

RAFT



RAFT PATENTS: WO9801478/EP0910587 WO9905099/US6512081 WO9931144/US6747111 US6642318 WO05113612/EP1751194 B
WO07100719 WO961515/US6291620/EP0791016B WO9504026/US5830966 WO0177198/US7064151 US6355718/US6355718

RAFT Fundamentals – A History and Recent Developments

CSIRO Manufacturing Flagship

Graeme Moad

MACRO 2016 – Istanbul – 17 July 2016

CSIRO MANUFACTURING
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Reversible Addition Fragmentation Chain Transfer

RAFT Polymerization – Description and History

RAFT Application and Development 2011-2015

Conclusions and Outlook

Radical Polymerization

By volume, most commercial polymer production involves radical polymerization

Advantages

- Simple to implement
- Low cost
- Compatible with a wide range of monomers

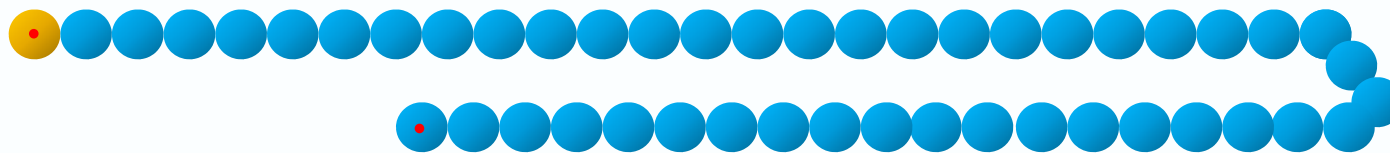
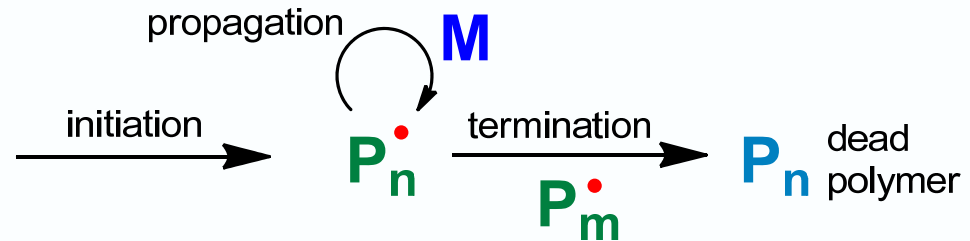
Disadvantages

- Relatively broad molecular weight distribution (high dispersity)
- Limited control over polymer architecture & end group functionality

Radical Polymerization

Process involves adding a source of radicals to a monomer (**M**)

Chains are continuously initiated, propagate, and die



Radical Polymerization

Advantages

- Simple to implement
- Low cost
- Compatible with a wide range of monomers

Disadvantages

- Broad molecular weight distribution (high dispersity)
- Little control over polymer architecture & end group functionality

RAFT Polymerization

Advantages

- Simple to implement
- Low cost
- Compatible with a wide range of monomers
- Narrow molecular weight distribution (low dispersity)
- Intricate control over polymer architecture & end group functionality
- Is a **Reversible Deactivation Radical Polymerization (RDRP)**

The RAFT reviews

Aust. J. Chem. **2005**, *58*, 379-410

Aust. J. Chem. **2006**, *58*, 669-92

Polymer **2008**, *49*, 1079-131

Acc. Chem. Res. **2008**, *41*, 1133-42

Aust. J. Chem. **2009**, *62*, 1402-72

Aust. J. Chem. **2012**, *65*, 985-1076

Chem. Asian J. **2013**, *8*, 1634-1644

Disadvantages



- Need to select a RAFT agent for the specific polymerization and process conditions

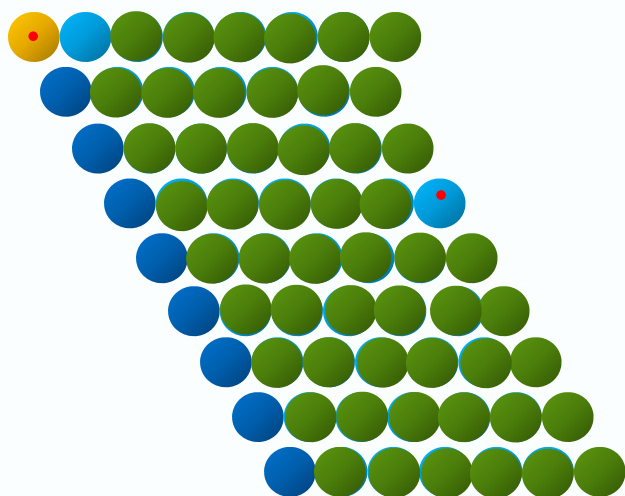
RAFT Polymerization

Simply add a source of radicals to a monomer (**M**) and a **RAFT agent**

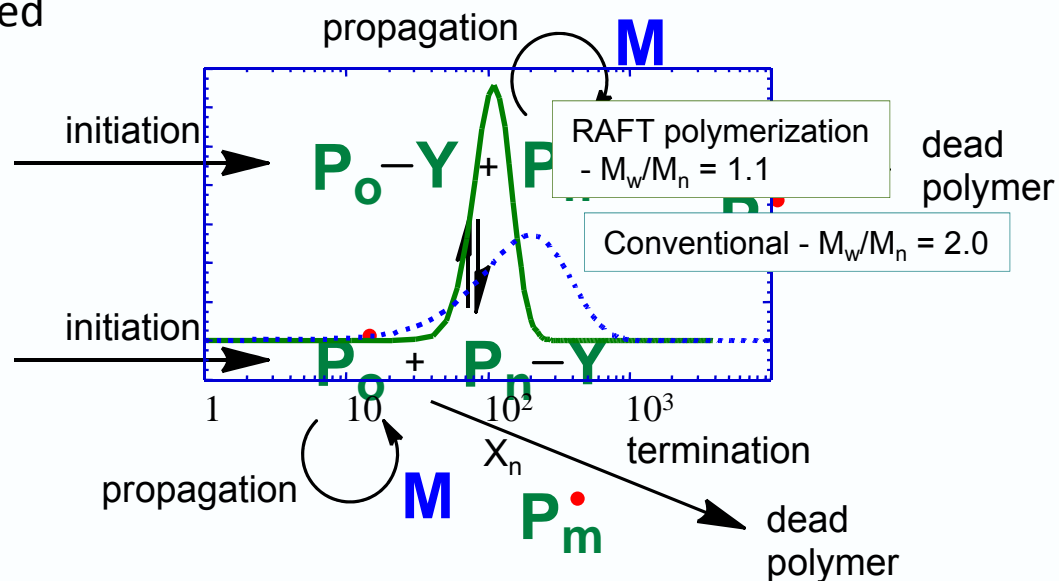
- Chains continuously initiated, propagate, and die (same number as in conventional polymerization)

However,

- More chains (number = moles of RAFT agent)
- On average, all chains grow simultaneously
- Narrow molecular weight distribution
- End-groups  ,  (largely) preserved

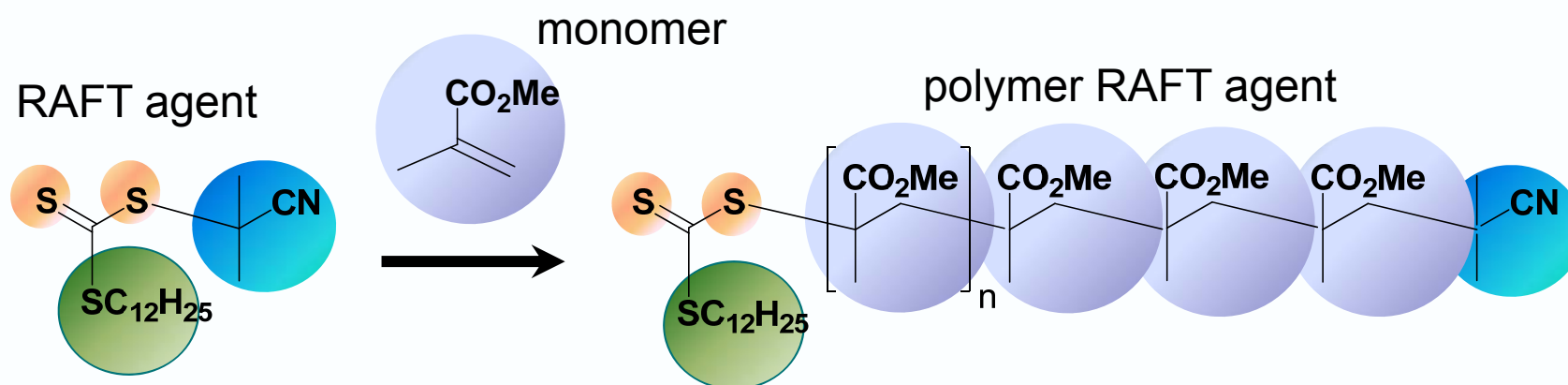


Aust. J. Chem. **2005**, *58*, 379-410
Aust. J. Chem. **2006**, *58*, 669-92
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Aust. J. Chem. **2009**, *62*, 1402-72
Aust. J. Chem. **2012** (in press)



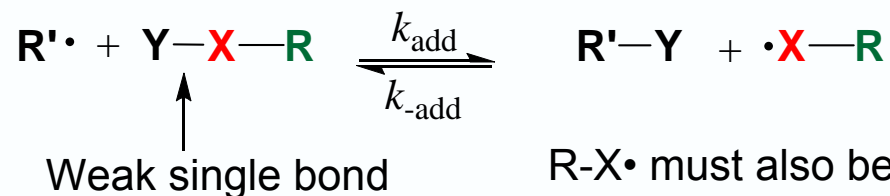
RAFT Agent

- Reacts with radicals by Reversible Addition-Fragmentation chain Transfer
- Determines molar mass
~ [monomer consumed]/[RAFT agent]



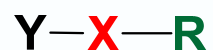
Chain Transfer

Chain transfer by homolytic substitution

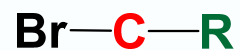


R-X• must also be able to efficiently reinitiate polymerization

Typical transfer agents



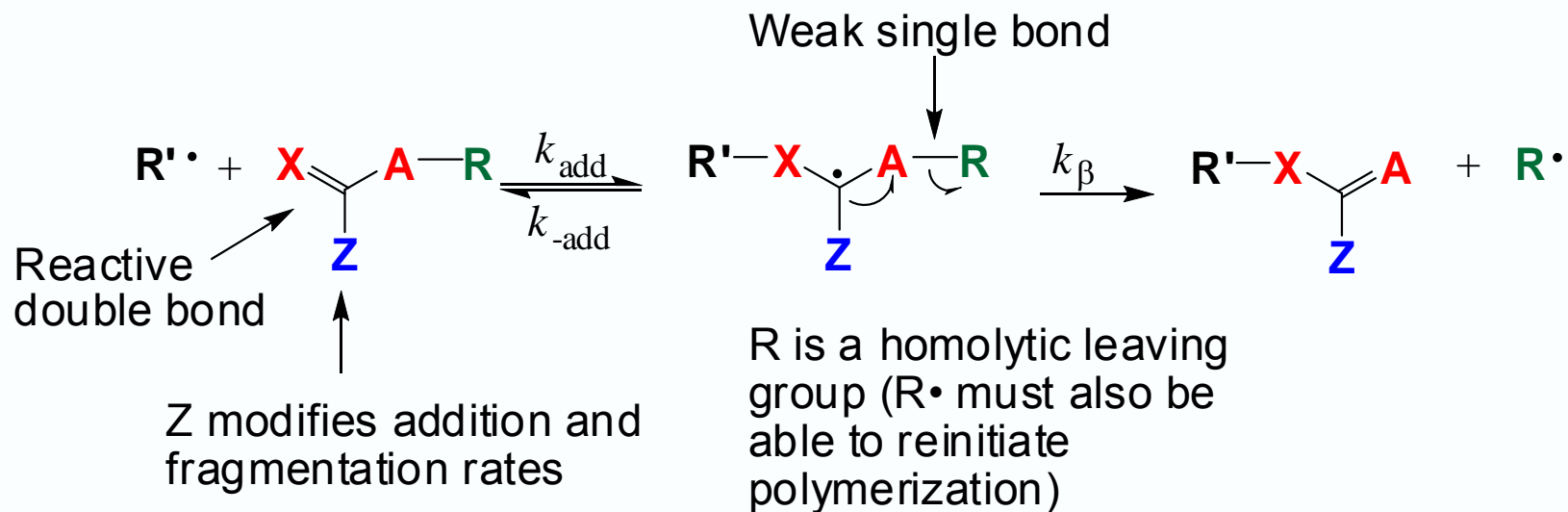
thiols



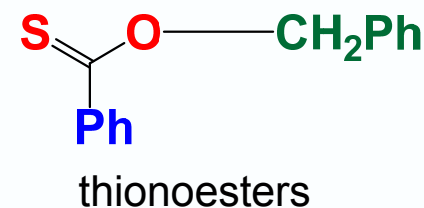
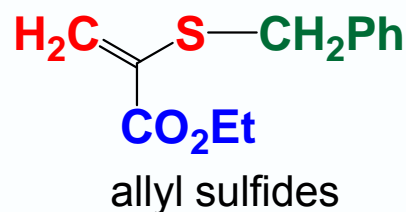
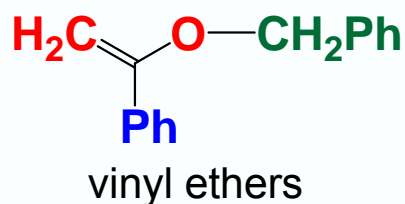
halocarbons

Chain Transfer

Chain transfer by (irreversible) addition-fragmentation



Typical addition fragmentation transfer agents



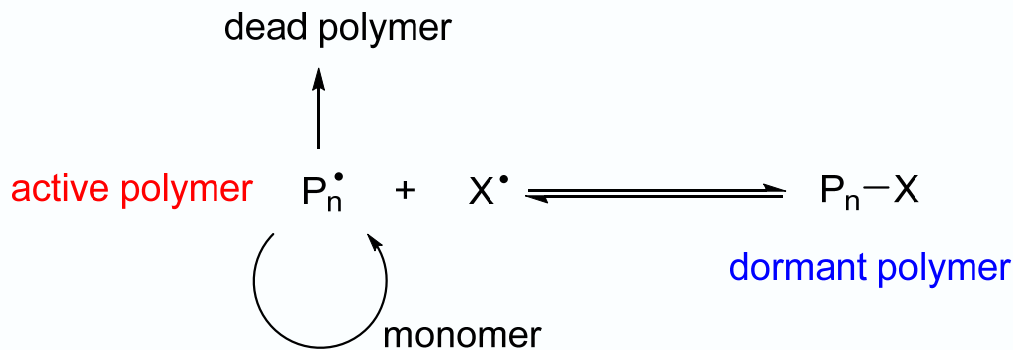
Chain Transfer

- Chain transfer does not effect polymerization kinetics.
(the concentration of radicals is not affected)
- Under ideal conditions the molecular weight dispersity ($\mathcal{D} = M_w/M_n$) will be 2.0.
- Historically, a transfer constant ($C_{tr} = k_{tr}/k_p$) of 1.0 has been called “ideal” because the ratio of monomer to transfer agent (and thus the molecular weight) remains constant throughout the polymerization.
(many irreversible addition-fragmentation transfer agents have $C_{tr} \sim 1$)
- If the transfer constant is >1.0 the molecular weight will increase linearly with monomer conversion.

