a glass of ice– the crucial O-ring seals to become brittle and fail, a property that by Professor Richard Feynman, using a glass of ice-water, before the commission investigating the cause of the disaster (Feynman 1993). Perfluorinated ma Professor Richard Feynman, using a glass of ice-water, before the presidential
mmission investigating the cause of the disaster (Feynman 1993).
Perfluorinated materials, or materials coated with a thin fluorocarbon layer,

commission investigating the cause of the disaster (Feynman 1993).
Perfluorinated materials, or materials coated with a thin fluorocarbon layer, possess the additional property of having a very low surface energy. This mea Perfluorinated materials, or materials coated with a thin fluorocarbon layer, possess the additional property of having a very low surface energy. This means that water or oil, placed on a fabric surface that has been cove sess the additional property of having a very low surface energy. This means that
water or oil, placed on a fabric surface that has been covered by fluorine atoms, does
not soak into the fabric (figure 8) but remains as dr not soak into the fabric (figure 8) but remains as droplets on the surface, which can
be easily removed by wiping. Now, many carpets and items of upholstered furniture not soak into the fabric (figure 8) but remains as droplets on the surface, which can
be easily removed by wiping. Now, many carpets and items of upholstered furniture
are protected by fluorocarbon surfaces (e.g. Scotchga be easily removed by wiping. Now, many carpets and items of upholstered furniture
are protected by fluorocarbon-surfaces (e.g. Scotchgard[®] treatment, 3M Co.). Simi-
larly, fluorocarbon-based paint is weatherproof and is are protected by fluck
larly, fluorocarbon-ba
surfaces (figure 9).
Much smaller fully Nuch smaller fully fluorinated molecules, such as perfluorobutane, were also first
Much smaller fully fluorinated molecules, such as perfluorobutane, were also first
epared as part of the Manhattan project and even now new

surfaces (figure 9).
Much smaller fully fluorinated molecules, such as perfluorobutane, were also first
prepared as part of the Manhattan project and, even now, new uses for such com-
pounds are being developed. Nycomed Am Much smaller fully fluorinated molecules, such as perfluorobutane, were also first
prepared as part of the Manhattan project and, even now, new uses for such com-
pounds are being developed. Nycomed Amersham estimates that prepared as part of the Manhattan project and, even now, new uses for such compounds are being developed. Nycomed Amersham estimates that a perfluorocarbon fluid used as an ultrasound contrast imaging agent for visualizing fluid used as an ultrasound contrast imaging agent for visualizing heart disease (fig-
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applications such as gaskets and lubricants. (Photograph: Popperfoto Ltd.)

positions such as gaskets and lubricants. (Photograph: Popperfoto Ltd.)

Uure 10) and liver damage (Carmichael 1998) will be worth £ 1000 million in sales by 2005. A particularly interesting property of perfluorocarbon (PFC) fluids is that ure 10) and liver damage (Carmichael 1998) will be worth \pounds 1000 million in sales
by 2005. A particularly interesting property of perfluorocarbon (PFC) fluids is that
they readily absorb large quantities of oxygen (Cla by 2005. A particularly interesting property of perfluorocarbon (PFC) fluids is that
they readily absorb large quantities of oxygen (Clark & Gollan 1966), and this idea
was adopted by the director James Cameron in his film they readily absorb large quantities of oxygen (Clark & Gollan 1966), and this idea
was adopted by the director James Cameron in his film *The Abyss*, in which deep-sea
divers were shown to be 'breathing' such oxygenated was adopted by the director James Cameron in his film *The Abyss*, in which deep-sea divers were shown to be 'breathing' such oxygenated liquids. This is not completely $\frac{1}{0}$ babies has recently been cleared by the FDA. science fiction because the use of PFCs for filling the deflated lungs of premature
babies has recently been cleared by the FDA.
Anaesthesia, and, consequently, medical surgery, has also been revolutionized by
organofluori

Anaesthesia, and, consequently, medical surgery, has also been revolutionized by

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Figure 8. A droplet of oil on a textile treated with a 'super repellent' fluorocarbon surface prepared by plasma polymerization. (Photograph: Professor J. P. S. Badyal, University of Durham, UK.)

Figure 9. The Japanese Shinkansen `bullet trains' are decorated and weatherproofed with fluorocarbon paint. (Photograph: Popperfoto Ltd.)

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Figure 10. Heart imaging using perfluorocarbon image contrast agents. Perfluorocarbon Figure 10. Heart imaging using perfluorocarbon image contrast agents. Perfluorocarbon
microbubbles (green) contrast with the heart wall (grey) and make evaluation of this dog's
heart easier (Photograph: Dr. A. K. Fahlyik N Figure 10. Heart imaging using perfluorocarbon image contrast
microbubbles (green) contrast with the heart wall (grey) and make
heart easier. (Photograph: Dr A. K. Fahlvik, Nycomed Amersham.)

have now been replaced by safer, more easily handled alternatives such as halothane (CF₂-CHClBr) So far, we have focused on applications of molecules that have had most, or all,
So far, we have focused on applications of molecules that have had most, or all,
their hydrogen atoms replaced by fluorine, but even when a