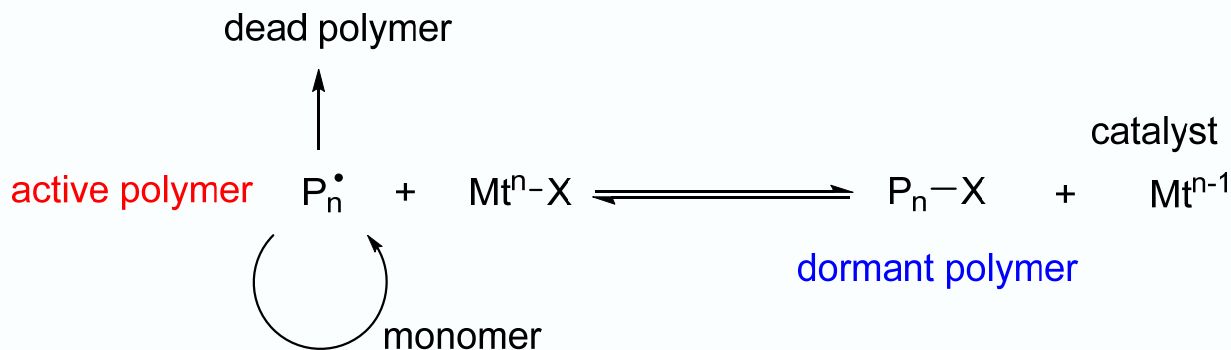
Mechanisms for Reversible Deactivation Radical Polymerization (RDRP)

Stable radical-mediated radical polymerization (SRMP)

e.g., nitroxide-mediated radical polymerization (NMP)



Atom transfer radical polymerization (ATRP)



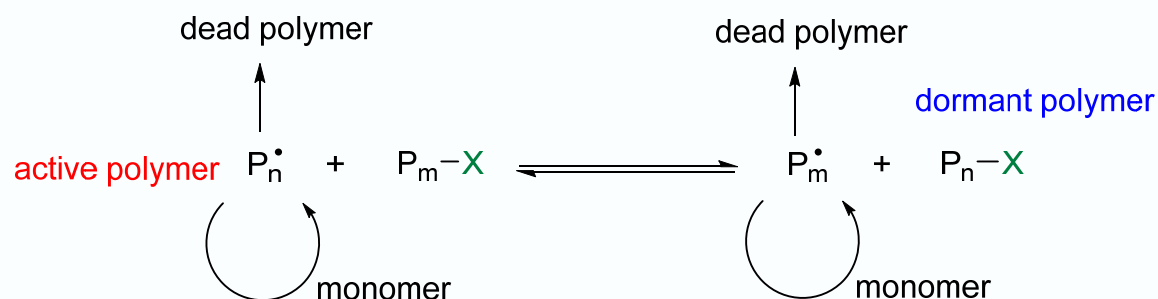
Control through persistent radical effect

RDRP Mechanisms

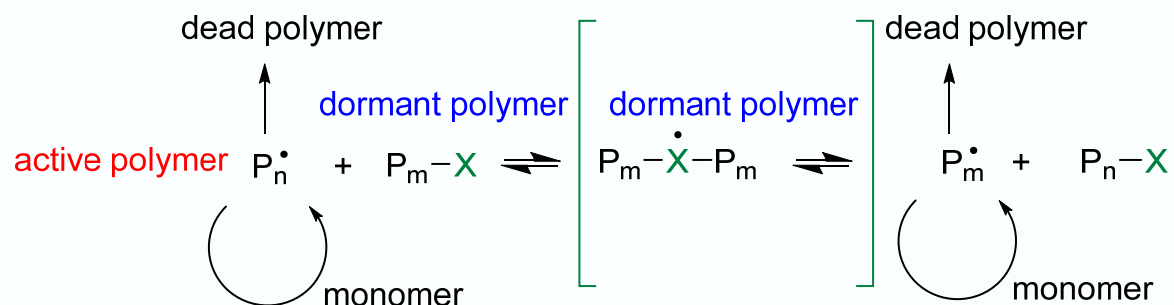
Radical polymerization with degenerate chain transfer

e.g. tellurium mediated polymerization (TERP)

Iodine transfer polymerization (ITP)



Reversible addition-fragmentation chain transfer (RAFT)



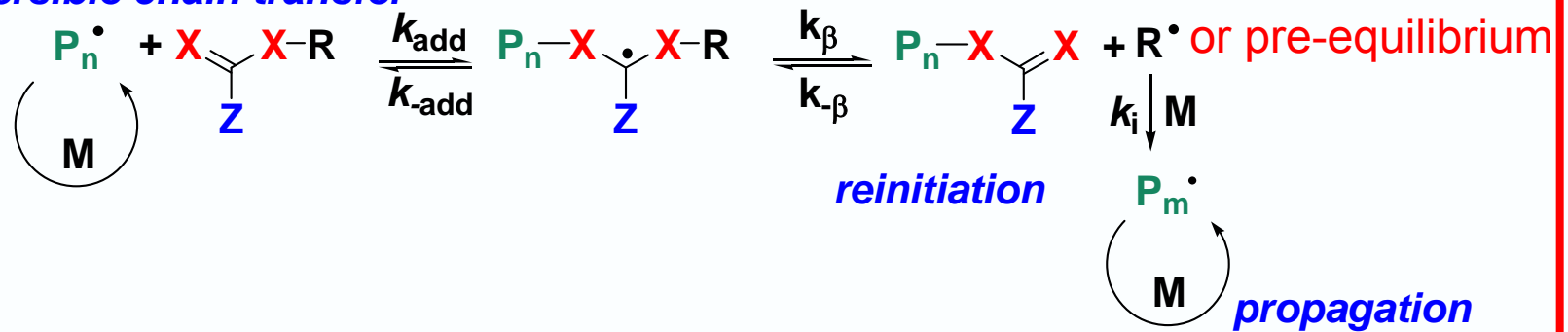
Mechanism of RAFT Polymerisation

The RAFT equilibria are chain transfer reactions. Radicals are neither formed nor destroyed. Ideally the polymerization kinetics are similar to those in conventional radical polymerization

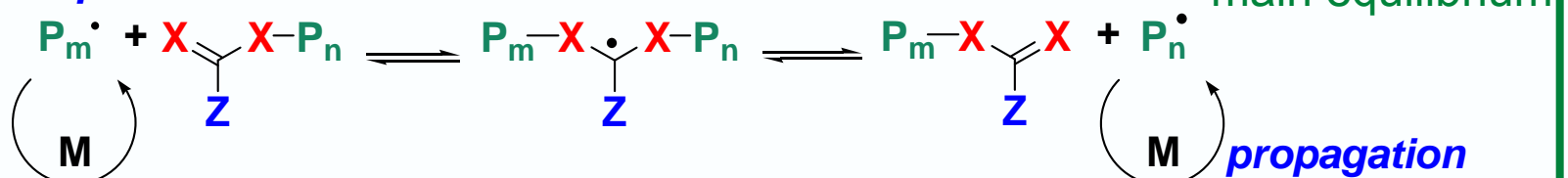
initiation



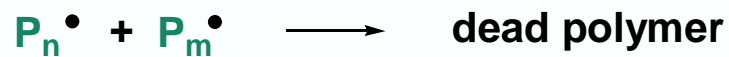
reversible chain transfer



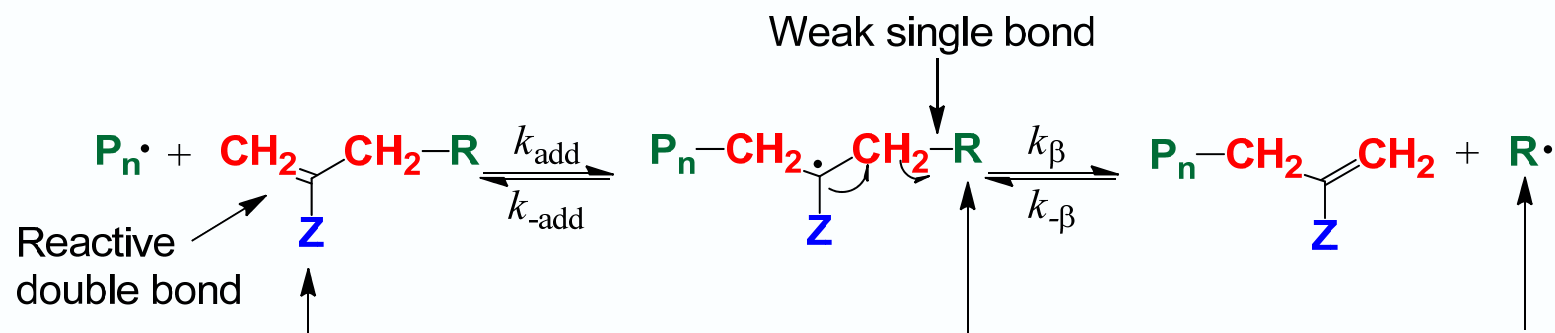
chain equilibration



termination



Macromonomer RAFT



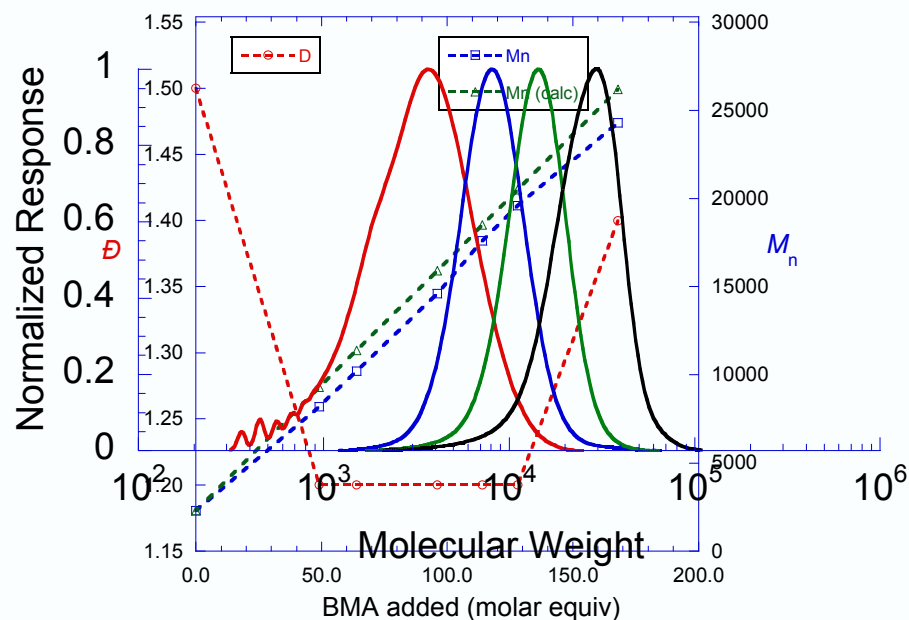
Z modifies addition and fragmentation rates

R is a homolytic leaving group, R• must be able to efficiently reinitiate polymerization

PMMA macromonomer RAFT agent (8.5 g, M_n 2300, \bar{D} 1.5, ...) and for PMMA-*block*-PBMA after additions of 33.6, 59.8, and 88.2 g of BMA

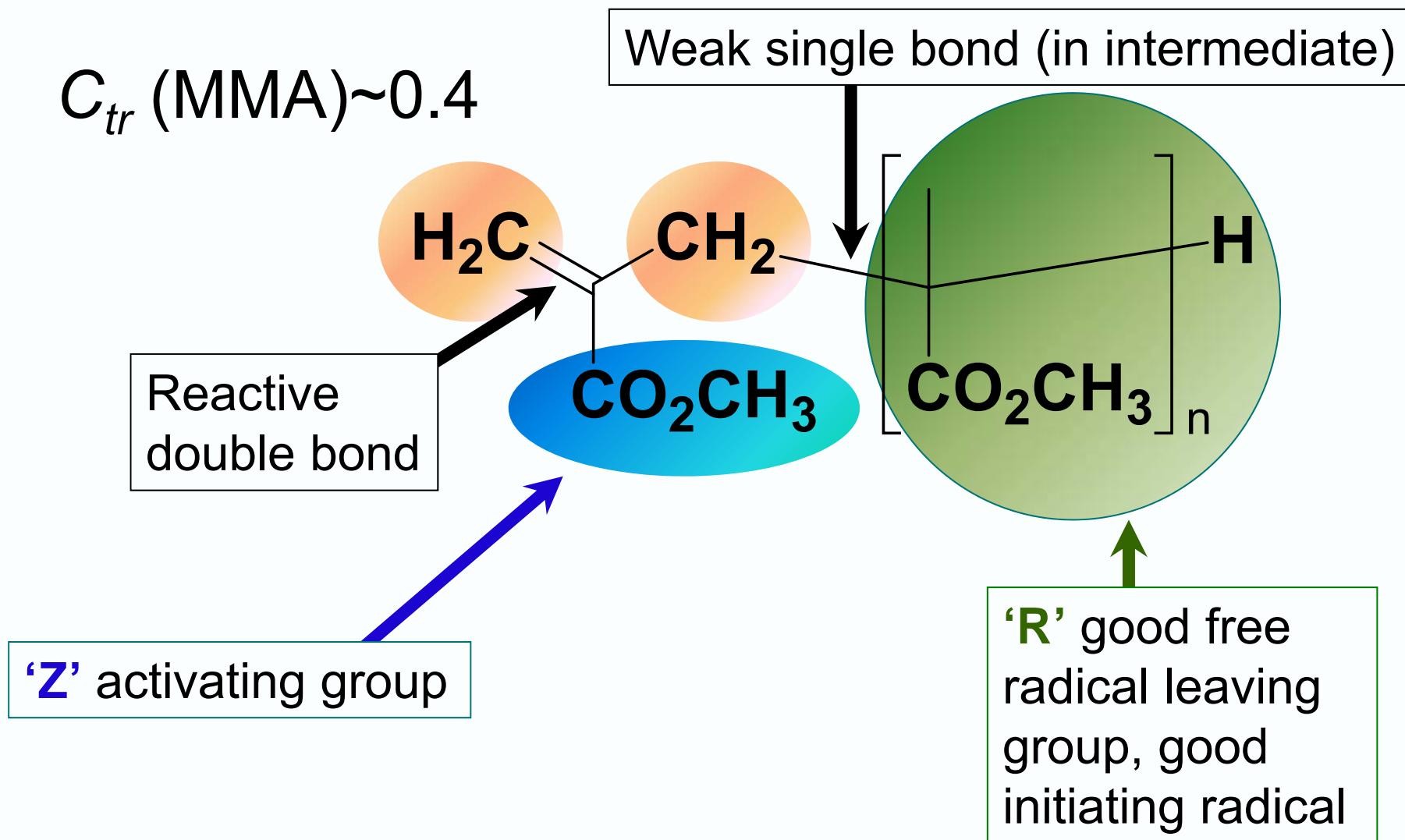
Starved feed emulsion polymerization (instantaneous conversion > 90%)

Krstina et al *Macromolecules*, 1995, 28, 5381-5385



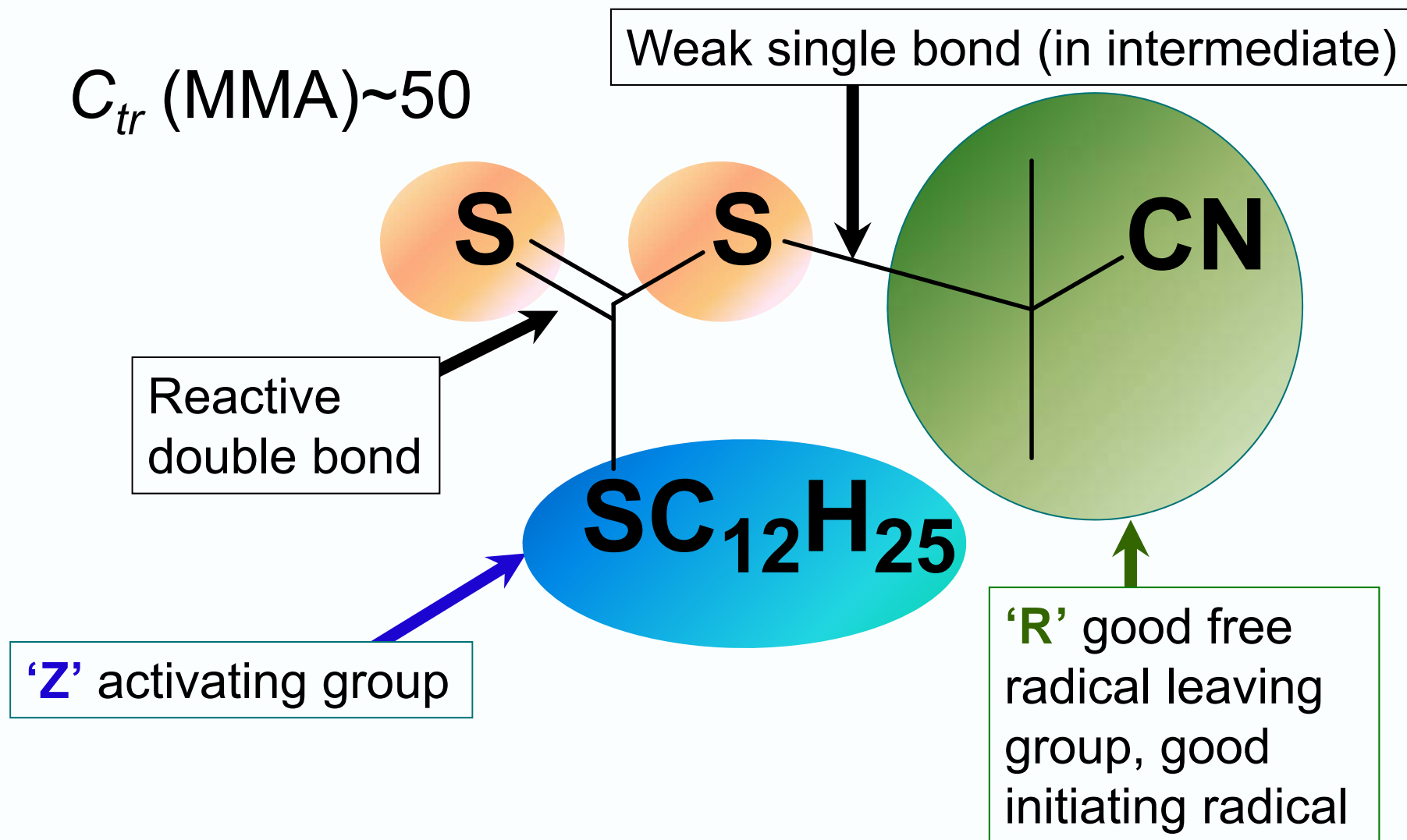
“Macromonomer” RAFT Agent

C_{tr} (MMA) ~ 0.4

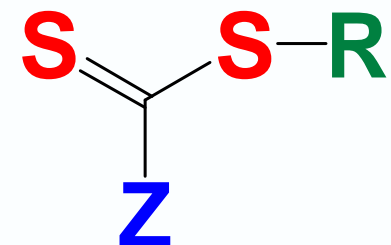


Trithiocarbonate RAFT Agent

C_{tr} (MMA) ~50



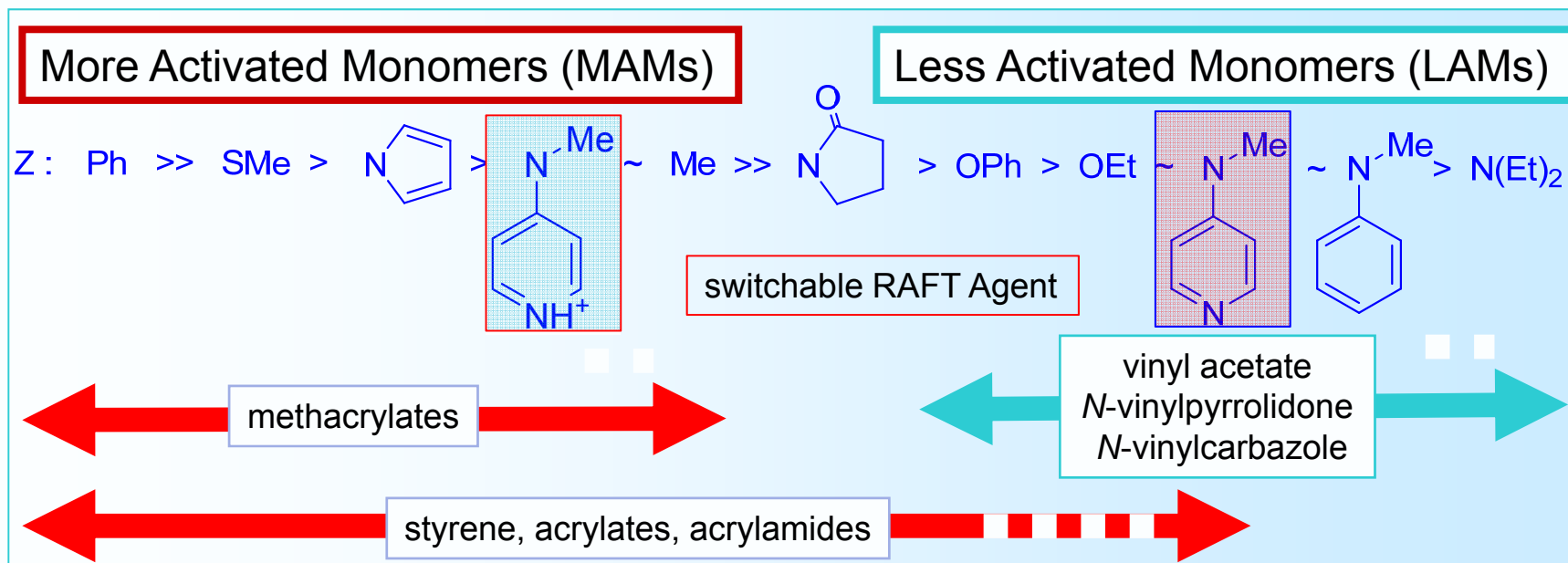
Effectiveness of RAFT Agents



Strong dependence on Z substituent

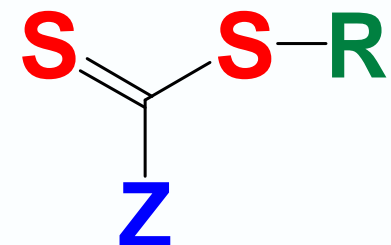
More active RAFT agents retard or inhibit polymerization of LAMs

Less active RAFT agents provide little or poor control over the polymerization of MAMs

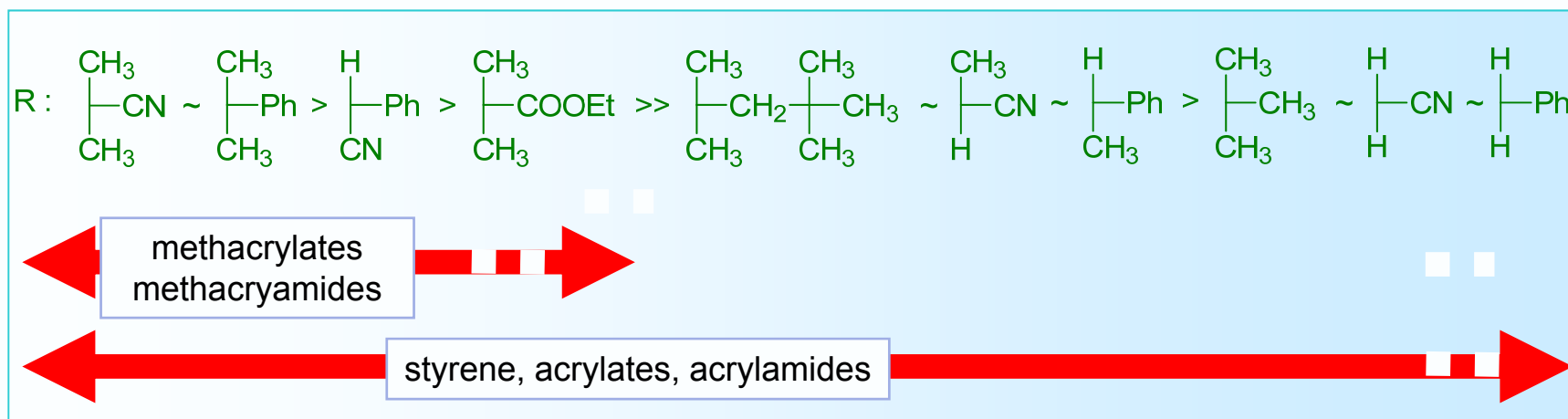


Macromolecules 2003, 36, 2273-83

Effectiveness of RAFT Agents



Strong dependence on **R** substituent



Transfer constants decrease in the series where homolytic leaving group **R** is Tertiary >> secondary > primary

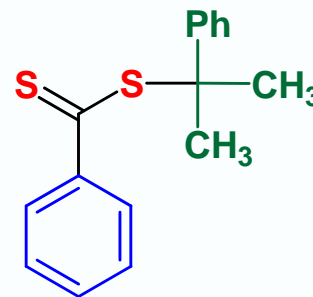
where α -substituent on **R** is CN ~ Ph >> CO₂R >> alkyl

where chain length of **R** is > 2 >> 1 (significant penultimate unit effect)

Types of RAFT agents

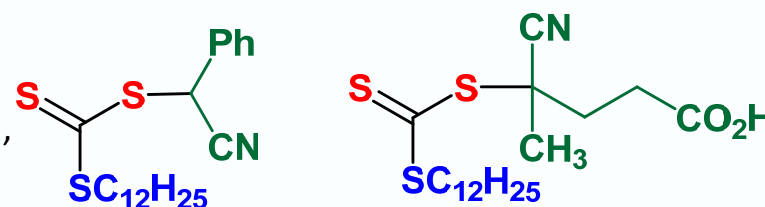
Dithiobenzoates

- Very high transfer constants
- Prone to hydrolysis
- May give retardation when used in high concentrations



Trithiocarbonates

- are readily synthesized
- high transfer constants (effective with activated monomers, e.g., acrylates, styrene)
- give less retardation and are more hydrolytically stable (than dithiobenzoates)

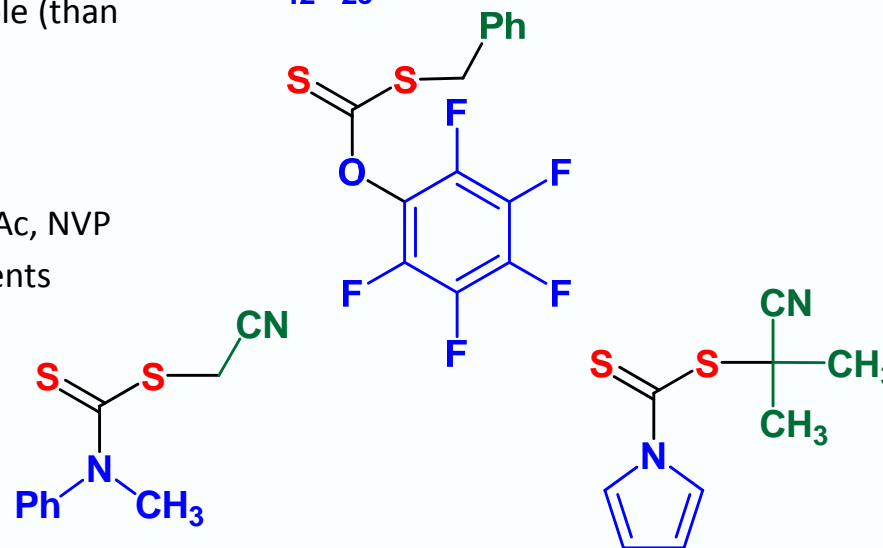


Xanthates

- lower transfer constants
- more effective with less activated monomers, e.g., VAc, NVP
- Made more active by electron-withdrawing substituents

Dithiocarbamates

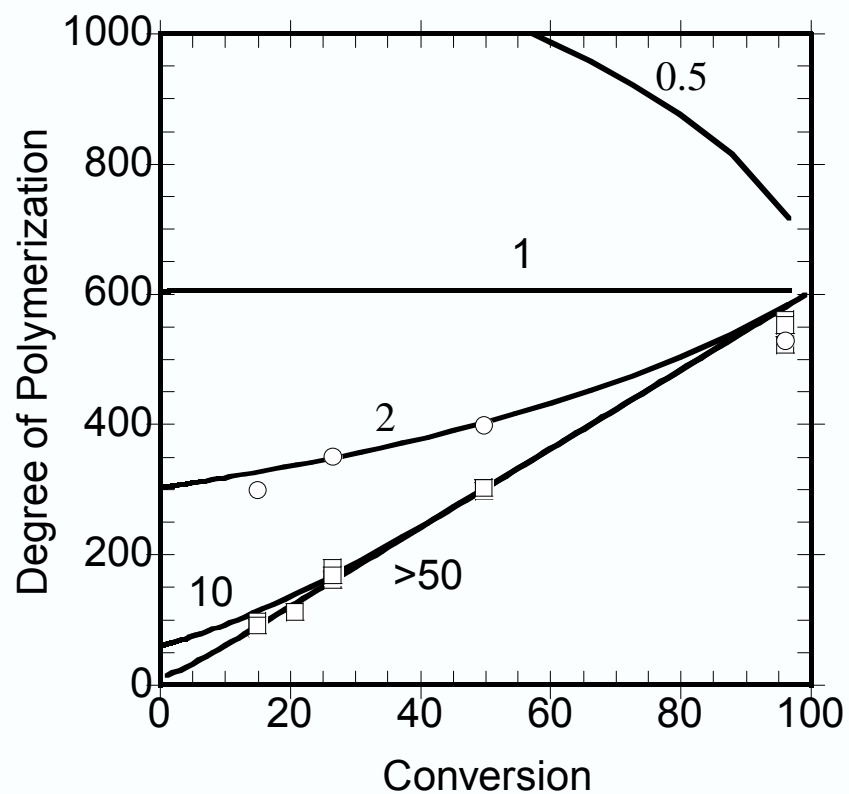
- Activity determined by substituents on N



Macromol. Symp. **2007**, 248, 104-116

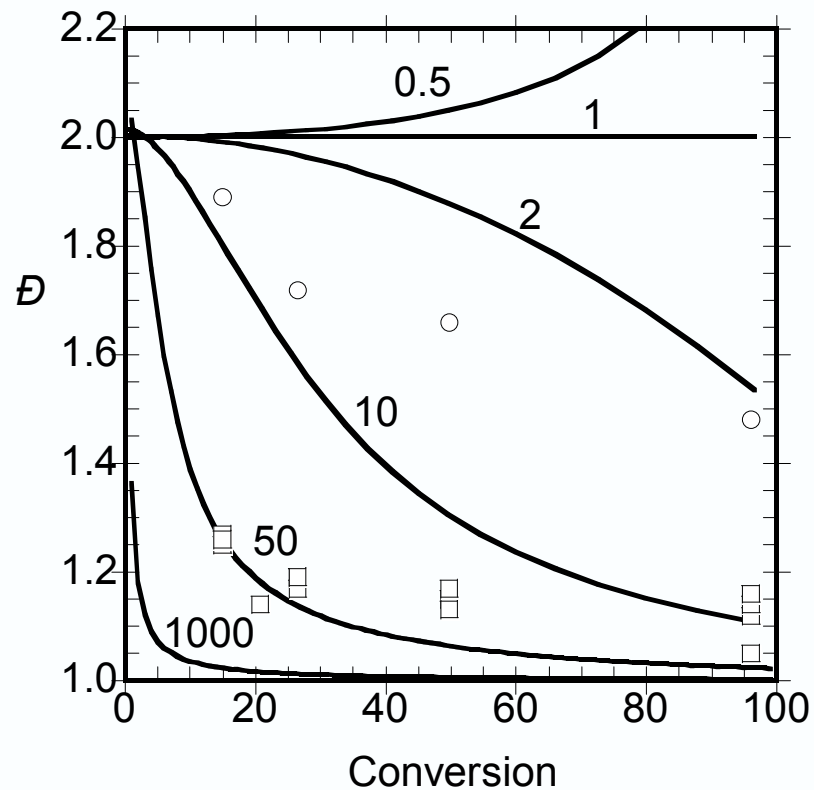
RAFT Polymerization

Dependence of degree of polymerization on transfer constant and monomer conversion



RAFT Polymerization

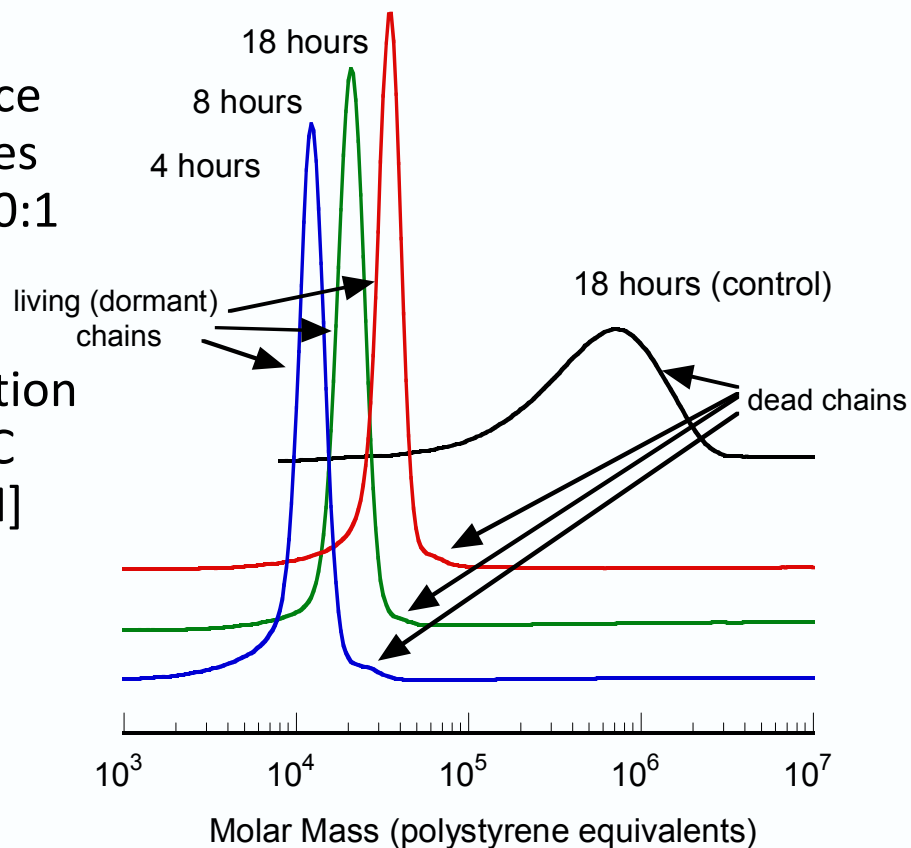
Dependence of dispersity ($\mathcal{D} = M_w/M_n$) on transfer constant and monomer conversion



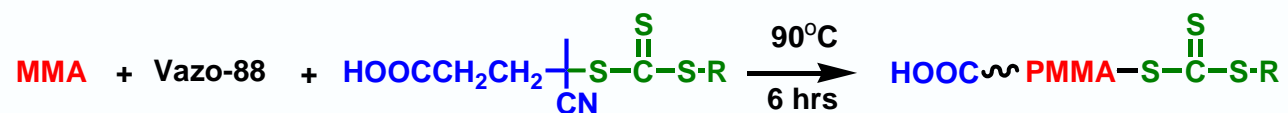
RAFT Polymerization

Ideally, the target molecular weight should be substantially lower than molecular weight seen in the absence of RAFT agent. This usually translates to ratios $[\text{RAFT agent}]:[\text{initiator}] > 10:1$

Example is bulk thermal polymerization of styrene and acrylonitrile at 100 °C with cumyl dithiobenzoate [0.123 M]