 $\frac{1}{\sqrt{5}}$
 $\frac{1}{\sqrt{5}}$ (CF_3 –CHClBr).
So far, we have focused on applications of molecules that have had most, or all,
of their hydrogen atoms replaced by fluorine, but even when a single fluorine atom
is introduced into a naturally occurring So far, we have focused on applications of molecules that have had most, or all, of their hydrogen atoms replaced by fluorine, but even when a single fluorine atom is introduced into a naturally occurring system, useful e of their hydrogen atoms replaced by fluorine, but even when a single fluorine atom
is introduced into a naturally occurring system, useful effects can be found. Fried $\&$
Sabo (1954) prepared the first singly fluorinated is introduced into a naturally occurring system, useful effects can be found. Fried $\&$ Sabo (1954) prepared the first singly fluorinated steroids, which proved to be considerably more biologically active than the parent Sabo (1954) prepared the first singly fluorinated steroids, which proved to be considerably more biologically active than the parent steroids. Since this early finding, many pharmaceuticals that owe their bioactivity to th siderably more biologically active than the parent steroids. Since this early finding,
many pharmaceuticals that owe their bioactivity to the presence of fluorine atoms in
their structures have been developed, and particul many pharmaceuticals that owe their bioactivity to the presence of fluorine atoms in
their structures have been developed, and particularly successful fluorinated drugs
have been marketed as antibiotic, antifungal, antica their structures have been developed, and particularly successful fluorinated drugs
have been marketed as antibiotic, antifungal, anticancer and antiviral agents. For
example, Prozac® (Eli Lilley), the controversial antide example, Prozac[®] (Eli Lilley), the controversial antidepressant drug, owes its ability
to easily traverse the blood-brain barrier, and, therefore, deliver its effect to the
brain, to the presence of a trifluoromethyl gr to easily traverse the blood-brain barrier, and, therefore, deliver its effect to the to easily traverse the blood-brain barrier, and, therefore, deliver its effect to the brain, to the presence of a trifluoromethyl group (CF₃) (figure 11). The widespread use of fluorinated drugs is indicated by the fact brain, to the presence of a trifluoromethyl group (CF_3)
use of fluorinated drugs is indicated by the fact that
among the worldwide top 20 bestselling drugs of 1993.
Many agrochemicals are used regularly for plant prot e of fluorinated drugs is indicated by the fact that $Prozac^{(B)}$ and $Cipro^{(B)}$ were
nong the worldwide top 20 bestselling drugs of 1993.
Many agrochemicals are used regularly for plant protection as herbicides, insec-
ides an

among the worldwide top 20 bestselling drugs of 1993.
Many agrochemicals are used regularly for plant protection as herbicides, insec-
ticides and fungicides. Some well-known brand-name fluorinated agrochemicals, all Many agrochemicals are used regularly for plant protection as herbicides, insec-
ticides and fungicides. Some well-known brand-name fluorinated agrochemicals, all
manufactured and used in large tonnages, are shown in figur ticides and fungicides. Some well-known brand-name fluorinated agrochemicals, all
manufactured and used in large tonnages, are shown in figure 11. The number of
fluorinated agrochemicals in general use continues to grow, a manufactured and used in large tonnages, are shown in figure 11. The number of
fluorinated agrochemicals in general use continues to grow, and, indeed, of all the
plant protection products (herbicides, pesticides, fertiliz *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 11. Pharmaceuticals and agrochemicals that have fluorine atoms in their structure.

ing field trials, nearly half of the molecules contain fluorine atoms. Thus, biologically ing field trials, nearly half of the molecules contain fluorine atoms. Thus, biologically active molecules containing fluorine atoms will undoubtedly play an increasing role, worldwide in health-care and agriculture in the ing field trials, nearly half of the molecules contain fluorine atoms. The active molecules containing fluorine atoms will undoubtedly play and worldwide, in health-care and agriculture in the new millennium.
In total, the tive molecules containing fluorine atoms will undoubtedly play an increasing role,
pridwide, in health-care and agriculture in the new millennium.
In total, the combined value of all commercially available products that c

worldwide, in health-care and agriculture in the new millennium.
In total, the combined value of all commercially available products that contain
fluorine atoms, of which only a fraction of applications (Banks *et al.* 199 In total, the combined value of all commercially available products that contain fluorine atoms, of which only a fraction of applications (Banks *et al.* 1994) are outlined above, was estimated by Rozen (1992) to be in th fluorine atoms, of which only a fraction of applications (Banks et al . 1994) are lined above, was estimated by Rozen (1992) to be in the region of \$50 billion year in sales, a figure that has undoubtedly grown and conti ed above, was estimated by Rozen (1992) to be in the region of \$50 billion per
ar in sales, a figure that has undoubtedly grown and continues to increase.
We have discussed the importance of fluorinated compounds to the ge

but, of course, the importance of fluorinated compounds to the general public,
but, of course, the invention of chemical reactions and synthetic methodology, the
study of chemical processes, and the development of fundamen We have discussed the importance of fluorinated compounds to the general public,
but, of course, the invention of chemical reactions and synthetic methodology, the
study of chemical processes, and the development of fundam but, of course, the invention of chemical reactions and synthetic methodology, the study of chemical processes, and the development of fundamental understanding of the chemistry of fluorinated systems had to be established study of chemical processes, and the development of fundamental understanding
of the chemistry of fluorinated systems had to be established before any practical,
commercial applications arose. Thus, the role of academia, i industry, is extremely important and will undoubtedly continue.

try, is extremely important and will undoubtedly continue.
4. Approaches to the synthesis of organofluorine compounds,
current research on direct-fluorination processes proaches to the synthesis of organofluorine compou
current research on direct-fluorination processes

current research on direct-fluorination processes
As we have seen, organofluorine chemistry is a subject that cuts across the whole of the chemical and pharmaceutical arenas, and, consequently, there is a great deal
of ongoing research in this field involving groups across the world. As an example As we have seen, organofluorine chemistry is a subject that cuts across the whole
of the chemical and pharmaceutical arenas, and, consequently, there is a great deal
of ongoing research in this field involving groups acros of the chemical and pharmaceutical arenas, and, consequently, there is a great deal
of ongoing research in this field involving groups across the world. As an example
of current research work in organofluorine chemistry, w of ongoing research in this field involving groups across the world. As an example of current research work in organofluorine chemistry, we will focus, in this section, on our recent work concerning direct-fluorination met of current research work in organofluorine chemistry, we will focus, in this section,
on our recent work concerning direct-fluorination methodology, although, of course,
it is not intended to suggest that this is the only on our recent
it is not if
from it!
Before is not intended to suggest that this is the only important research challenge, far
m it!
Before we can explore and exploit the chemistry of organofluorine molecules,
must first synthesize them. However, as nature has foun

from it!
Before we can explore and exploit the chemistry of organofluorine molecules,
we must first synthesize them. However, as nature has found, this is not a triv-
ial task, and much current research is focused upon the Before we can explore and exploit the chemistry of organofluorine molecules, we must first synthesize them. However, as nature has found, this is not a trivial task, and much current research is focused upon the developmen ial task, and much current research is focused upon the development of convenient, safe, efficient and economic methods for the introduction of fluorine atoms