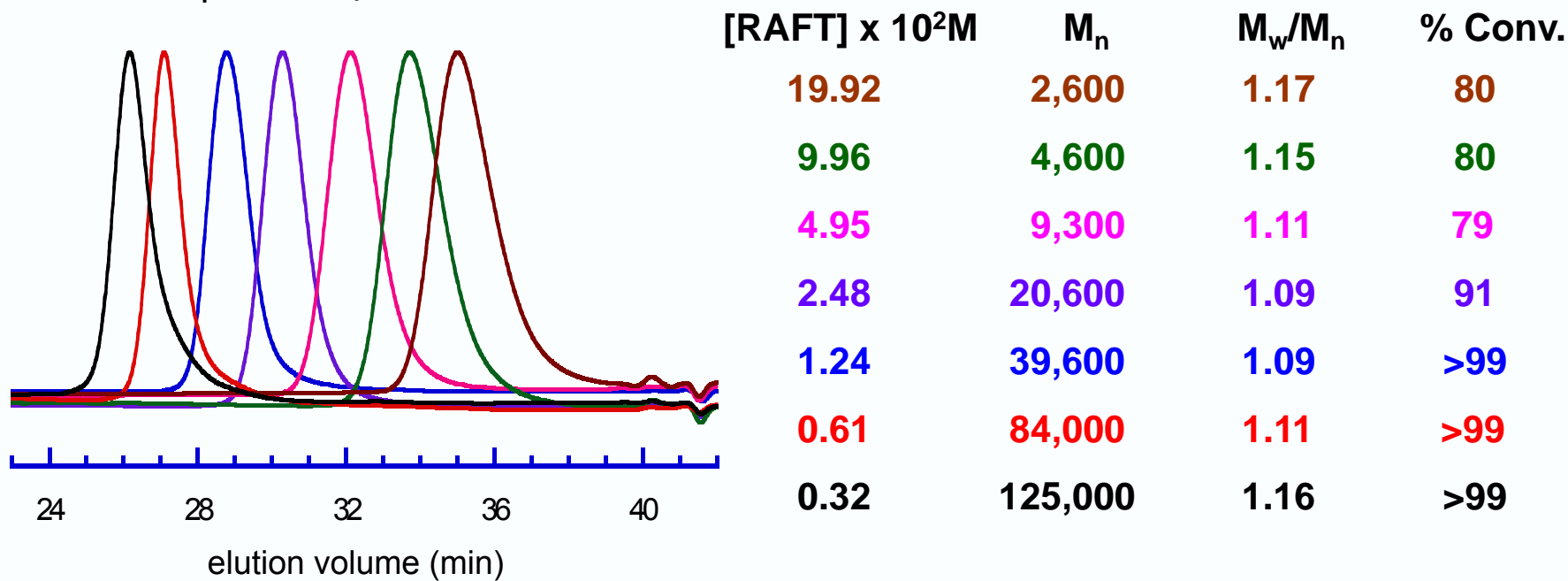


High Conversion Acid End-functional PMMA



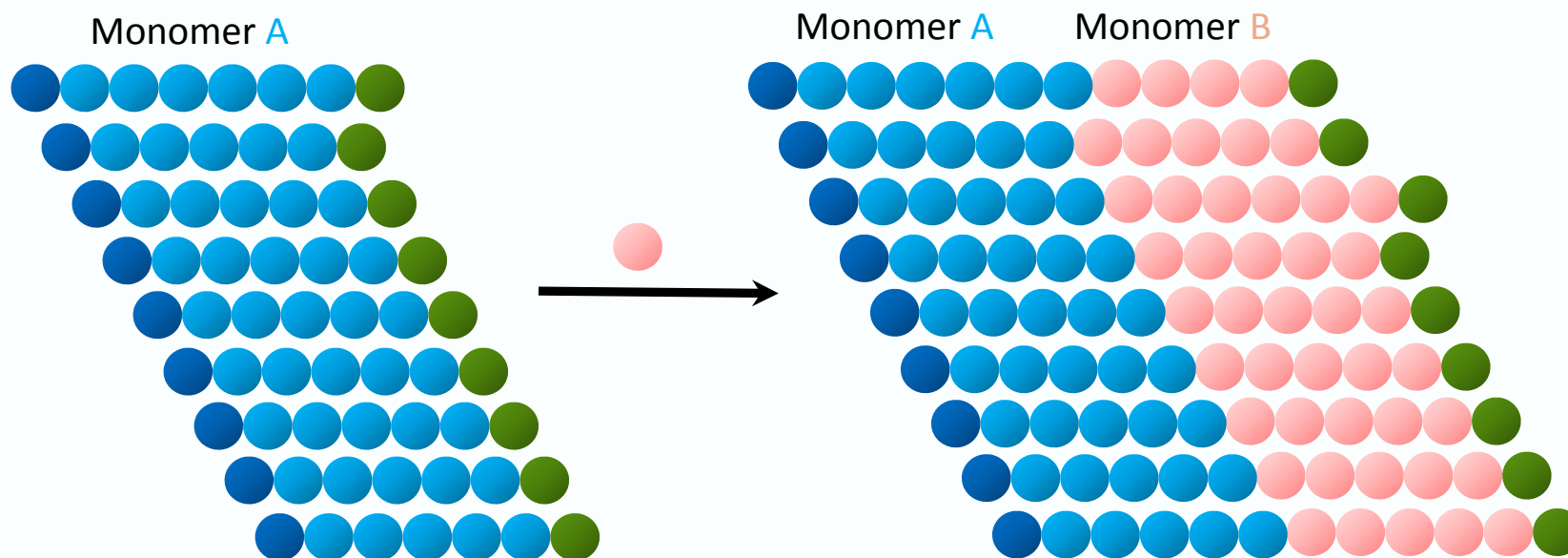
Over ~50-fold range of RAFT agent concentrations
Little retardation

Low dispersities / Monomodal distributions



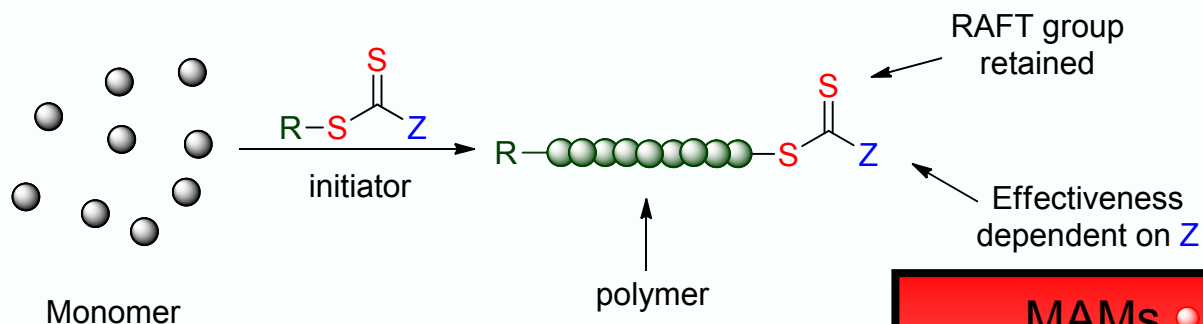
RAFT Polymerization

Because RAFT end-groups are (largely) preserved, **block** copolymers can be prepared by sequential addition of monomers.

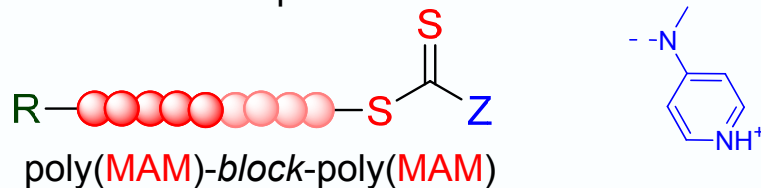


Block copolymers have a wide range of applications as dispersants, surfactants and undergo self-assembly to form nanoreactors and vehicles for delivery of actives in the biomedical, personal care and agrichemical fields. They also allow control of morphology in polymer blends.

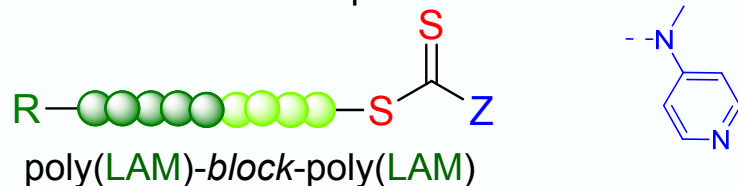
Guide to Block Copolymer Synthesis



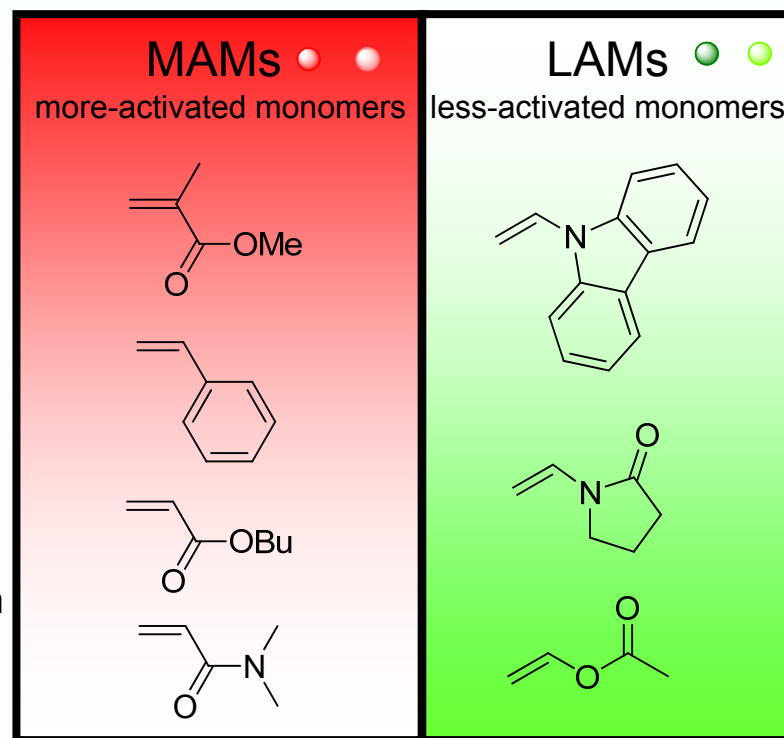
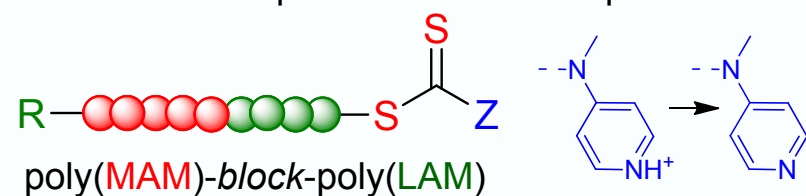
Switchable RAFT protonated form



Switchable RAFT non-protonated form



Switchable RAFT protonated $\xrightarrow{\text{switch}}$ non protonated form

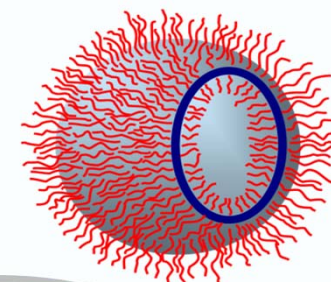
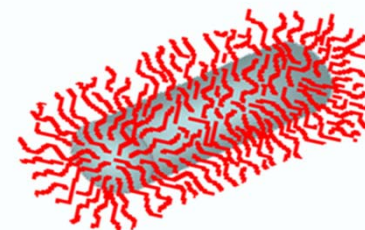
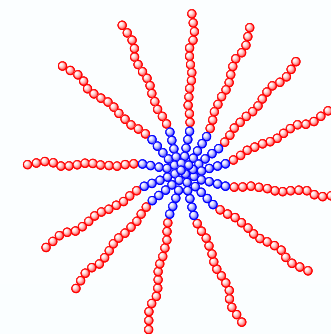
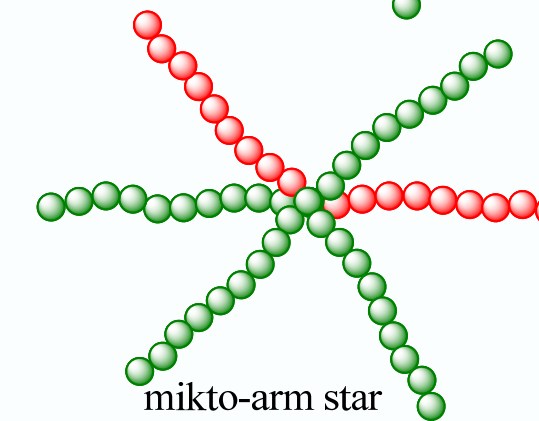
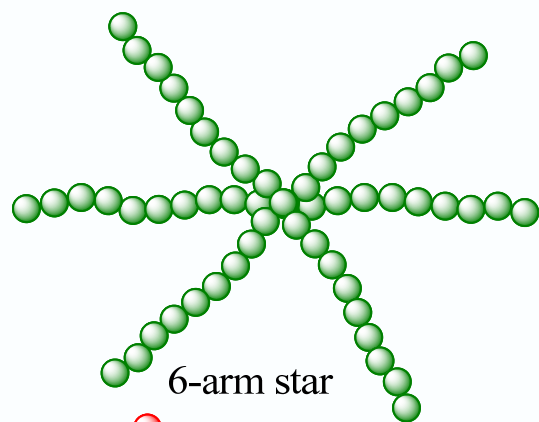
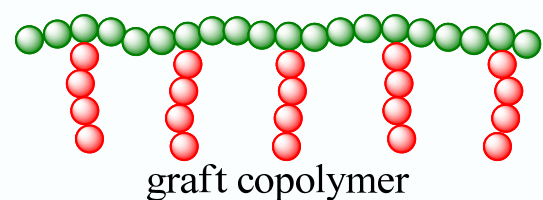
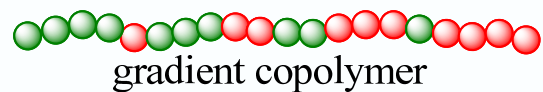
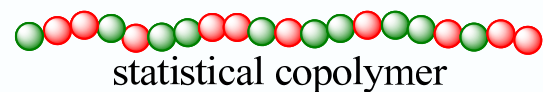


J Am Chem Soc **2009**, *131*, 6914-15

Macromolecules **2009**, *42*, 9384-6

RAFT Architectures

A wide range of architectures can be formed by choice of RAFT agent and sequence of monomer additions or by self assembly or ...



RAFT Polymerization 2011-2014

Rate of publication on RAFT continues unabated

- >1/3 of publications on RAFT have appeared during 2011-2014. Includes 2500 new journal papers and 350 patents (Scifinder™)

Continued focus on applications

- Biomedical
- Industrial
- Energy

Developments in kinetics, mechanism, new RAFT agents, end group transformation

Commercial availability of RAFT Agents

Polymer therapeutics, biopolymer conjugates, functional particles, delivery, targeting

Functional surfaces

Sequence control

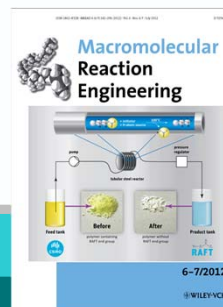
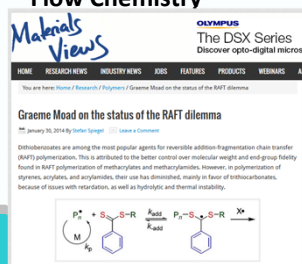
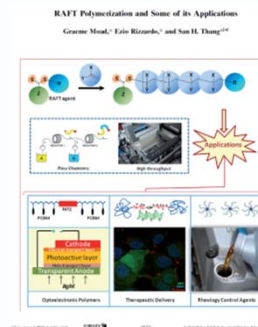
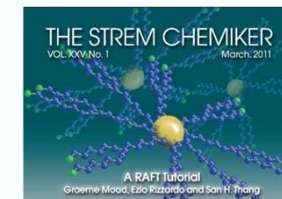
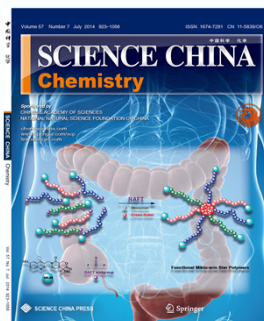
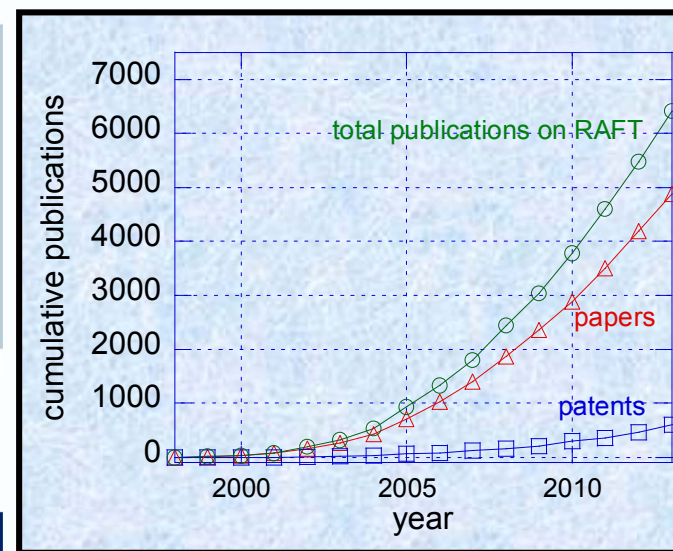
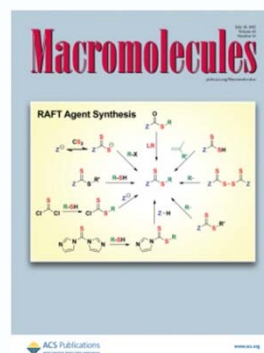
- Precision synthesis
- Multiblock copolymers