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Figure 12. Modern fluorine generation. The fluorine cell room used in the manufacture of per-Figure 12. Modern fluorine generation. The fluorine cell room used in the manufacture of per-
fluorocarbon gases and fluids, F2 Chemicals Ltd, Preston, UK. (Photograph: M. Atherton, F2
Chemicals Ltd Figure 12. Modern
fluorocarbon gases
Chemicals Ltd.) Chemicals Ltd.)
into organic species. The author's current research, in collaboration with Professor

into organic species. The author's current research, in collaboration with Professor
Richard Chambers at the University of Durham, UK, has focused upon developing
the use of the element itself fluorine gas (F_2) to accom into organic species. The author's current research, in collaboration with
Richard Chambers at the University of Durham, UK, has focused upon
the use of the element itself, fluorine gas (F_2) to accomplish this task.
In the use of the element itself, fluorine gas (F_2) to accomplish this task.
In 1886, the French chemist Henri Moissan isolated the first sample of pure ele-

mental fluorine (F_2) by electrolysis, and this process is essentially still in use today.
In the UK alone, BNFL produces $ca.1500$ t of fluorine per annum (figure 12) for In 1886, the French chemist Henri Moissan isolated the first sample of pure ele-
mental fluorine (F_2) by electrolysis, and this process is essentially still in use today.
In the UK alone, BNFL produces *ca*. 1500 t of f mental fluorine (F_2) by electrolysis, and this process is essentially still in use today.
In the UK alone, BNFL produces *ca*. 1500 t of fluorine per annum (figure 12) for
the synthesis of UF₆ for the uranium-235 enr In the UK alone, BNFL produces *ca*. 1500 t of fluorine per annum (figure 12) for
the synthesis of UF₆ for the uranium-235 enrichment process, which is essential to
the nuclear electricity generation industry. Moissan q the synthesis of UF_6 for the uranium-235 enrichment process, which is essential to
the nuclear electricity generation industry. Moissan quickly discovered that fluorine
is a tremendously reactive, toxic and corrosive ga the nuclear electricity generation industry. Moissan quickly discovered that fluorine
is a tremendously reactive, toxic and corrosive gas, and his initial studies of reac-
tions between fluorine and various organic molecul is a tremendously reactive, toxic and corrosive gas, and his initial studies of reactions between fluorine and various organic molecules, such as methane, resulted in explosions. Quite understandably, it was nearly 30 year tions between fluorine and various organic molecules, such as methane, resulted in explosions. Quite understandably, it was nearly 30 years before other chemists got involved in research using fluorine gas, and even now th explosions. Quite understandably, it was involved in research using fluorine gas, and violently reactive still generally prevails.
The problem with direct-fluorination re volved in research using fluorine gas, and even now the image of fluorine being
plently reactive still generally prevails.
The problem with direct-fluorination reactions is that a large amount of heat is
nerated upon trans

violently reactive still generally prevails.
The problem with direct-fluorination reactions is that a large amount of heat is
generated upon transforming a carbon-hydrogen bond in an organic molecule into
a carbon-fluorine The problem with direct-fluorination reactions is that a large amount of heat is
generated upon transforming a carbon-hydrogen bond in an organic molecule into
a carbon-fluorine bond, and this can lead to the uncontrolled generated upon transforming a carbon-hydrogen bond in an organic molecule into
a carbon-fluorine bond, and this can lead to the uncontrolled reactions or explo-
sions witnessed by Moissan. Fluorine has now been 'tamed', to a carbon–fluorine bond, and this can lead to the uncontrolled reactions or explo-
sions witnessed by Moissan. Fluorine has now been 'tamed', to some extent, by
odilution in an inert gas such as nitrogen, using low tempera sions witnessed by Moissan. Fluorine has now been 'tamed', to some extent, by dilution in an inert gas such as nitrogen, using low temperatures and appropriate
solvents, and a growing number of effective direct-fluorination processes have been
reported (Hutchinson & Sandford 1997). The Durham group solvents, and a growing number of effective direct-fluorination processes have been
reported (Hutchinson & Sandford 1997). The Durham group recently found that
direct-fluorination reactions could be efficiently carried ou formic acid. The preparation of Sandford 1997). The Durham group recently found that
direct-fluorination reactions could be efficiently carried out in acidic media such as
formic acid. The preparation of fluorinated 1,3-di direct-fluorination reactions could be efficiently carried out in acidic media such as
formic acid. The preparation of fluorinated 1,3-dicarbonyl compounds (Chambers *et*
al. 1996) by direct-fluorination technology (figu formic acid. The preparation of fluorinated 1,3-dicarbonyl compounds (Chambers *et al.* 1996) by direct-fluorination technology (figure 13) first carried out at Durham in 1993, has been scaled up to a manufacturing proces al. 1996) by direct-fluorination technology (figure 13) is
1993, has been scaled up to a manufacturing process is
to supply customers in the pharmaceutical industry.
The chemistry of fluoro-dicarbonyl molecules has no 93, has been scaled up to a manufacturing process by F2 Chemicals Ltd (BNFL) supply customers in the pharmaceutical industry.
The chemistry of fluoro-dicarbonyl molecules has not been explored, even though

The chemistry of fluoro-dicarbonyl molecules has not been explored, even though *Phil. Trans. R. Soc. Lond.* A (2000)

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 G. Sandford Downloaded from rsta.royalsocietypublishing.org

Figure 13. Recent successful reactions using fluorine gas.

chemists would expect such derivatives to be extremely versatile `building blocks', because a realistic large-scale preparative route to this class of compounds has not chemists would expect such derivatives to be extremely versatile 'building blocks', because a realistic large-scale preparative route to this class of compounds has not been available previously. The exploration of the che because a realistic large-scape
been available previously.
(Hutchinson *et al.* 1998).
As recently as 1992, mos en available previously. The exploration of the chemistry of these systems awaits

iutchinson *et al.* 1998).