RAFT Crosslinking Polymerization

- Porous functional monoliths
- Mikto-arm copolymers

High Throughput RAFT polymerization

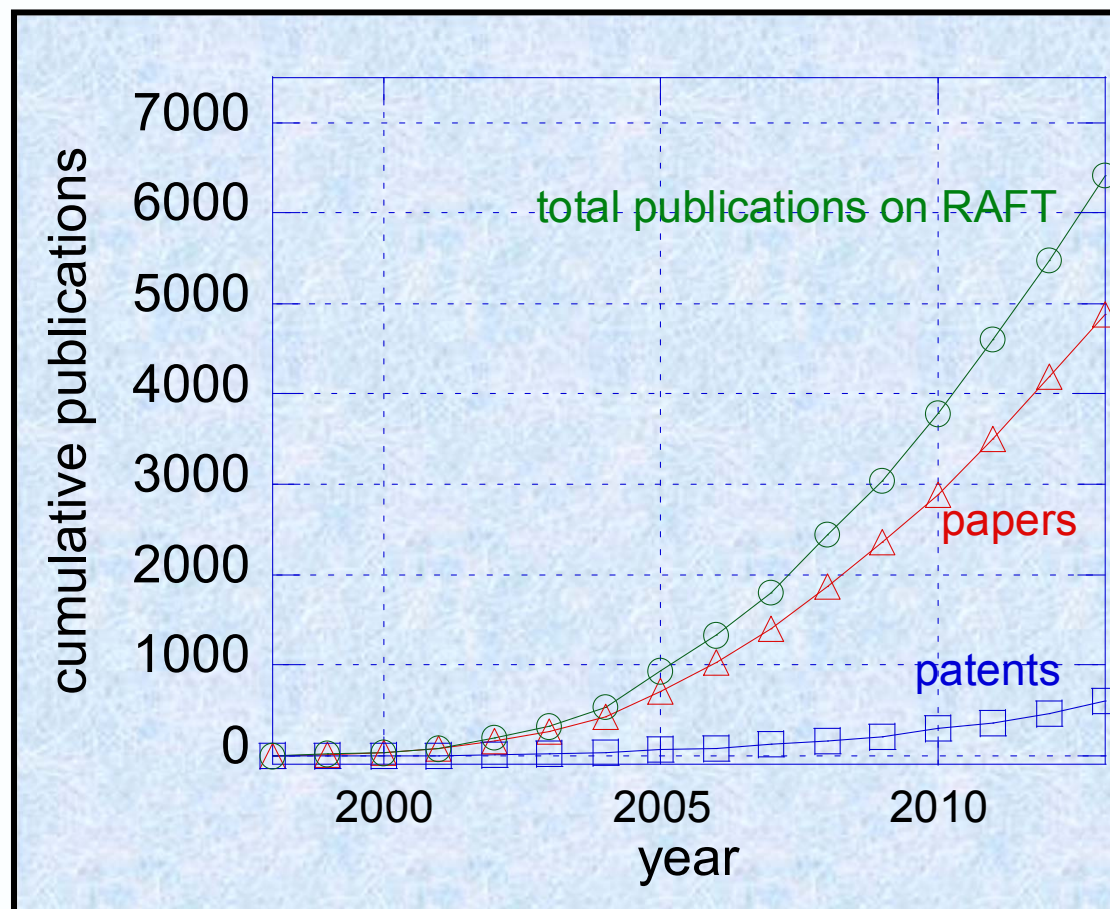
- Automated parallel synthesis
- Flow Chemistry



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 - 350 patents
- (Scifinder™)



RAFT Polymerization 2011-2014

Developments in kinetics,
mechanism, new RAFT
agents, end-group
transformation

Makrials Views OLYMPUS The DSX Series Discover opto-digital microsc

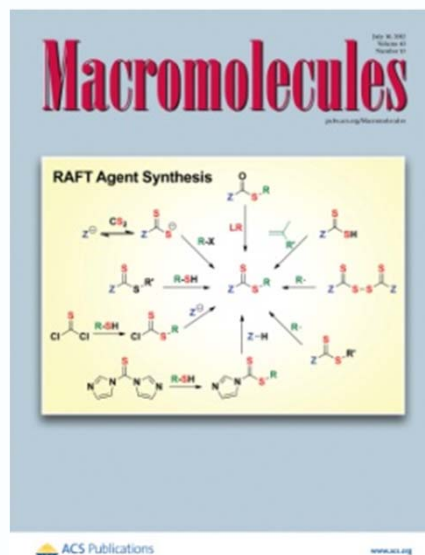
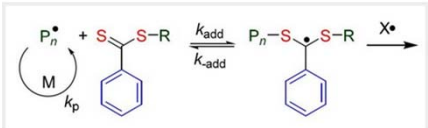
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Graeme Moad on the status of the RAFT dilemma

January 30, 2014 By Stefan Spiegel Leave a Comment

Dithiobenzoates are among the most popular agents for reversible addition-fragmentation chain transfer (RAFT) polymerization. This is attributed to the better control over molecular weight and end-group fidelity found in RAFT polymerization of methacrylates and methacrylamides. However, in polymerization of styrenes, acrylates, and acrylamides, their use has diminished, mainly in favor of trithiocarbonates, because of issues with retardation, as well as hydrolytic and thermal instability.



Volume 41 Number 1 25 January 2012 Pages 493-726

Chem Soc Rev

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TUTORIAL REVIEW
Cover: J. M. Terry
Support for the synthesis of block copolymers using controlled/living polymerization from water and CO₂ gas

RAFT Polymerization 2011-2014

Commercial availability of RAFT Agents

Commercial Quantities

Research Quantities



Product Catalogue:

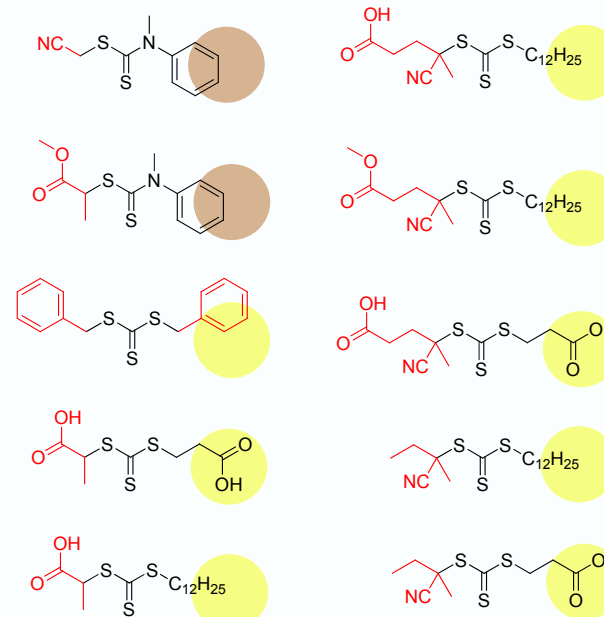
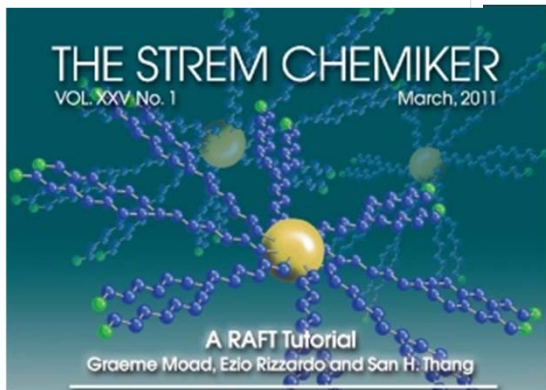
RAFT: Choosing the Right Agent to Achieve Controlled Polymerization

The RAFT Process
Classes of RAFT Agents
RAFT Agent to Monomer Compatibility Table
(Related Content)

The RAFT Process
RAFT or Reversible Addition-Fragmentation chain Transfer is a form of living radical polymerization. RAFT polymerization was discovered at CSIRO in 1988. It soon became the focus of intensive research, since the method allows synthetic tailoring of macromolecules with complex architectures including block, graft, comb, and star structures with predetermined molecular weight. RAFT polymerization is applicable to a very wide range of monomers under a large number of experimental conditions, including the preparation of water-soluble materials.¹

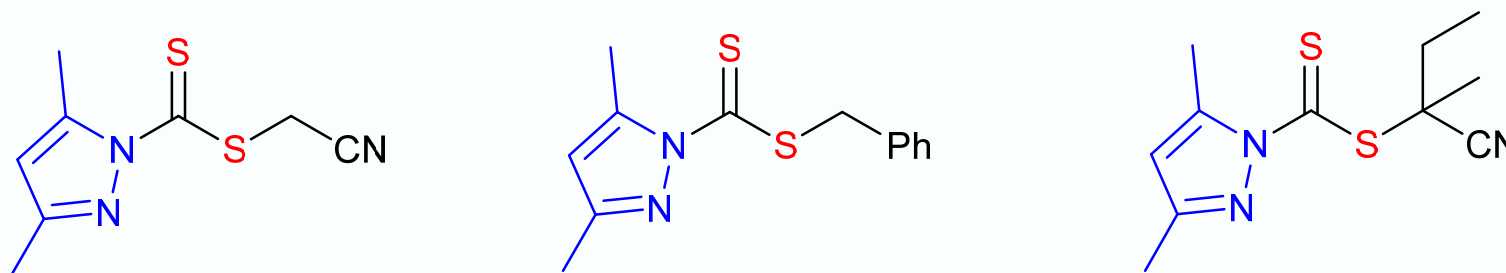
The RAFT process involves conventional free radical polymerization of a substituted monomer in the presence of a suitable chain transfer agent (RAFT agent or CTA). Commonly used RAFT agents include thiocarbonylthio compounds such as dithiobenzenes,¹ dithiocarbamates,^{4,5} s-triisobutylcarbonates,⁶ and xanthates,⁷ which mediate the polymerization via a reversible chain-transfer process. Use of a proper RAFT agent allows synthesis of polymers with low polydispersity index (PDI) and high functionality as shown below in Figure 1.

Dr. Graeme Moad, Research Team Leader at CSIRO Materials Science and Engineering — "Alairch™ Materials Science's catalogue of diverse RAFT agents enables scientists to rationally design and synthesize novel polymeric materials."
Dr. John Chiefari, Principal Research Scientist at CSIRO Materials Science and Engineering — "The variety of RAFT agents currently available allows scientists to explore new exploitation areas as diverse as biomedical, agricultural, personal care and industrial materials."
CSIRO, the Commonwealth Scientific and Industrial Research Organisation, is Australia's national science agency and one of the largest and most diverse research agencies in the world, and had this to say — "CSIRO's RAFT technology is a process for making better polymers. Alairch™ Materials Science (under licence from CSIRO) offers a diverse range of innovative RAFT agents and have now expanded their catalogue to include macro-RAFT agents and copolymers prepared using RAFT technology. CSIRO is excited to make the new custom research & development services that Alairch™ Materials Science offers researchers seeking to evaluate the performance of tailored RAFT polymers."

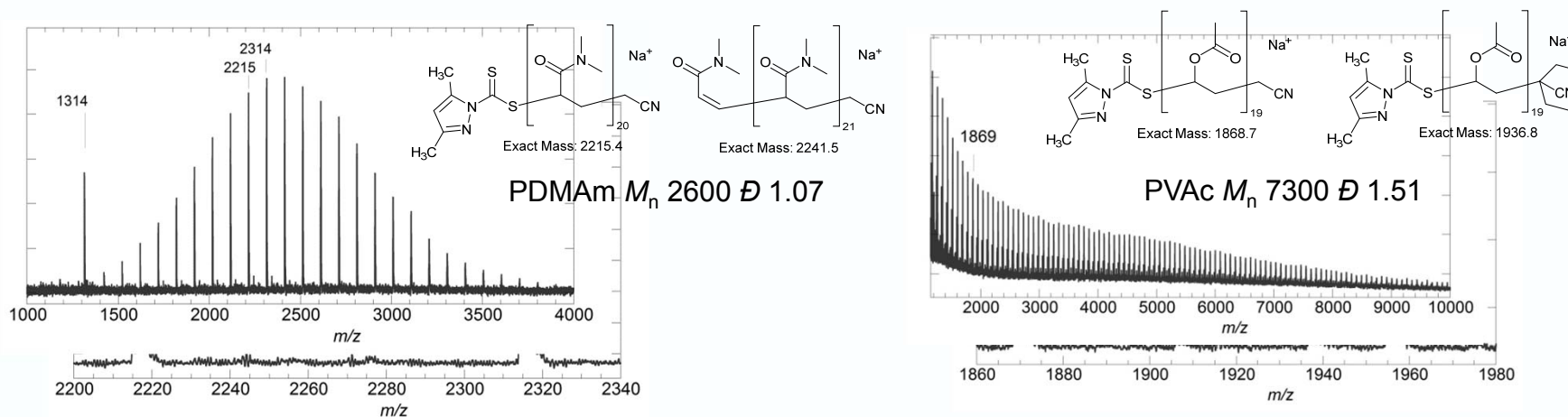


<http://www.boronmolecular.com/Products/Raft-Agents>

Dithiocarbamate RAFT agents with broad applicability – the 3,5-Dimethyl-1H-pyrazole-1-carbodithioates



- Readily synthesized (commercially available)
- Similar activity to trithiocarbonates with acrylates, acrylamides
- Good control over vinyl acetate (though some retardation)

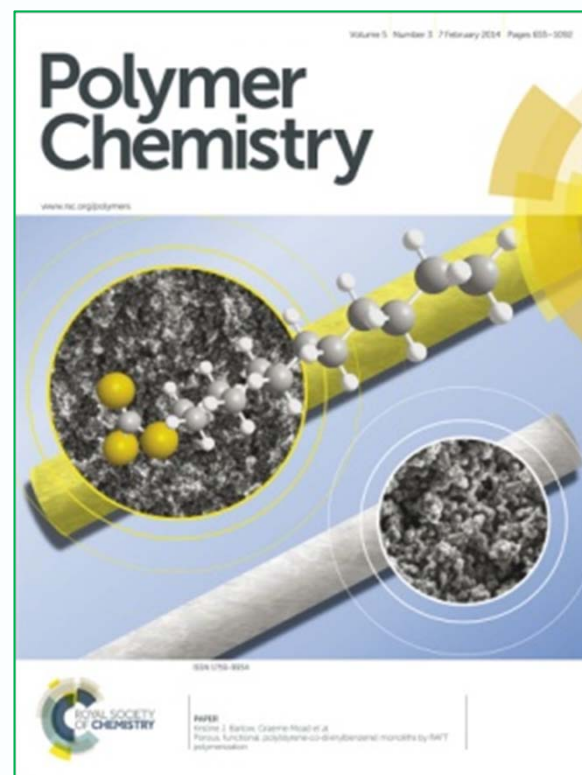


Gardiner et al., *Polym. Chem.* **2015**, doi: 10.1039/C5PY01382H.

RAFT Polymerization 2011-2014

RAFT Crosslinking Polymerization

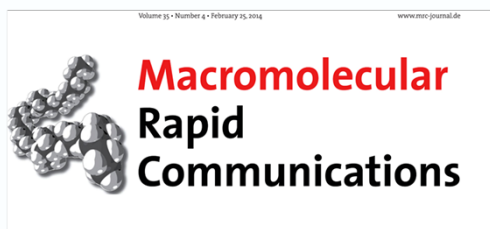
- Porous functional monoliths
- Mikto-arm copolymers



RAFT Polymerization 2011-2014

High Throughput RAFT polymerization

- Automated parallel synthesis
- Flow Chemistry



Rapid and Systematic Access to Quasi-Diblock Copolymer Libraries Covering a Comprehensive Composition Range by Sequential RAFT Polymerization in an Automated Synthesizer (pages 492–497)

Joris J. Haven, Carlos Guerrero-Sanchez, Daniel J. Keddie and Graeme Moad
Article first published online: 29 AUG 2013 | DOI: 10.1002/marc.201300459



A versatile, cost-effective approach to the rapid, fully unattended preparation of systematic quasi-diblock copolymer libraries by sequential RAFT polymerization in an automated synthesizer is reported.

[Abstract](#) | [Full Article \(HTML\)](#) | [Enhanced Article \(HTML\)](#) | [PDF\(1104K\)](#)
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Guest-Edited by: I. R. Lutz, B. Sumerlin, and K. Matyjaszewski
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Encompassing all aspects of synthetic and biological macromolecules, and related topics
Impact Factor 5.231 | 24 Issues per Year

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Paper
One pot synthesis of higher order quasi-block copolymer libraries via sequential RAFT polymerization in an automated synthesizer

Joris J. Haven¹, Carlos Guerrero-Sanchez^{1*}, Daniel J. Keddie^{2,3}, Graeme Moad^{2,3}, San H. Thang² and Ulrich S. Schubert^{2,3}

Show Affiliations

Polym. Chem., 2014, Advance Article
DOI: 10.1039/C4PY00496E
Received 08 Apr 2014, Accepted 15 May 2014
First published online 16 May 2014

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Abstract | Cited by | Related Content

Recently developed sequential reversible addition–fragmentation chain transfer (RAFT) polymerization protocols allow the rapid, fully unattended preparation of quasi-block copolymer libraries that cover a wide range of copolymer compositions in an automated synthesizer. This contribution explores the scope and limitations of this sequential approach for the synthesis of higher order quasi-multiblock copolymers (including copolymer sequences of BAB, CABC and ABCD). These syntheses illustrate the utility of this high-throughput approach to the one pot synthesis of functional polymers of increased complexity. Additionally, the use of an experimental technique for method development is highlighted.