As recently as 1992, most advanced organic chemistry textbooks offered the view

at for example 'direct fluori

(Hutchinson *et al.* 1998).
As recently as 1992, most advanced organic chemistry textbooks offered the view
that, for example, 'direct fluorination of aromatic rings with F_2 is not feasible at
room temperature because As recently as 1992, most advanced organic chemistry textbooks offered the view
that, for example, 'direct fluorination of aromatic rings with F_2 is not feasible at
room temperature because of the extreme reactivity of that, for example, 'direct fluorination of aromatic rings with F_2 is not feasible at
room temperature because of the extreme reactivity of F_2 ... at low temperatures,
the reaction is not of preparative significance' room temperature because of the extreme reactivity of F_2 ... at low temperatures,
the reaction is not of preparative significance' (March 1992). However, the Durham
group found that direct-fluorination reactions of many the reaction is not of preparative significance' (March 1992). However, the Durham
group found that direct-fluorination reactions of many aromatic systems (figure 13)
could also be effectively carried out in acidic media (group found that direct-fluorination reactions of many aromatic systems (figure 13) could also be effectively carried out in acidic media (Hutchinson *et al.* 1998). Controlled selective fluorination of diverse systems su could also be effectively carried out in acidic media (Hutchinson *et al.* 1998). Controlled selective fluorination of diverse systems such as heterocycles and carbohy-
drate derivatives is now possible using techniques de *drate deriva*
al. 1998).
The pote ate derivatives is now possible using techniques developed recently (Hutchinson *et* 1998).
The potential for using fluorine gas as a reagent is only just beginning to be
cognized and apart from the process described abov

al. 1998).
The potential for using fluorine gas as a reagent is only just beginning to be recognized, and, apart from the process described above, only one selectively fluorinated molecule, 5-fluoro-uracil (an anticancer drug) is currently manufactured using recognized, and, apart from the process described above, only one selectively fluori-
nated molecule, 5-fluoro-uracil (an anticancer drug) is currently manufactured using
fluorine. The development of new, potentially highnated molecule, 5-fluoro-uracil (an anticancer drug) is currently manufactured using
fluorine. The development of new, potentially high-tonnage uses, of fluorine gas is
particularly timely because new plasma procedures re fluorine. The development of new, potentially high-tonnage uses, of fluorine gas is
particularly timely because new plasma procedures recently announced by BNFL
(Bailey *et al.* 1997) allow for the recovery of fluorine gas particularly timely because new plasma procedures recently announced by BNFL (Bailey *et al.* 1997) allow for the recovery of fluorine gas and uranium metal from 'spent' uranium hexafluoride. The nuclear arms race and nuc (Bailey *et al.* 1997) allow for the recovery of fluorine gas and uranium metal from 'spent' uranium hexafluoride. The nuclear arms race and nuclear electricity industry have generated tens of thousands of tons of uranium storem is exampled in containers in containers in the state in the series in the situation of the situation of the western α is situation of the western US. The nuclear situation of the situation of the situation of the have generated tens of thousands of tons of uranium hexafluoride, which is presently
stored in containers in, for example, the deserts of the western US. This situation
cannot continue indefinitely, and useful redeployment stored in containers in, for example, the deserts of the western US. This situation
cannot continue indefinitely, and useful redeployment of the fluorine 'trapped' in
uranium hexafluoride will clearly be beneficial on envi cannot continue indefinitely, and useful redeployment of the fluorine 'trapuranium hexafluoride will clearly be beneficial on environmental grounds alo viding, of course, that new uses for the regenerated fluorine can be f viding, of course, that new uses for the regenerated fluorine can be found.
5. Organofluorine chemistry in the new millennium

The successful exploration of the chemistry of organic compounds containing fluorine The successful exploration of the chemistry of organic compounds containing fluorine
and the wide variety of applications found for such materials, e.g. in pharmaceuticals
and as materials used in space flight, suggests t The successful exploration of the chemistry of organic compounds containing fluorine
and the wide variety of applications found for such materials, e.g. in pharmaceuticals
and as materials used in space flight, suggests th bright. and as materials used in space flight, suggests that the future of the subject is very bright.
One of the major driving forces for chemistry at present is the continued need for

humankind to develop new pharmaceuticals, either for the treatment of previously

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Figure 14. A and B are mirror images (enantiomers). Enantiomers A and B may have considerably different chemical properties and physiological effects.