Macromolecular Reaction Engineering
6-7/2012
WILEY-VCH

Polymer Libraries
the sky is the limit

Continuous Flow Processing at CSIRO



Vapourtec - R2/R4 system

Flow Chemistry techniques enable efficient scale up to access larger quantities of materials

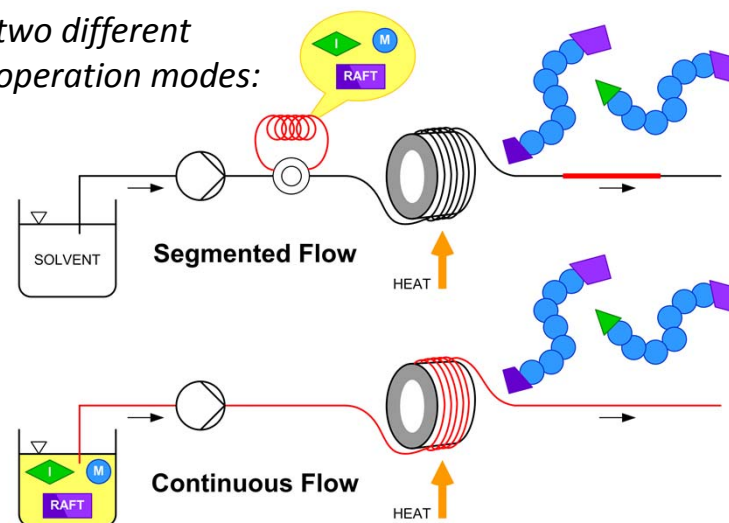
Applying to RAFT technology

- Access RAFT agents
- Polymer synthesis



tubular reactor units:

two different operation modes:



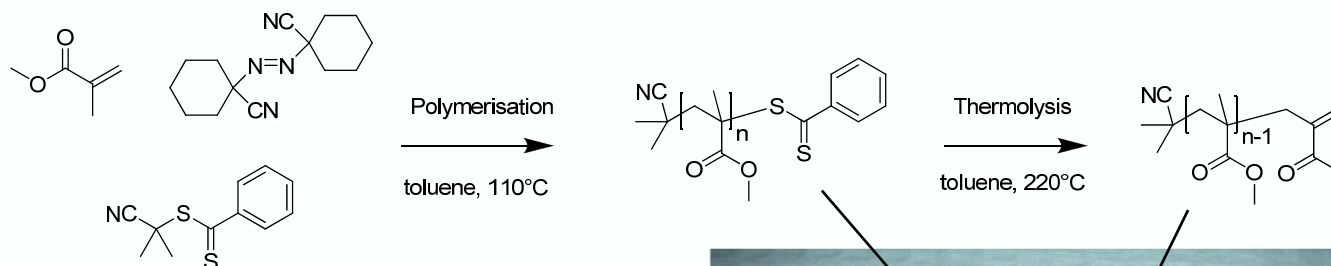
Flow Thermolysis – Two Step Process

Reaction conditions:

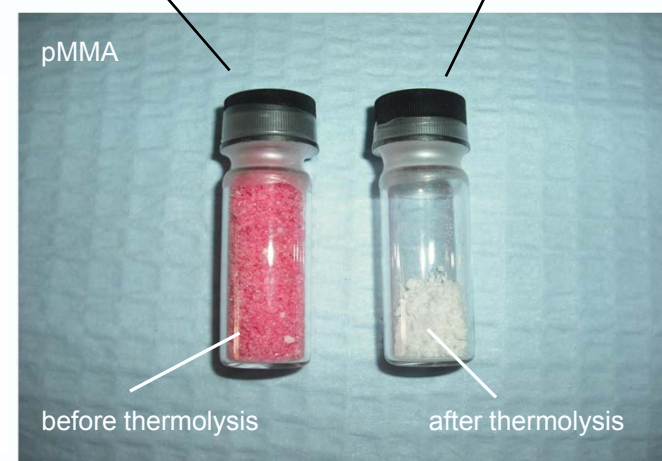
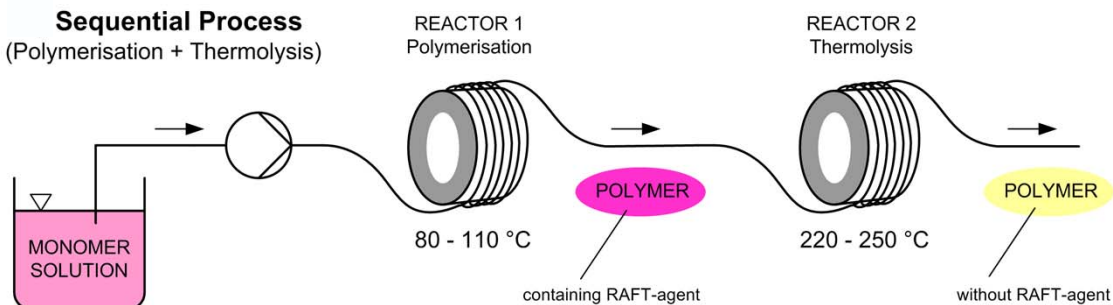
SS reactor coil – 10 ml

Reaction time: 60 min

Reaction temperature: 220 – 250 °C



Sequential Process
(Polymerisation + Thermolysis)



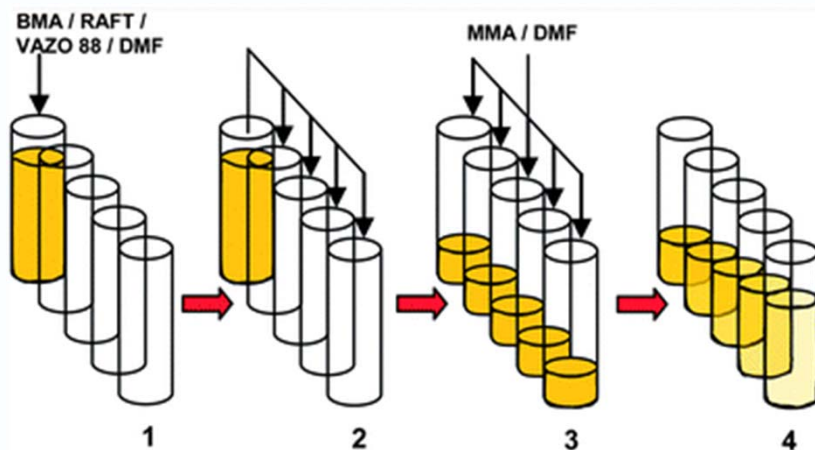
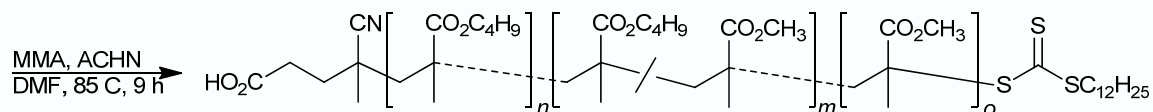
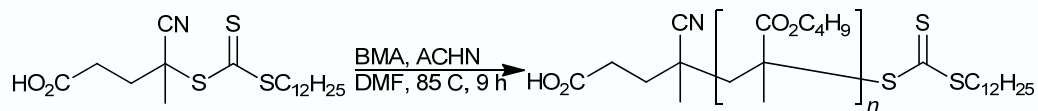
polymer	reactor 1 (polymerisation)	reactor 2 (thermolysis)	molar ratio M/R/I	T [°C]	t [h]	conversion [%]	M _n [g/mol]	Đ [-]
pMA	10 ml	5 ml	100/1.2/0.3	110 / 230	2 / 1	97 / 85	7700	1.29
pMA	batch	batch	100/1.2/0.3	110 / 230	2 / 1	97 / 64	9200	1.33
pMMA	10 ml	5 ml	100/1.2/0.4	100 / 220	2 / 1	46 / ~100	7500	1.19
pMMA	10 ml	5 ml	100/1.2/0.4	110 / 220	2 / 1	59 / ~100	7300	1.15
pMMA	2 × 10 ml	5 ml	100/1.2/0.4	110 / 220	4 / 1	84 / ~100	8700	1.17

polymerisation

thermolysis

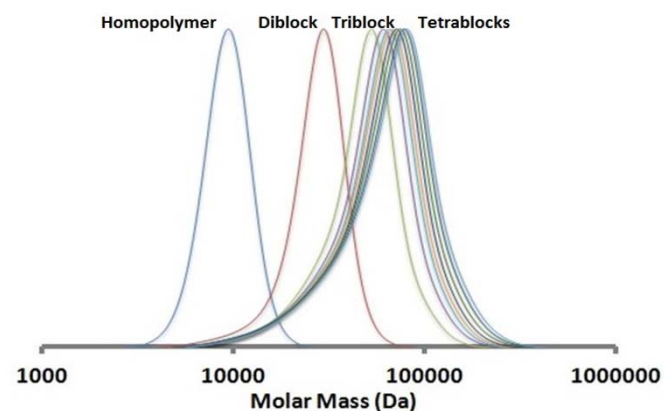
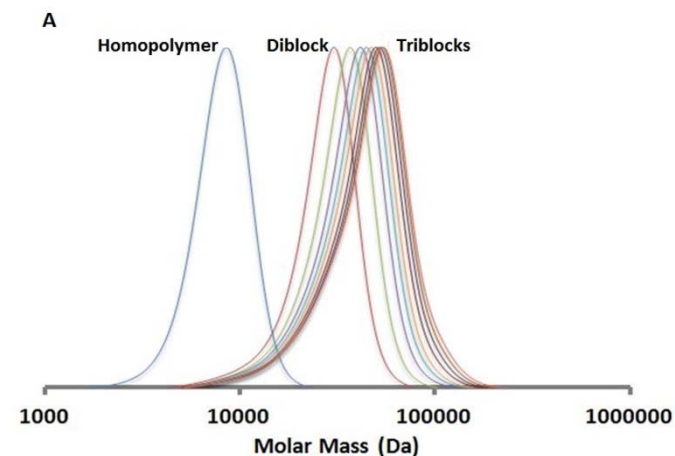
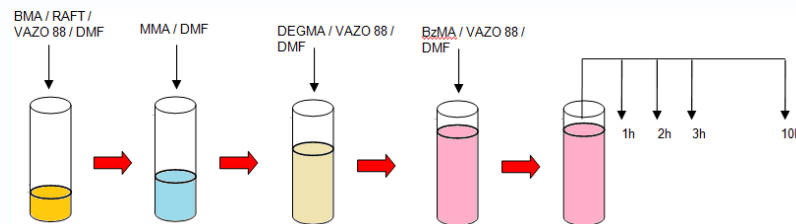
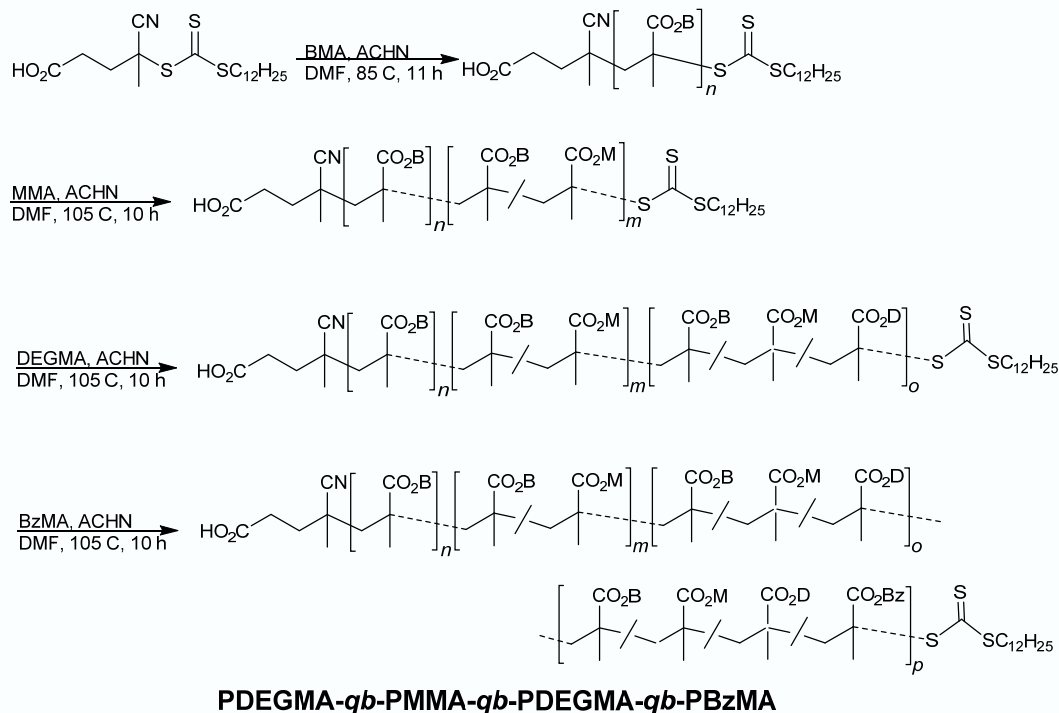
High-Throughput RAFT

Protocol for performing high-throughput RAFT Polymerization have been developed using the Chemspeed™ platform



High-Throughput RAFT

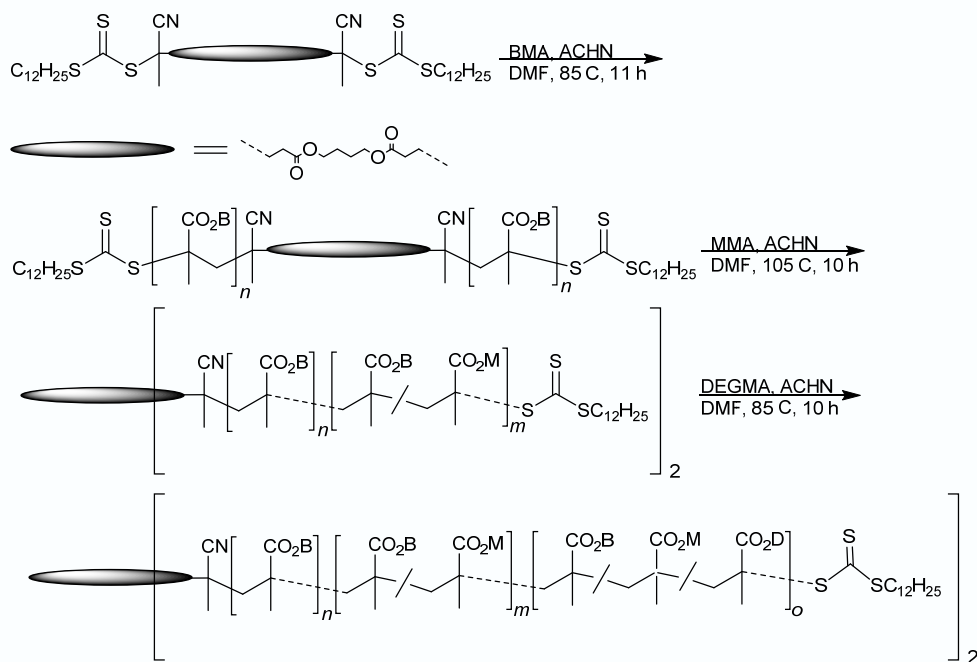
Protocol for performing high-throughput RAFT Polymerization have been developed using the Chemspeed™ platform



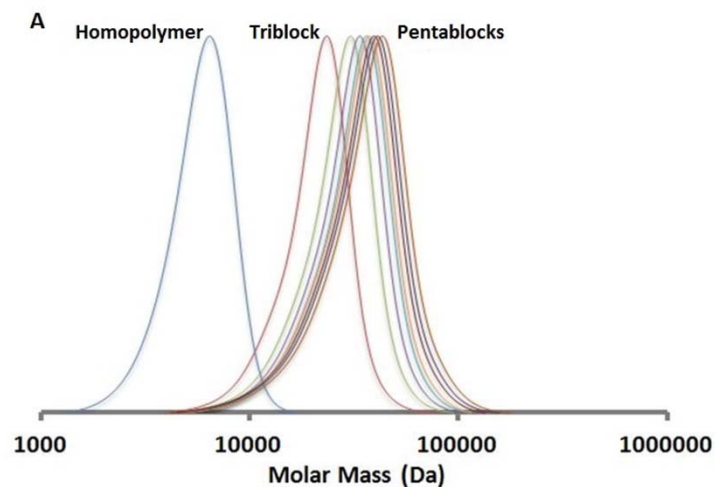
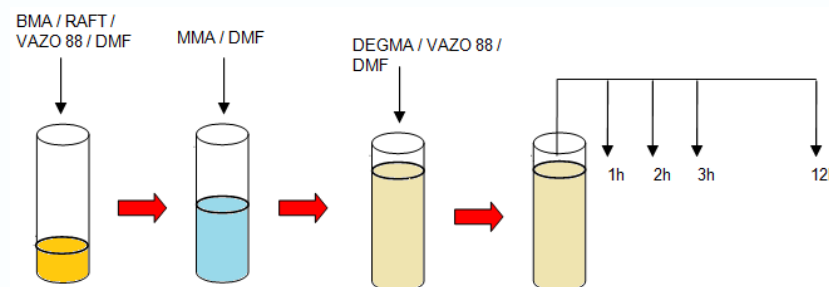
Haven et al. *RAFT Polym. Chem.* 2014, doi: 10.1039/C4PY00496E

High-Throughput RAFT – multiblock synthesis

Protocol for performing high-throughput RAFT Polymerization have been developed using the Chemspeed™ platform



PDEGMA-qb-PMMA-qb-PBMA-qb-PMMA-qb-PDEGMA



RAFT: a process for making better polymers

There are commercial applications in a wide range of industrial and consumer products including polymers for:

- drug delivery
- biomaterials
- personal care
- agrichemicals
- industrial lubricants
- adhesives and dispersants
- paints
- electronics



RAFT Polymerization 2011-2014

Continued focus on applications

- Biomedical
- Industrial
- Energy

REVIEW

www.rsc.org/polymers | Polymer Chemistry

Functional polymers for optoelectronic applications by RAFT polymerization

Graeme Moad,^{*} Ming Chen, Matthias Häussler, Almar Postma, Ezio Rizzardo and San H. Thang

Received 11th June 2010, Accepted 13th July 2010

DOI: 10.1039/c0py00179a

This review focuses on the approaches to the synthesis of functional polymers for optoelectronic applications that make use of radical polymerization with reversible addition-fragmentation chain transfer (RAFT) polymerization. Optoelectronic applications include hole/electron transport in photovoltaics (OPVs), light emitting diodes (OLEDs and PLEDs), thin-film transistors (TFTs), sensors, light-harvesting and related applications. In this context we consider metallopolymers (polymers that incorporate a metal or possess metal ligating functionality as a pendant group to the backbone, as an end-group or as a connecting group), organic semiconductors (polymers with an organic semiconductor moiety either as a block or as a pendant group), and various surfaces, nanoparticles and quantum dots that are formed by RAFT polymerization or where a RAFT-synthesized polymer forms an integral part of the process or structure.