considerably different chemical properties and physiological effects.
incurable illnesses, such as cancer or Aids, or to provide more effective medicines than
are currently available. It is of great concern that nature has incurable illnesses, such as cancer or Aids, or to provide more effective medicines than
are currently available. It is of great concern that nature has developed antibodies
capable of resisting the many effective antibiot are currently available. It is of great concern that nature has developed antibodies capable of resisting the many effective antibiotics that have been in general use are currently available. It is of great concern that nature has developed antibodies
capable of resisting the many effective antibiotics that have been in general use
over the past 50 years (Niccolai *et al.* 1997), and, a capable of resisting the many effective antibiotics that have been in general use
over the past 50 years (Niccolai *et al.* 1997), and, at present, only one antibiotic,
vancomycin, is still effective against all forms of vancomycin, is still effective against all forms of bacteria. If this situation changes, health treatments could revert to the conditions of the days before the general use of penicillin, where bacterial infection (pneumonia, tuberculosis, etc.) often proved $\bar{\circ}$ fatal. Humankind must continue to find either new naturally occurring medicines of penicillin, where bacterial infection (pneumonia, tuberculosis, etc.) often proved
fatal. Humankind must continue to find either new naturally occurring medicines
(e.g. Taxol[®], isolated from the bark of the Pacific y fatal. Humankind must continue to find either new naturally occurring medicines (e.g. Taxol[®]), isolated from the bark of the Pacific yew tree, is very active against cancer), or develop non-natural biologically active m (e.g. Taxol[®]), isolated from the bark of the Pacific yew tree, is very active against cancer), or develop non-natural biologically active molecules. The preparation of organic molecules that are rendered biologically ac cancer), or develop non-natural biologically active molecules. The preparation of organic molecules that are rendered biologically active by the presence of at least one fluorine atom continues to offer one route towards organic molecules that are rendered biologically active by the presence of at least
one fluorine atom continues to offer one route towards addressing this issue, and,
indeed, the fluoro-quinolone antibacterial agents (e.g one fluorine atom continues to offer one route towards addressing this issue, and, indeed, the fluoro-quinolone antibacterial agents (e.g. Cipro \mathcal{B} , figure 12) show the potential of this approach. The number of fluor indeed, the fluoro-quinolone antibacterial agents (e.g. Cipro^{fg}
potential of this approach. The number of fluorine-containing
agricultural chemicals in general use will undoubtedly grow.
Effective methodology for the pre

tential of this approach. The number of fluorine-containing pharmaceuticals and
ricultural chemicals in general use will undoubtedly grow.
Effective methodology for the preparation of new selectively fluorinated 'building
 agricultural chemicals in general use will undoubtedly grow.
Effective methodology for the preparation of new selectively fluorinated 'building
blocks' and fluorinated natural-product analogues must continue to evolve to p Effective methodology for the preparation of new selectively fluorinated 'building
blocks' and fluorinated natural-product analogues must continue to evolve to provide
a large diversity of fluorocarbon structures essential blocks' and fluorinated natural-product analogues must continue to evolve to provide
a large diversity of fluorocarbon structures essential in drug-discovery programmes,
although recent work concerning direct-fluorination a large diversity of fluorocarbon structures essential in drug-discovery programmes,
although recent work concerning direct-fluorination processes, described above, and
the availability of other fluorinating reagents, has although recent work concerning direct-fluorination processes, described above, and
the availability of other fluorinating reagents, has gone some way towards addressing
this important issue. Of immediate concern, however, the availability of other fluorinating reagents, has gone some way towards addressing
this important issue. Of immediate concern, however, is the lack of methodology for
synthesizing selectively fluorinated chiral molecule this important issue. Of immediate concern, however, is the lack of methodology for
synthesizing selectively fluorinated chiral molecules, where a fluorine atom is attached
to a stereogenic carbon centre. Chiral molecules synthesizing selectively fluorinated chiral molecules, where a fluorine atom is attached
to a stereogenic carbon centre. Chiral molecules contain a carbon atom (stereogenic
centre) attached to four different groups, and in to a stereogenic carbon centre. Chiral molecules contain a carbon atom (stereogenic centre) attached to four different groups, and in these situations two possible molecular orientations arise, where A has a 'mirror image' centre) attached to four different groups, and in these situations two possible molecular orientations arise, where A has a 'mirror image' B (an enantiomer), which, although structurally the same, in the way a right and a ular orientations arise, where A has a 'mirror
although structurally the same, in the way a right
have extremely different properties (figure 14).
The travic case of the use of the hydrocarbo

The translation of the same, in the way a right and a left hand are, can actually
the extremely different properties (figure 14).
The tragic case of the use of the hydrocarbon derivative phthalidomide in the
fils, where bo The tragic case of the use of the hydrocarbon derivative phthalidomide in the 1960s, where both enantiomers of the phthalidomide drug were administered to preg-The tragic case of the use of the hydrocarbon derivative phthalidomide in the 1960s, where both enantiomers of the phthalidomide drug were administered to pregnant women, unfortunately showed that one enantiomer gave the d 1960s, where both enantiomers of the phthalidomide drug were administered to pregnant women, unfortunately showed that one enantiomer gave the desired effect of lowering the patients blood pressure, but the other enantiome nant women, unfortunately showed that one enantiomer gave the desired effect of lowering the patients blood pressure, but the other enantiomer led to deformation of the foetus. Indeed, to register a new pharmaceutical with lowering the patients blood pressure, but the other enantiomer led to deformation
of the foetus. Indeed, to register a new pharmaceutical with the FDA in the US at
present, each mirror image of the drug molecule must be is of the foetus. Indeed
present, each mirror
biological activity.
Consequently befo present, each mirror image of the drug molecule must be isolated and screened for
biological activity.
Consequently, before selectively fluorinated molecules can be exploited fully in the
drug-discovery arena, methods for

Consequently, before selectively fluorinated molecules can be exploited fully in the organic systems (which is hard enough!) but the selective synthesis of one enantiomer

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of the derived fluorinated molecule, rather than a mixture of two mirror images, is
urgently required. of the derived fluori
urgently required.
Once the prepara urgently required.
Once the preparation of chiral selectively fluorinated molecules has been mas-

tered, the preparation of chiral selectively fluorinated molecules has been mas-
tered, the application of such 'building blocks' to the preparation of many struc-
turally diverse systems using the developing techniques of Once the preparation of chiral selectively fluorinated molecules has been mas-
tered, the application of such 'building blocks' to the preparation of many struc-
turally diverse systems using the developing techniques of c tered, the application of such 'building blocks' to the preparation of many structurally diverse systems using the developing techniques of combinatorial chemistry as part of drug-discovery programmes, will undoubtedly ar turally diverse systems using the developing techniques of combinatorial chemistry
as part of drug-discovery programmes, will undoubtedly arise. Combinatorial chem-
istry (Gordon & Kerwin 1998) could, as an example, involv istry (Gordon & Kerwin 1998) could, as an example, involve taking a fluorinated 'building block' and reacting this with ten different substrates in the same reaction vessel, to yield a mixture of ten initial fluorine-containing products. This mixture of initial products would then be reacted with a further ten different substrates and 'building block' and reacting this with ten different substrates in the same reaction
vessel, to yield a mixture of ten initial fluorine-containing products. This mixture of
initial products would then be reacted with a fu vessel, to yield a mixture of ten initial fluorine-containing products. This mixture of
initial products would then be reacted with a further ten different substrates and
after this second series of reactions a mixture of initial products would then be reacted with a further ten different substrates and
after this second series of reactions a mixture of a total of 100 different selectively
fluorinated final products would be obtained, in tw after this second series of reactions a mixture of a total of 100 different selectively
fluorinated final products would be obtained, in two easy steps, all of which could be
tested for biological activity. In principle, b fluorinated final products would be obtained, in two easy steps, all of which could be tested for biological activity. In principle, by increasing the number of reactions and the number of substrates in each step, millions tested for biological activity. In principle, by increasing the number of reactions and
the number of substrates in each step, millions of selectively fluorinated molecules
could be synthesized by these types of process, i the number of substrates in each step, millions of selectively fluorinated molecules
could be synthesized by these types of process, increasing the chance of discovering
a lead compound in the search for the next fluorinecould be synthesized by these types of process, increasing the chance of discovering
a lead compound in the search for the next fluorine-containing 'blockbuster' drug.
Systems containing many fluorine atoms will also conti

role in tomorrow's society. The possibility that chemically inert perfluorocarbons Systems containing many fluorine atoms will also continue to play an important
role in tomorrow's society. The possibility that chemically inert perfluorocarbons
could act as artificial blood substitutes (Ritter 1998) (bot role in tomorrow's society. The possibility that chemically inert perfluorocarbons
could act as artificial blood substitutes (Ritter 1998) (both PFCs and blood dissolve
oxygen) remains an important long-term goal, especial are diminishing and have the added possibility of HIV infection.
The potential for the synthesis of new highly fluorinated polymeric systems, both oxygen) remains an important long-term goal, especially since public blood supplies

in the bulk and at surfaces, is also considerable and of widespread utility. The The potential for the synthesis of new highly fluorinated polymeric systems, both
in the bulk and at surfaces, is also considerable and of widespread utility. The
widely criticized chlorofluorocarbons (CFCs) and related hy in the bulk and at surfaces, is also considerable and of widespread utility. The widely criticized chlorofluorocarbons (CFCs) and related hydrochlorofluorocarbons (HCFCs) have been used as feedstocks for the synthesis of a widely criticized chlorofluorocarbons (CFCs) and related hydrochlorofluorocarbons
(HCFCs) have been used as feedstocks for the synthesis of a number of 'downstream'
commercial products; for example, CF_2HCl (refrigerant) (HCFCs) have been used as feedstocks for the synthesis of a number of 'downstream' commercial products; for example, CF_2HCl (refrigerant) is the precursor of a number of important polymers, such as the highly versatile P commercial products; for example, CF_2HCl (refrigerant) is the precursor of a number
of important polymers, such as the highly versatile PTFE. The more environmentally
friendly hydrofluorocarbons (HCFCs), the replacements of important polymers, such as the highly versatile PTFE. The more environmentally friendly hydrofluorocarbons (HCFCs), the replacements for CFCs, could also yield similarly valuable and useful downstream high-performance come. similarly valuable and useful downstream high-performance materials in the years to come.
Come. Direct fluorination of a wide range of hydrocarbon polymers could also provide

routes to the fabrication of important new materials. For example, the perfluorinated Direct fluorination of a wide range of hydrocarbon polymers could also provide
routes to the fabrication of important new materials. For example, the perfluorinated
analogue of polypropylene could be made readily available routes to the fabrication of important new materials. For example, the perfluorinated
analogue of polypropylene could be made readily available by harnessing developing
techniques in direct fluorination, because continuous analogue of polypropylene could be made readily available by harnessing developing
techniques in direct fluorination, because continuous flow processes, being developed
by the Durham group, could potentially be used for th techniques in direct fluorination, because continuous flow processes, being developed
by the Durham group, could potentially be used for the perfluorination of a wide
range of systems including high-molecular-weight polyme

6. Conclusions

6. Conclusions
Molecules containing fluorine touch on everybody's lives in the developed world on
a daily basis and the new millennium will see an even greater number of fluorinated Molecules containing fluorine touch on everybody's lives in the developed world on
a daily basis and the new millennium will see an even greater number of fluorinated
materials in everyday use, providing that methods of sy Molecules containing fluorine touch on everybody's lives in the developed world on
a daily basis and the new millennium will see an even greater number of fluorinated
materials in everyday use, providing that methods of sy a daily basis and the new millennium will see an even greater number of fluorinated
materials in everyday use, providing that methods of synthesizing these fascinating
systems and their fundamental chemistry continues to b materials in everyday use, providing that methods of synthesizing these fascinating
systems and their fundamental chemistry continues to be developed. The prediction
of Professor Simons (1950), made 50 years ago, that he w systems and their fundamental chemistry continues to be developed. The prediction
of Professor Simons (1950), made 50 years ago, that he would one day travel in
an aircraft consisting of plastics, lubricants, etc., fabrica of Professor Simons (1950), made 50 years ago, that he would one day travel in
an aircraft consisting of plastics, lubricants, etc., fabricated from fluorine-containing
systems, has only partly been borne out but, after th an aircraft consisting of plastics, lubricants, etc., fabricated from fluorine-containing
systems, has only partly been borne out but, after the considerable developments
of recent years, can now be replaced by a much more systems, has only partly been borne out but, after the considerable developments of recent years, can now be replaced by a much more general vision. In the new millennium, man could be travelling home in cars powered by en *Phil. Trans. R. Soc. Lond.* A (2000)