Organic &
Biomolecular
Chemistry

Cite this: *Org. Biomol. Chem.*, 2011, **9**, 6111

www.rsc.org/obc

Dynamic Article Links

PAPER

Block copolymers containing organic semiconductor segments by RAFT polymerization†‡

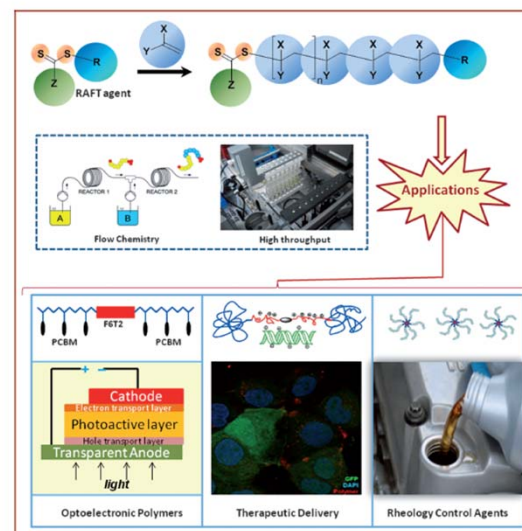
Ming Chen,^{*} Matthias Häussler,^{*} Graeme Moad^{*} and Ezio Rizzardo

Received 21st February 2011, Accepted 9th June 2011

DOI: 10.1039/c1ob05276d

RAFT Polymerization and Some of its Applications

Graeme Moad,^{*} Ezio Rizzardo,^{*} and San H. Thang^{†[a]}



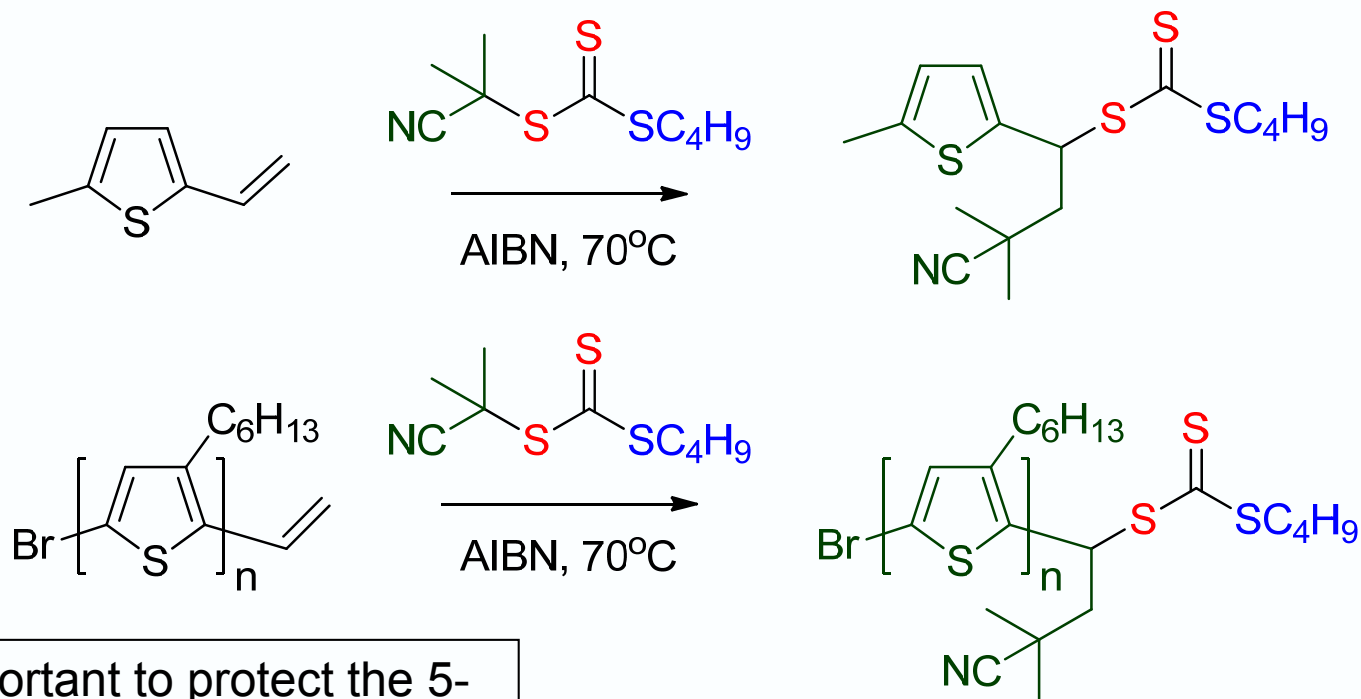
Chem. Asian J. 2013, 8, 1634–1644

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Polythiophene based Macro-RAFT Agents

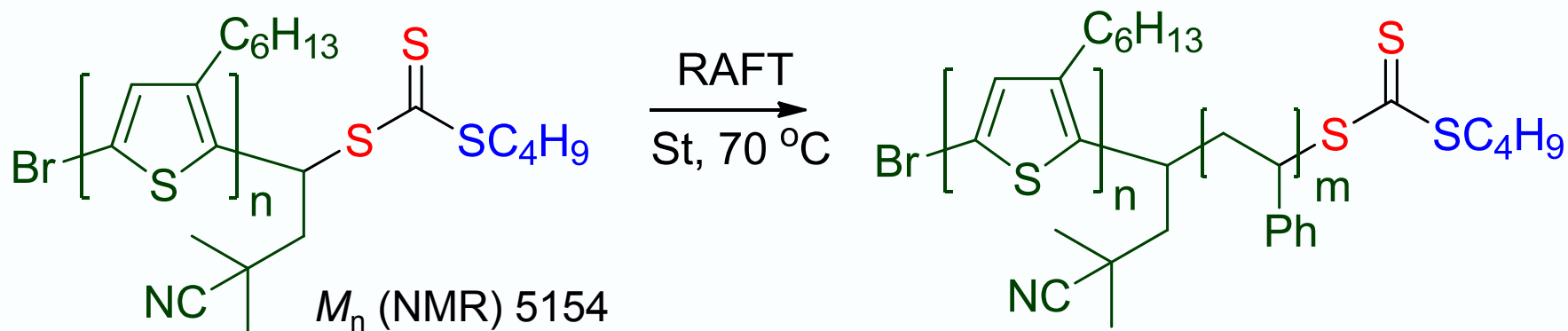


Important to protect the 5-position of the thiophene ring to avoid side reactions

Chen, M.; Haeussler, M.; Moad, G.; Rizzardo, E., Block Polymers Containing Organic Semiconductor Segments by RAFT Polymerization. *Org. Biomolecular Chem.* **2011**, *9*, 6111-6119.

Poly(3-hexylthiophene)-*block*-polystyrene

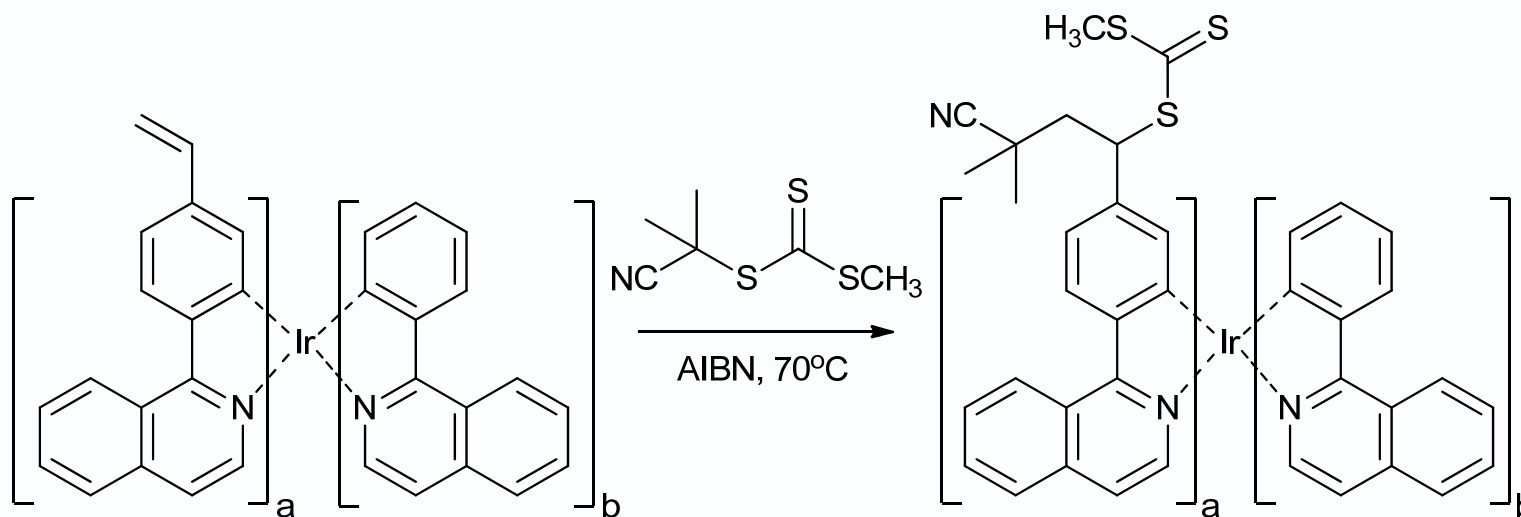
Bulk styrene polymerization at 70 °C



mole ratio			GPC			
Styrene	Macro-RAFT	AIBN	Time (h)	Conv. (%)	M_n	M_w/M_n
2000	4	1	20	57	86600	1.12

Chen, M.; Haeussler, M.; Moad, G.; Rizzardo, E., Block Polymers Containing Organic Semiconductor Segments by RAFT Polymerization. *Org. Biomolecular Chem.* **2011**, *9*, 6111-6119.

Polymer Light-Emitting Diodes (PLEDS)



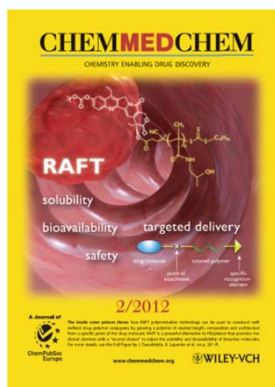
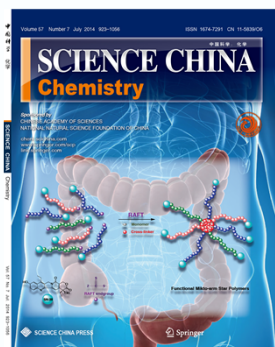
Macro-RAFT agent synthesis from iridium complex by single unit monomer insertion. Examples prepared with $a=1,2,3$; $b=2,1,0$. Used in mediating RAFT polymerization of “host monomer”.

R. Adhikari et al. *J Inst Image Inform Televis Eng*
2012, 66, 370-376

RAFT Polymerization 2011-2014

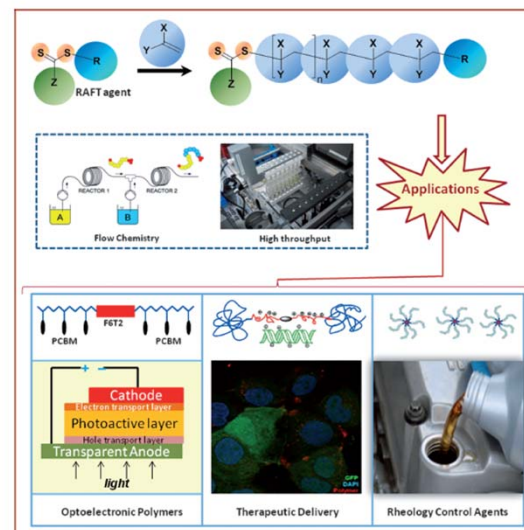
Continued focus on applications

- Biomedical
- Industrial
- Energy



RAFT Polymerization and Some of its Applications

Graeme Moad,[®] Ezio Rizzardo,[®] and San H. Thang^{©[a]}



Chem. Asian J. 2013, 8, 1634–1644

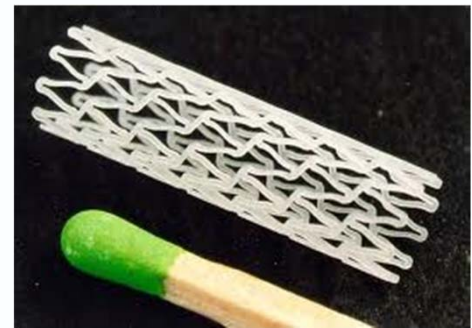
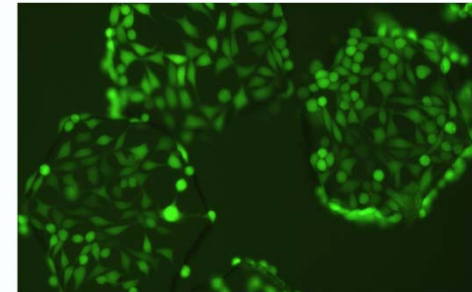
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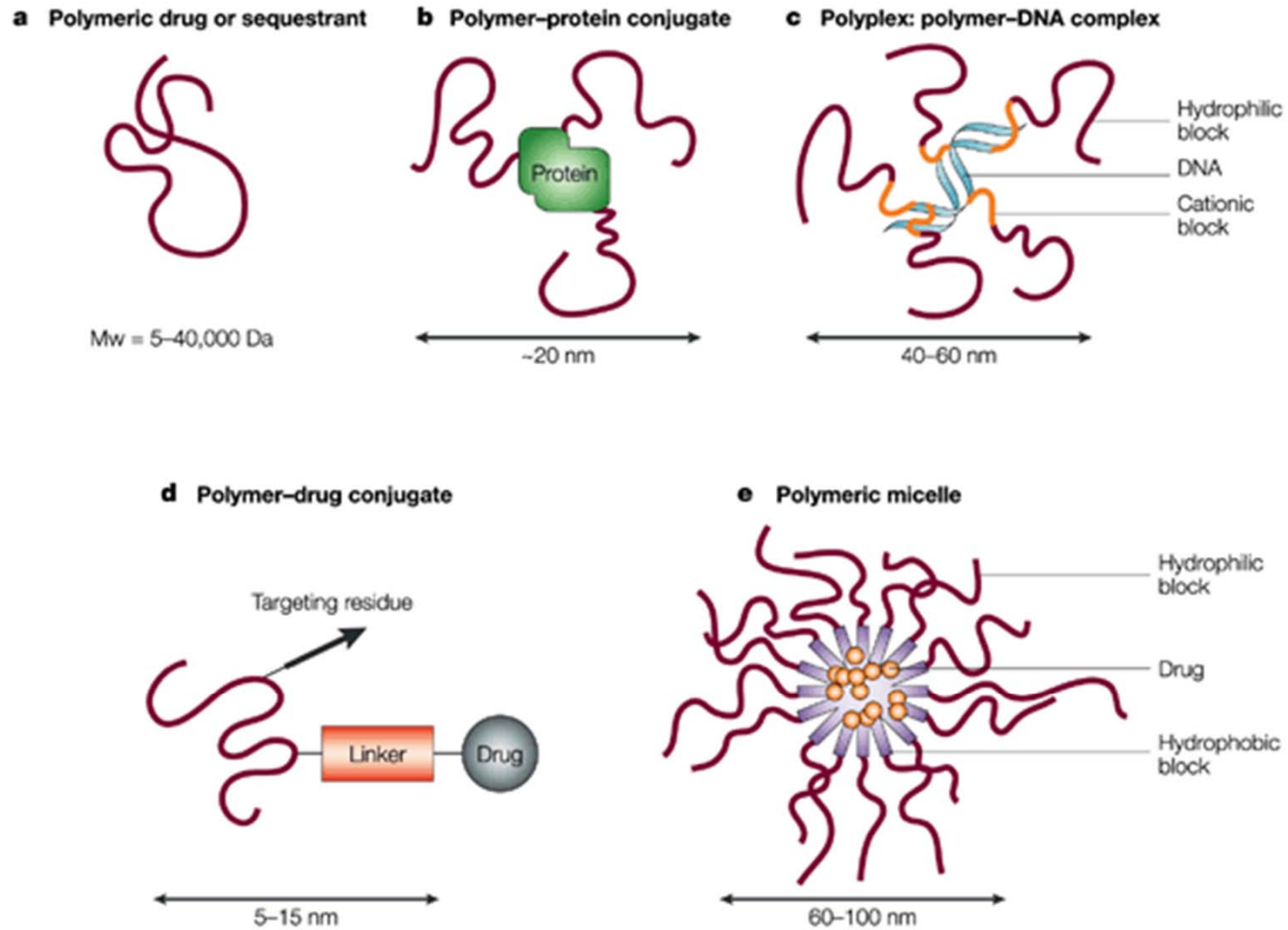
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RAFT Biomaterials