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Organofluorine chemistry
fluorocarbon greases and fabricated from fluorocarbon polymers to houses coated by fluorocarbon greases and fabricated from fluorocarbon polymers to houses coated by
weatherproof fluorinated paints. On entering the home, furnished with carpets with
fluorinated surfaces that never need cleaning, fluorocar fluorocarbon greases and fabricated from fluorocarbon polymers to houses coated by
weatherproof fluorinated paints. On entering the home, furnished with carpets with
fluorinated surfaces that never need cleaning, fluorocar weatherproof fluorinated paints. On entering the home, furnished with carpets with
fluorinated surfaces that never need cleaning, fluorocarbon kitchenware is used to
prepare food that was grown with the aid of fluorinated fluorinated surfaces that never need cleaning, fluorocarbon kitchenware is used to prepare food that was grown with the aid of fluorinated agricultural agents. Illnesses are detected by fluorocarbon imaging agents and trea prepare food that was grown with the aid of fluorinated agricultural agents. Illnesses

are detected by fluorocarbon imaging agents and treated using fluorinated drugs in
operations carried out under fluorocarbon gas anaesthetics.
Nature has never learned how to use the element called fluorine, but humankind
 Nature has never learned how to use the element called fluorine, but humankind research into the synthesis and chemistry of these fascinating molecules continues to thrive.

thrive.
It is a pleasure to thank The Royal Society for their award of a University Research Fellowship,
and Professor B. D. Chambers (Durham, UK) for his continued advice and encouragement. It is a pleasure to thank The Royal Society for their award of a University Research Fellowship and Professor R. D. Chambers (Durham, UK) for his continued advice and encouragement.

References

- Bailey, G. H., Whitehead, C., Gilchrist, P. & Webster, D. A. 1997 Separation of isotopes by ionisation for processing of nuclear fuel materials. PCT Int. patent WO 97/34684.
- Banks, R. E., Sharp, D. W. A. & Tatlow, J. C. (eds) 1986 *Fluorine: the first one hundred years*. Elsevier. \bar{c}
	- Banks, R. E., Smart, B. E. & Tatlow, J. C. 1994 *Organofluorine chemistry. Principles and commercial applications*. New York: Plenum. Banks, R. E., Smart, B. E. & Tatlow, J. C. 1994 *Organofluorine chemistry. Principles and*

	commercial applications. New York: Plenum.

	Bayliff, A. E. & Chambers, R. D. 1988 Stable perfluorinated carbanions. *J. Chem. Soc.*
	- *commercial applications.*
 Trans. 1, pp. 201–208.
 Trans. 1, pp. 201–208. Bayliff, A. E. & Chambers, R. D. 1988 Stable perfluorinated c
 Trans. 1, pp. 201–208.

	Carmichael, H. 1998 Special agents. *Chem. Brit.*, pp. 30–33.

	Chambers, B. D. 1973 Elucrine in erasnic abeniatry. Wilsy.
	- Trans. 1, pp. 201–208.
Carmichael, H. 1998 Special agents. *Chem. Brit.*, pp. 30–33.
Chambers, R. D. 1973 *Fluorine in organic chemistry*. Wiley.
Chambers, B. D. ⁶: Middleton, B. 1977 Bearrangements involved.
	-
	- Carmichael, H. 1998 Special agents. *Chem. Brit.*, pp. 30–33.
Chambers, R. D. 1973 *Fluorine in organic chemistry*. Wiley.
Chambers, R. D. & Middleton, R. 1977 Rearrangements involving azaprismanes. *J. Chem. Soc.*
Perkin **PERECT:** R. D. 1973 Fluorine in or
 Perkin Trans. 1, pp. 1500–1504.
 Perkin Trans. 1, pp. 1500–1504. Chambers, R. D., & Middleton, R. 1977 Rearrangements involving azaprismanes. J. Chem. Soc.

	Perkin Trans. 1, pp. 1500–1504.

	Chambers, R. D., Greenhall, M. P. & Hutchinson, J. 1996 Direct fluorination of 1,3-dicarbonyl

	co
	- *Perkin Trans. 1*, pp. 1500–1504.
hambers, R. D., Greenhall, M. P. &
compounds. *Tetrahedron* 52, 1–8.
prk. J. C. & Collan. F. 1966 Survive Chambers,R. D., Greenhall, M. P. & Hutchinson, J. 1996 Direct fluorination of 1,3-dicarbonyl
compounds. *Tetrahedron* 52, 1–8.
Clark, L. C. & Gollan, F. 1966 Survival of mammals breathing organic liquids equilibrated wit
- YSICAL
:INGINEERING
ENCES compounds. *Tetrahedron* 52, 1–8.
ark, L. C. & Gollan, F. 1966 Survival of mammals breathing
oxygen at atmospheric pressure. *Science* 152, 1755-1756.
wnman, B. B. 1993. What do you, care what other people this Clark,L. C. & Gollan, F. 1966 Survival of mammals breathing organic liquids equilibrated v

oxygen at atmospheric pressure. *Science* **152**, 1755–1756.

Feynman, R. P. 1993 *What do you care what other people think?* Lond
	- oxygen at atmospheric pressure. *Science* 152, 1755–1756.
Feynman, R. P. 1993 *What do you care what other people think?* London: Harper Collins.
Fossey, J., Lefort, D. & Sorba, J. 1995 *Free radicals in organic chemistry*
	-
	- Feynman, R. P. 1993 What do you care what other people think? London: Harper Collins.
Fossey, J., Lefort, D. & Sorba, J. 1995 *Free radicals in organic chemistry*. Wiley.
Fried, J. & Sabo, E. F. 1954 9 α -fluoro derivativ *Soc.* 76, 1.455–1456.
Soc. 76, 1455–1456.
Idashira H. 1986 In E Fried, J. & Sabo, E. F. 1954 9 α -fluoro derivatives of cortisone and hydrocortisone. *J. Am. Chem.*
 Soc. **76**, 1455–1456.

	Goldwhite, H. 1986 In *Fluorine: the first one hundred years* (ed. R. E. Banks, D. W. A. Sharp
	- $Soc. 76, 1455–1456.$

	oldwhite, H. 1986 In Fluorine: the first or

	& J. C. Tatlow), pp. 109–132. Elsevier.

	orden F. M. & Kerwin, J. F. 1998. Cemb Goldwhite, H. 1986 In *Fluorine: the first one hundred years* (ed. R. E. Banks, D. W. A. Sharp & J. C. Tatlow), pp. 109–132. Elsevier.
Gordon, E. M. & Kerwin, J. F. 1998 *Combinatorial chemistry and molecular diversity in*
	- *discovery*. Wiley.
discovery. Wiley.
ency D B & Q²H₄ Gordon, E. M. & Kerwin, J. F. 1998 *Combinatorial chemistry and molecular diversity in drug*
discovery. Wiley.
Harper, D. B. & O'Hagan, D. 1994 The fluorinated natural products. *Nat. Prod. Rep.*, pp. 123–
133
	- 133. Harper, D. B. & O'Hagan, D. 1994 The fluorinated natural products. *Nat. Prod. Rep.*, pp. 123–
133.
Hutchinson, J. & Sandford, G. 1997 Elemental fluorine in organic chemistry. *[Top. Curr. Chem.](http://ernesto.ingentaselect.com/nw=1/rpsv/cgi-bin/linker?ext=a&reqidx=/0340-1022^28^29193L.1[aid=538870])*
193. 1–43
	- Hutchinson, J. & Sandford, G. 1997 Elemental fluorine in organic chemistry. Top. Curr. Chem. 193, 1–43. Hutchinson,J., & Sandford, G. 1997 Elemental fluorine in organic chemistry. Top. Curr. Chem.

	193, 1–43.

	Hutchinson, J., Sandford, G. & Vaughan, J. F. S. 1998 Alkylation and d[ecarboxylation of ethyl](http://ernesto.ingentaselect.com/nw=1/rpsv/cgi-bin/linker?ext=a&reqidx=/0040-4020^28^2954L.2867[aid=538871,doi=10.1063/1.112959])

	2-fluoro-3-oxobutano
	- 193, 1–43.
utchinson, J., Sandford, G. & Vaughan, J. F. S. 1998 Alkylation and decarboxylation of ethyl
2-fluoro-3-oxobutanoate as a route to functionalised α -fluoroketones *Tetrahedron* 54, 2867–
2876 2876. 2-fluoro-3-oxobutanoateas a route to functionalised α -fluoroketones *Tetrahedron* 54, 2867–2876.
 $\frac{1}{6}$ March, J. 1992 *Advanced organic chemistry*, 4th edn. Wiley.
	-
	- Midgley, T. & Henne, A. L. 1930 Organic fluorides as refrigerants. *Ind. Engng Chem.* 22, 542– 545.

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 G. Sandford Downloaded from rsta.royalsocietypublishing.org

- $G.$ *Sanafora*
Niccolai, D., Tarsi, L. & Thomas, R. J. 1997 The renewed challenge of antibacterial chemother-
ADV. J. Chem. Soc. Chem. Commun., pp. 2333–2342. **MATHEMATICAL,
PHYSICAL
& ENGINEERING
SCIENCES** ccolai, D., Tarsi, L. & Thomas, R. J. 1997 The renewed
apy. *J. Chem. Soc. Chem. Commun.*, pp. 2333–2342.
ab. C. A., Prakash, G. K. S. & Sammor, J. 1985. Super.
	- apy. *J. Chem. Soc. Chem. Commun.*, pp. 2333–2342.
Olah, G. A., Prakash, G. K. S. & Sommer, J. 1985 *Superacids*. Wiley.
	- Ritter, S. K. 1998 Passing a blood test. *Chem. Engng News*, pp. 37-44.
	- Ulah, G. A., Prakash, G. K. S. & Sommer, J. 1985 *Superacids*. Wiley.
Ritter, S. K. 1998 Passing a blood test. *Chem. Engng News*, pp. 37–44.
R[owland, F. S. 1996 Stratos](http://ernesto.ingentaselect.com/nw=1/rpsv/cgi-bin/linker?ext=a&reqidx=/0570-0833^28^2935L.1786[aid=538873])pheric ozone depletion by chlorofluorocarbons. *Angew Ed. Engl.* 35, 1998 Passing a b
Ed. Engl. 35, 1786–1798.
Ed. Engl. 35, 1786–1798.
Eggen S. 1992 In Sunthetic 1
	- Ed. Engl. 35, 1786–1798.
Rozen, S. 1992 In *Synthetic fluorine chemistry* (ed. G. A. Olah, R. D. Chambers & G. K. S. Prakash), p. 143. Wiley.
	- Scherer, K. V., Ono, T., Yamanouchi, K., Fernandez, R., Henderson, P. & Goldwhite, H. 1985 Prakash), p. 143. Wiley.
herer, K. V., Ono, T., Yamanouchi, K., Fernandez, R., Henderson, P. & Goldwhite, H. 1985
Stable tert-perfluoroalkyl radicals by addition of fluorine or trifluoromethyl to a perfluo-
roalkene, *L. A* roalkene. *K. V.*, Ono, T., Yamanouchi, K., Ferna
Stable tert-perfluoroalkyl radicals by additionalkene. *J. Am. Chem. Soc.* **107**, 718–719. Stabletert-perfluoroalkyl radicals by addition of fluorine or trifluoromethyl to a perfluoroalkene. *J. Am. Chem. Soc.* 107, 718–719.
Seebach, D. 1990 Organic synthesis—where now? *Angew. Chem. Int. Ed. Engl.* 29, 1320–13
	- roalkene. *J. Am. Chem. Soc.* 107, 718
Seebach, D. 1990 Organic synthesis—wh
Simons, J. 1950 *Chem. Engng* 57, 129.
Thereux, B. 1982 *The mosquite seest* Le Simons, J. 1950 *Chem. Engng* 57, 129.
Theroux, P. 1982 *The mosquito coast*. London: Penguin.
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(especially selective fluorination methods, heterocyclic, free radical and
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