- Synthetic surface coatings on materials for large scale production of cells
 - Increased safety (no transmission of disease)
 - Reduced costs (synthetic materials)
- Coating of biomedical devices
 - Anti-infection coatings
 - Reduction of rejection by the body i.e. “foreign body response”
 - Integration of devices into tissue
- Coatings on tissue engineering scaffolds
 - Synthetic coatings on scaffold materials e.g. textile meshes for hernia repair



Polymer Therapeutics

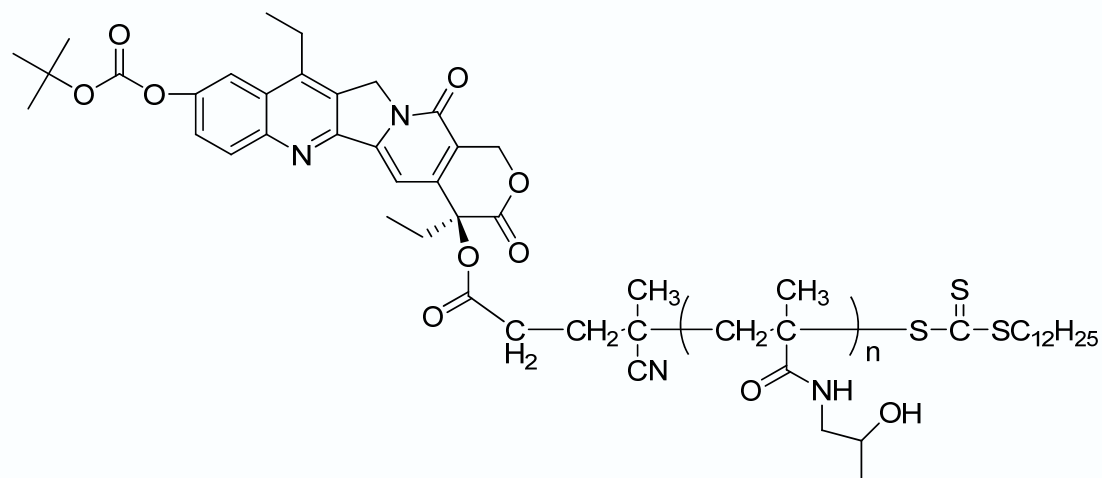
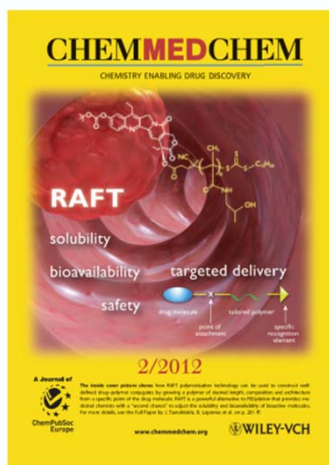
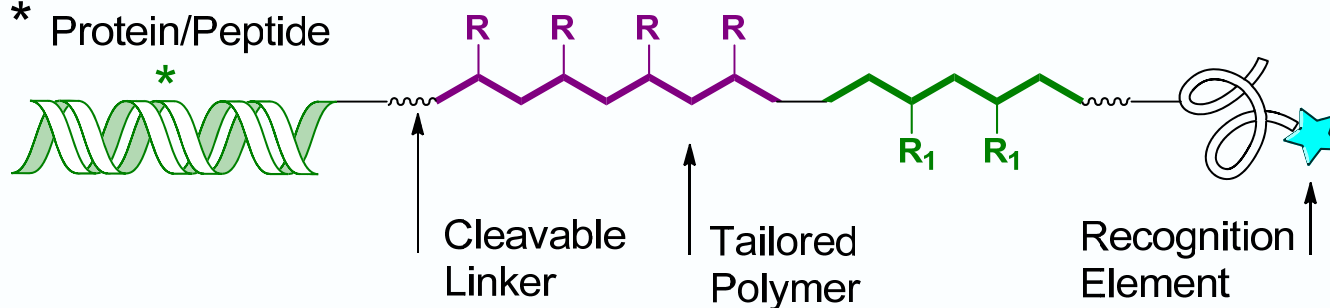


Nature Reviews | Drug Discovery

R. Duncan, 2003

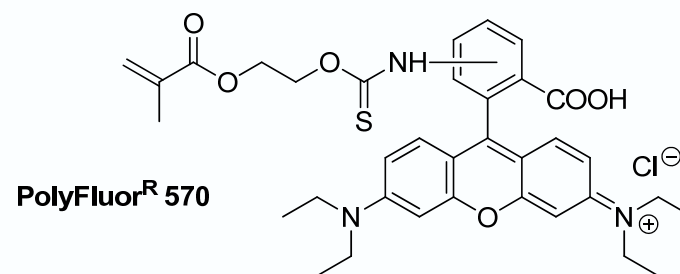
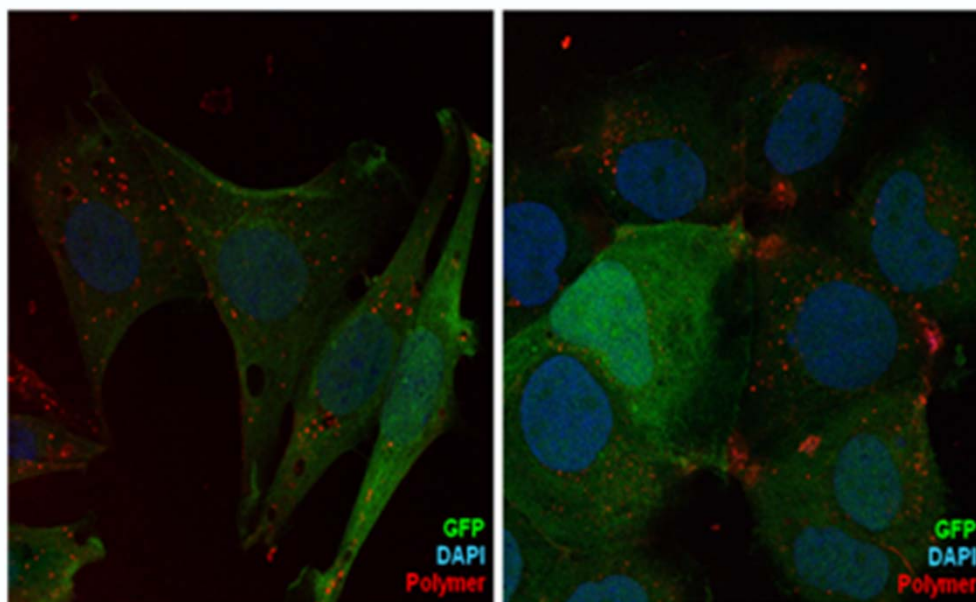
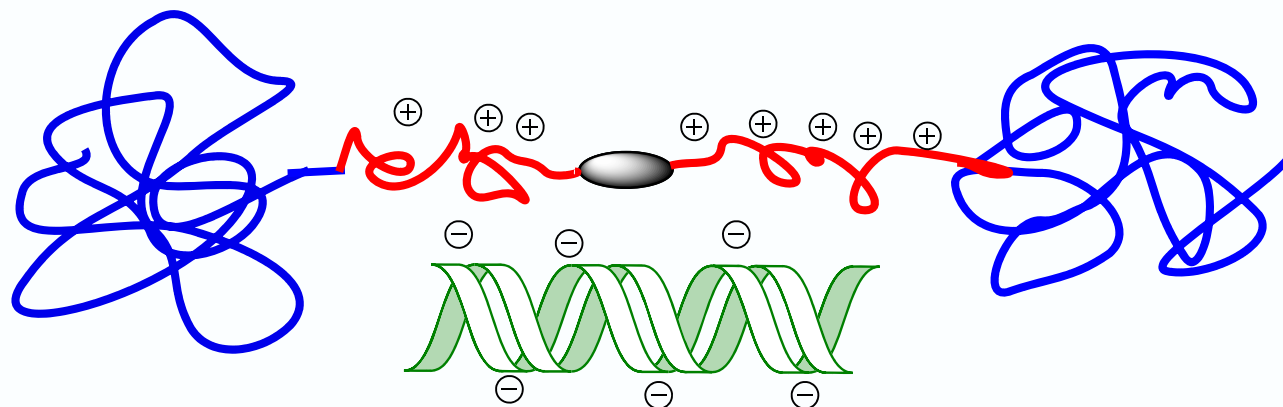
RAFT Biopolymer Conjugates

- * Small molecule
- * RNA
- * Protein/Peptide



Williams et al. *ChemMedChem* 2012, 7 (2), 281-291.

RAFT for siRNA Delivery



Confocal scanning microscopy images demonstrating cellular uptake of red fluorescent RAFT polymer-siRNA complex incorporating PolyFluor[®] 570

Hinton et al. *Biomaterials* 2012, 33 (30), 7631-7642.

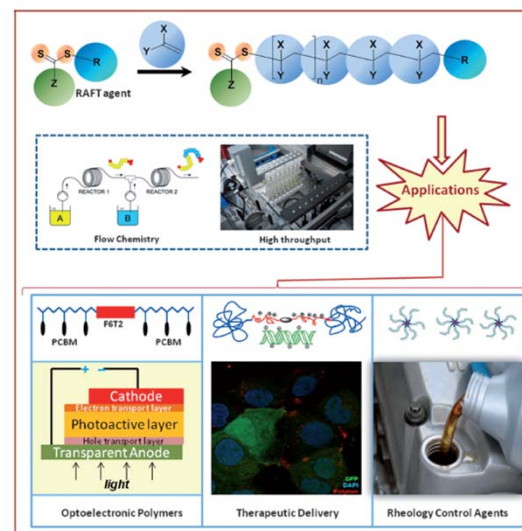
RAFT Polymerization 2011-2014

Continued focus on applications

- Biomedical
- Industrial
- Energy

RAFT Polymerization and Some of its Applications

Graeme Moad,[®] Ezio Rizzardo,[®] and San H. Thang^{©[a]}



Chem. Asian J. 2013, 8, 1634–1644

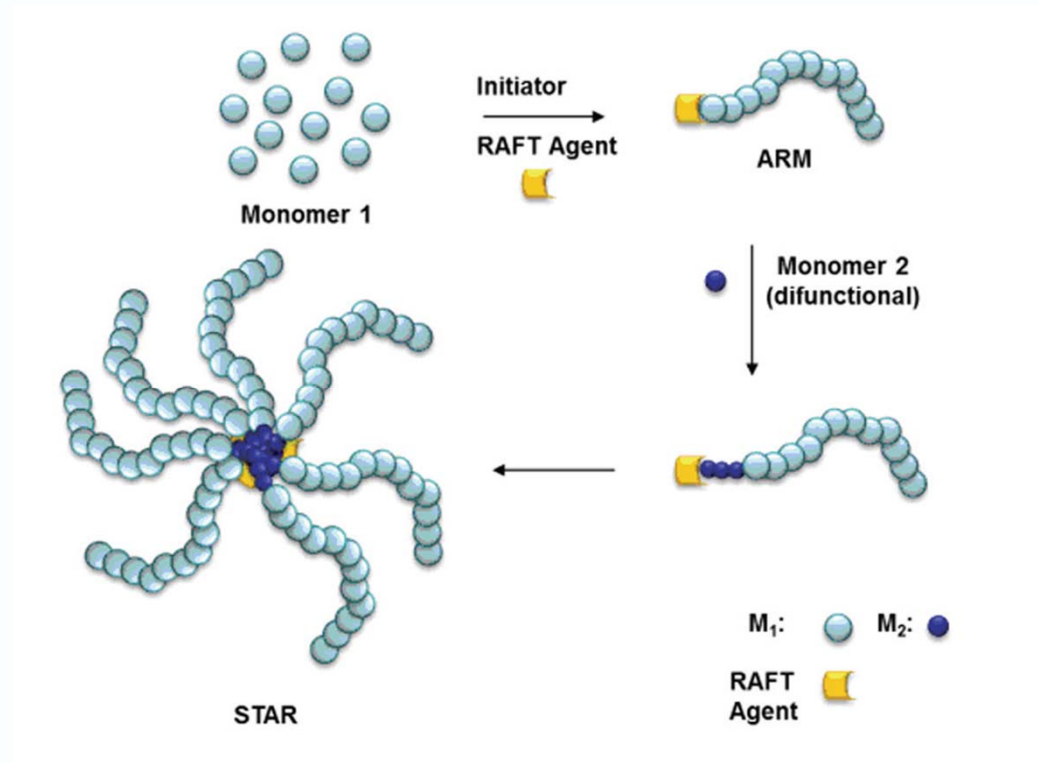
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Lubrizol's Asteric™ PMA Viscosity Modifiers

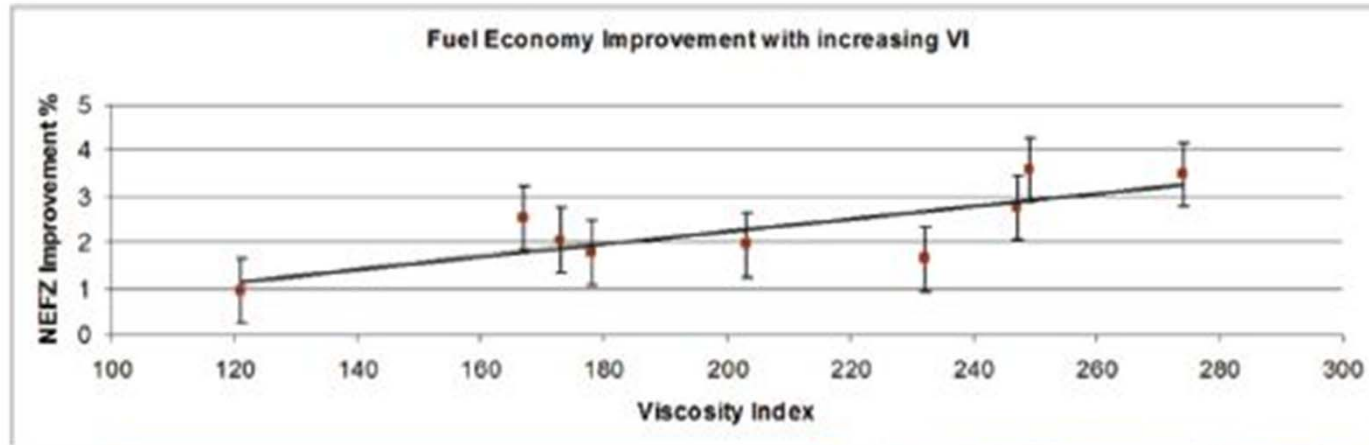
Lubrizol



- Next generation of fuel and energy efficient lubricants
 - Lower viscosity at cold temperatures
 - Higher viscosity index

Fuel Economy Improvement

Lubrizol



European drive cycle testing showed a linkage between increased viscosity index and greater vehicle fuel economy



Figure 3. Higher VI linkage to improved fuel efficiency.

Low Fouling Desalination Membranes



Antimicrobial testing (*Staphylococcus epidermidis*)



Control



With polymer brush

Reversible Addition Fragmentation Chain Transfer

RAFT Polymerization

Some Applications

Conclusions and Outlook

Take Home Messages

RAFT Polymerization can provide a multitude of polymers of varying size, shape and composition

Polymer chemists in collaboration with biologists, physicists, material scientists and others are developing a vast range of very exciting (many potential, some actual) products

Multidisciplinary teams are essential for success and so there is a need to collaborate

Acknowledgments

RAFT Team 2011-2015

Kristine Barlow
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Xiaojuan Hao
Joris Haven
Matthew Hendrikx
Tim Hughes
Tracey Hinton
Christian Hornung
Shadi Houshyar
Oliver Hutt

Daniel Keddie
Guoxin Li
Stuart Littler
Ivan Martinez-Botella
Roger Mulder
Tash Polyzos
Almar Postma
[Ezio Rizzardo](#)
Julien Rosselgong
Simon Saubern
[San Thang](#)
John Tsanaktsidis
Kathleen Turner
XiaoHu Wei
Charlotte Williams

Thank you

CSIRO Manufacturing Flagship
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